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Roumen Kaltchev

Dissolved Air Flotation

Equipment, Best Practice and Applications

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Preface

The idea of writing this book crept into my mind years ago. Still a young engineer in industrial effluent treatment, I was interested in the “little secrets” of some water treatment technologies and especially in the corresponding equipment. At that time, there was no Internet, and the books I could find were mostly general and almost never thematic. They described more or less succinctly the basics of the different treatment techniques and some installation sizing methods, but did not really go into the details of each technology and even less into the design and operation details of the equipment implementing it. It was difficult for me to find enough information to gain a good general knowledge of a particular subject, such as sedimentation, or the various filtration techniques, or dissolved air flotation, or sludge dewatering, because each one of these treatment technologies was described in a short chapter of a few dozens of pages at most. With the exception of a few books dedicated to biological treatment, it seemed that there was not enough to say about any one of these specific subjects to make a book. And yet...

When I later began to take a close interest in dissolved air flotation as part of my professional activities, I found mainly commercial literature in which the various manufacturers were extolling the virtues of their equipment and their expertise. I also found a large number of articles, research reports and case studies on the technology, as well as a number of publications that sought to explain the various aspects of the air microbubble formation process, to describe and even, for some, to model their behaviour, properties and ability to adhere to solid particles in the water. However, the vast majority of these publications, although interesting and useful, were more in the realm of basic research by professional researchers. Only rarely did I find practical information on the equipment design and the installation operation.

I decided to write this book for two reasons: Firstly, because I think that this kind of a thematic book can be interesting and useful for a wider audience consisting not only of readers specialised in flotation, but also of professionals working in the field of water treatment, willing to improve their general expertise on the subject; and secondly, because I think it is useful to include, besides the description of the different aspects of the process, also basic information on the equipment so that the reader can improve his or her analytical skills in the design and operation of the installations.

Without having the ambition to write an encyclopaedia on the subject, I have tried to make, in a way, an inventory of the flotation technology as such, of the surrounding equipment and techniques, as well as of the basic knowledge necessary for its implementation. I have preferred to avoid going into too much detail on the fundamental and scientific aspects of the process and to simplify certain explanations in order to keep only what seems to me to be essential for a practical understanding of things. I believe that the reader eager for details and wishing to know more about the scientific and fundamental side of the process could find numerous publications made by colleagues more qualified than me in the field of research, analysis and modelling of the phenomena. I have also tried to shed light on the concepts that have worked and those that didn't work so well. I have taken the liberty of commenting on the advantages and disadvantages of certain equipment and concepts because I believe that it is often difficult for non-specialists to form a fair and sufficiently well-argued opinion on many subjects. It is difficult, and even risky, to compare installations or experiences that are never quite the same and (often) simply too few in number to provide sufficiently reliable elements of comparison. The interpretations of certain phenomena, as well as the opinions and practical recommendations on certain equipment and concepts contained in the book, are the result of my experience in the field and are my own personal opinion.

The aim of the book is to provide the reader with a good general background in dissolved air flotation. It is intended for engineers and technicians working on the design of equipment and its integration into the overall treatment plant as well as in the operation of flotation plants, but also for

– Consultants and engineering offices, hoping that it will help them to make the most appropriate choices regarding the applications of this process, as well as in the equipment selections.
– Wastewater treatment plant operators, in the hope that it will help them to optimise the operation of their plants and improve their understanding and analysis of any problems they may encounter.
– Purchasers and contractors, who have to make sometimes difficult choices for reducing costs and, at the same time, ensure and guarantee the long-term performance and reliability of the plant.
– Students in environmental engineering and water treatment wishing to deepen their knowledge of this technology, on which courses are often rather brief.

Montagnole, France Roumen Kaltchev

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I would also like to thank my wife Sylvie for her encouragement to write this book and for her support.

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Symbols and Abbreviations

Alk	Alkalinity
API	American Petroleum Institute (type of oil separator)
As	Air to solids ratio, expressed as mg air/mg of solids or kg/kg or sometimes as Nm^3/kg
BOD	Biological Oxygen Demand, mg/l of g/l
CES	Chloroform Extractable Substances, mg/l
CFU	Cavitation Flotation Unit
COD	Chemical Oxygen Demand, mg/l or g/l
CPI	Corrugated Plate Interceptor (type of oil separator)
DAF	Dissolved Air Flotation
DGF	Dissolved Gaz Flotation
DM	Dry matter
DOC	Dissolved Organic Carbon, mg/l
G	Velocity Gradient, sec^{-1}
GDF	Gaz Diffused Flotation
GRP	Glass Reinforced Polyester
HEM	Hexane Extractable Materials, mg/l
IGF	Induced Gaz Flotation
MBBR	Moving Bed Biofilm Reactor or Moving Bed Bioreactor
MF	Microfiltration
NOM	Natural Organic Matter
POC	Particulate Organic Carbon, mg/l
PREN	Pitting Resistance Equivalent Number
RO	Reverse Osmosis
SDI	Silt Density Index
SI	Sludge Index, ml/g
SS	Suspended Solids, mg/l or g/l
SVI	Sludge Volume Index, or SI : Sludge Index, ml/g
TOC	Total Organic Carbon, mg/l
UF	Ultrafiltration
μm	Micrometre of micron, 1 μm = 0.001 mm

nm	Nanometre, 1 nm = 0.001 μm
ml	Millilitre
mV	Millivolt

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Chapter 1
Fundamentals of Dissolved Air Flotation

Dissolved air flotation is a process that aims to separate a solid phase from a liquid phase. In the field of water treatment, the preferred term is "clarification", probably because it has a "purifying" and "clean" connotation that corresponds well to the final effect sought by its implementation. Generally speaking, flotation, as a technology, uses the property of small air bubbles to adhere to solid particles and make them rise to the surface of the water like small buoys. Here the liquid phase is water and the gas is air, but it is obvious that the process is applicable in other liquids than water and with bubbles of another gas than the gas mixture air.

Air bubbles play the main role here. In dissolved air flotation, their diameter is usually between 10 and 150 μm with a majority average between 40 and 70 μm. In these dimensions, we speak of microbubbles, which is the term commonly used. These microbubbles can be obtained in several ways. For dissolved air flotation, these bubbles are generated in the following way:

It is well known that every gas has a limited solubility in every liquid. Depending on the properties of the gas and the liquid, the amount of gas that can dissolve in the liquid varies greatly. For example, carbon dioxide (CO_2) is almost 57 times more soluble (in litres of gas per litre of liquid) in water than nitrogen (N_2), not to mention ammonia (NH_3), whose solubility in water is (still in l/l) 42,800 times that of nitrogen (at 20 °C). For each gas/liquid pair, the quantity of gas likely to dissolve in the liquid varies mainly according to three main factors;

- Temperature—solubility decreases with increasing temperature.
- Pressure—solubility increases with increasing pressure. This increase is close to linear, i.e. if one increases the pressure twice, it is possible to dissolve almost twice as much gas in the same volume of liquid.
- The presence of other dissolved materials in the liquid—the solubility of the gas decreases as the amount of these materials increases.

It is this second phenomenon that is used for generating the air microbubbles necessary for dissolved air flotation. The implementation is quite simple: the pressure of

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the water is increased from about 1 bar (atmospheric pressure) to a pressure usually between 4 and 6 bar and, at the same time, air is injected (at the same pressure as the water, of course) so that it can dissolve in the water. If the saturation point is reached, the water will contain 4–6 times more dissolved air than is maximum possible at atmospheric pressure. This water (enriched or saturated with air) can then be simply brought back to atmospheric pressure to generate air bubbles in the water. Indeed, as the solubility of air is limited at any given pressure, the "excess" air that may have dissolved at a higher pressure no longer has enough room in the water at atmospheric pressure. Consequently, the volume of air dissolved above the maximum solubility limit at 1 bar leaves the water almost instantaneously in generating microbubbles dispersed in the water. This water containing the microbubbles, commonly referred to as white water because of the milky appearance imparted by the microbubbles, will then be mixed with the water to be treated in such a way that the microbubbles come into contact with the solid particles, adhere to them and rise them to the surface. There are four ways of bringing the microbubbles into the effluent.

– Pressurisation with recycled water. This consists of recycling a part of the clarified water through the pressurisation system and then reintroducing it into the effluent upstream of the DAF clarifier or in a so-called "contact zone" located inside the DAF clarifier.
– Pressurisation of the whole effluent flow through the pressurisation system. This method of pressurisation, known as direct or full flow pressurisation, is used more rarely, especially in certain cases of biological sludge thickening.
– Partial pressurisation, which consists of pressurising part of the incoming effluent and then reintroducing it into the circuit upstream of the DAF clarifier. This pressurisation method, like the previous one, reduces the hydraulic load on the DAF clarifier, but has certain disadvantages that will be discussed later in the in Chap. 3, which limit its use.
– Pressurisation with external clear water. Very little use in practice for obvious reason of water wastage.

The four pressurisation modes are shown schematically in Fig. 1.1.

To complete this presentation of the dissolved air flotation concept, it is worth mentioning that there is another flotation technology that also uses air bubbles for separating solid particles from water. It is called Induced Gas Flotation (IGF). In general, this clarification technology is similar to dissolved air flotation. The main difference is the method of producing the air bubbles—they are sometimes generated by porous diffusers, but more often by injectors or turbines dispersing mechanically air in the water at atmospheric pressure. These devices generate larger bubbles than those obtained with pressurised water expansion. Such bubbles are, in the vast majority of cases, less effective for clarification for a variety of reasons. This technology (IGF) is used in ore beneficiation, de-inking (paper industry), and especially in the oil industry for separating oil from produced water.

Clarification by flotation is, in a way, the opposite of clarification by sedimentation. In both cases it is a simple separation by gravity. Settling is based on the difference in specific weight between that of the water and that of the solid particles, which

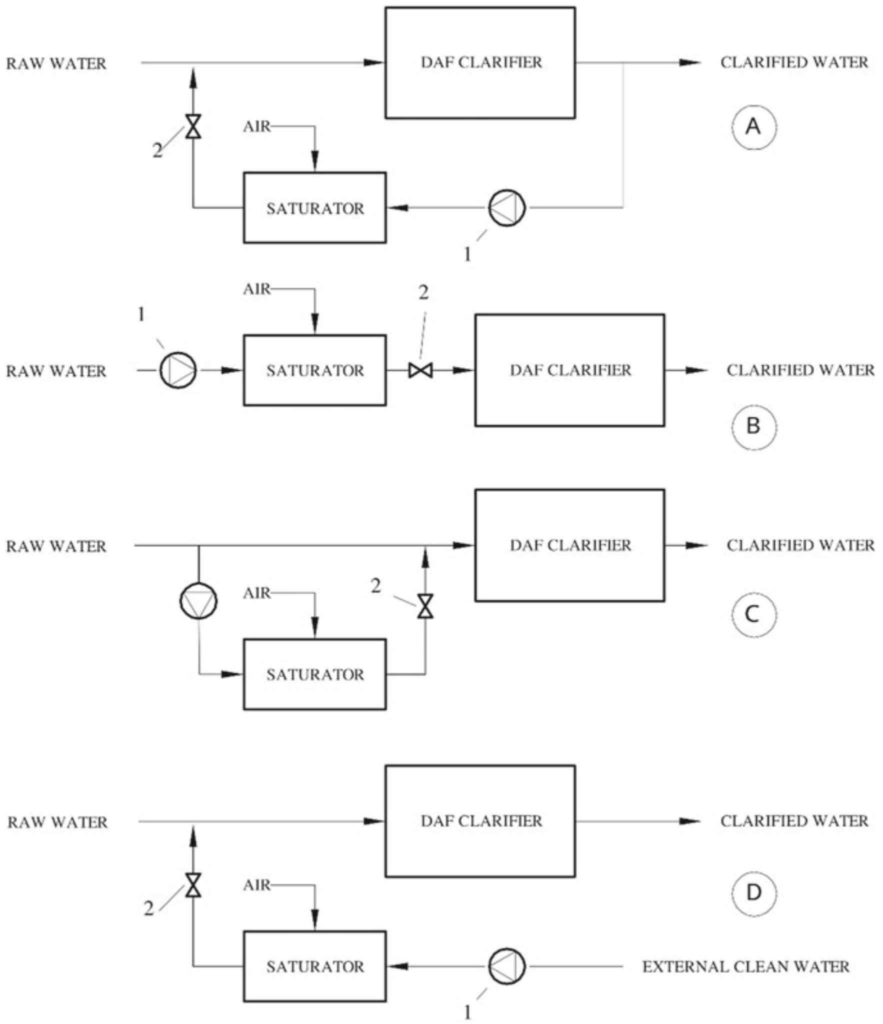

Fig. 1.1 Pressurisation modes 1—pressurisation pump, 2—pressure relief valve, A−recycled water pressurisation, B−full flow pressurisation, C−partial flow pressurisation, D−pressurisation with external clean water

are by definition heavier than the water if they settle. Of course, separation can also occur if the specific weight of the solid particles is lower than that of the water, in which case we would speak of clarification by natural flotation.

Dissolved air flotation is a microbubble assisted flotation. In practice it is used to separate solid particles whose specific weight is just about that of water. Frankly heavier particles than water, for example grains of sand, settle very well and it would be pointless to try to float them with microbubbles. Similarly, oil or hydrocarbon droplets (specific gravity 0.85–0.95 g/ml) of visible size do not need to be 'helped' by microbubbles to rise quickly to the water surface. But between these two somewhat extreme examples, there is a whole world of cases where the choice of clarification technology to be used is not nearly as obvious as it seems.

It is difficult to set a clear limit for the difference in specific weight between solid particles and water, beyond which sedimentation or respectively dissolved air flotation is undoubtedly recommended in all circumstances. There are many cases where the question arises as to whether it is better to clarify this or that effluent or concentrate this or that sludge by sedimentation or flotation. In practice, there is an overlap between these two clarification technologies, which has become more and more widespread in recent years. There are several reasons for that.

Firstly, a large proportion of the solids carried by so-called "natural" water (surface water or borehole water) used for drinking water production, or even more so, by domestic or industrial effluents, is made up of particles whose specific weight is very close to that of water. The same applies to the solid particles generated by the various chemical treatments often used for precipitating certain components or coagulating colloidal materials, or simply for modifying certain characteristics of the materials present in the water in order to facilitate their separation. In most cases, these particles are very slightly heavier than water and are therefore likely to settle. Despite this, settling will not automatically be the preferred option.

Secondly, it is very rare to have only one type of solid particles in the water. That would be too easy… More often than not, one is dealing with a multitude of particles of different origin and nature, with slightly different characteristics and behaviour. Some are heavier, others lighter. Some settle (or float) easily, others will be much more difficult and demanding in terms of the conditions to be met to allow their separation from the water…

Thirdly, the implementation of sedimentation or dissolved air flotation are two very different things. Each of these technologies has, like each process in the field of water treatment, its advantages and disadvantages. There are so many factors to consider that it would be imprudent to try to list them all here for fear of forgetting some. They will be discussed in detail for each of the equipment and applications as we go along.

Fourthly, for some specific reason, it might be sometimes necessary to seek another additional effect, other than simple clarification.

1.1 Brief Presentation of the Involved Elements

Firstly, it would probably be useful to provide some general clarification on the parameters commonly used in water treatment that every water specialist uses and handles on a daily basis throughout their career. These are parameters that quantify certain characteristics of the pollution present in the water such as:

– Suspended Solids (SS) or Total Suspended Solids (TSS)
– Chemical Oxygen Demand (COD)

- Biological Oxygen Demand (BOD)
- Total Organic Carbon (TOC)
- Colour
- Turbidity
- Fat content.

It should be highlighted that all these parameters (and certainly others not mentioned) provide some quantitative information, but not really qualitative information. Indeed, when we talk about TSS, COD, or TOC every day, sometimes we end up forgetting that these parameters do not represent something real and well defined. COD is not a single, specific material. One cannot fill a glass with COD and put it on the table. Each of these parameters is far from providing a clear and complete definition of the properties of the pollutants concerned. They only represent a certain "shadow" of reality and it would be wrong to take this "shadow" of a part of reality as a complete definition of that reality. For example, if we look at the side of a cylindrical glass on the table, we see a rectangular silhouette. But if we look at the same glass from the top of the table, we see a round figure. Which point of view is the closest to reality? A single point of view is not enough to get a clear idea of what we are looking at. By using these parameters every day, we sometimes tend to confuse the "thing" with a certain shadow of the "thing". In the daily business practice of water treatment equipment and plants manufacturers it is common to receive enquiries from customers with numbers as sole information—COD, BOD, TSS, fat or other such quantitative parameters. The question to the specialist is "What can you guarantee for the quality of the treated water and the cost of treatment?" It is obvious that it is impossible to answer such a question because little or nothing is known about the origin of the effluent, the nature of the TSS (e.g. mineral fillers such as talk or fibres?), the nature of the COD (e.g. dissolved sugars or emulsified proteins?) or the origin of the fats (e.g. particulate fat or fine emulsion?) Depending on the origin and nature of the pollutants, two effluents with identical characteristics presented in terms of TSS, BOD, TOC etc. may have very different properties and require very different treatment methods. The expected results after treatment can also be very different…

Thus, having a detailed knowledge of the origin of each of the parameters characterising the pollutants present in the water and its nature is a first indispensable condition for a good understanding of the real specific properties of each water to be treated and of the problems we will have to face.

1.1.1 The Total Suspended Solids (TSS)

This category includes particles with sizes between 1 μm and a few millimetres. The finest of these particles are generally responsible for turbidity because they are large enough to reflect light and limit its penetration into the water.

In reality, the lower limit of 1 μm is somewhat relative as the quantification of TSS depends on the measurement method. The most widely used method in practice is filtration through a filter with a standardised porosity of 0.45 μm. This method can be used for measuring TSS concentrations above 2–3 mg/l with varying degrees of reliability. Below this level, the accuracy of the measurement becomes a bit uncertain. This inaccuracy is nevertheless acceptable in practice because two details contributing to the difficulty of the measurement must be taken into account:

– The shape of the particles. It is obvious that it would be simple to consider that they all have a spherical shape and to take the diameter of the sphere. But this is almost never the case. Particles may in fact have shapes that are very different from the spherical shape and it is difficult to give them a single dimension that clearly characterises them.
– The mechanical properties of the particles. Indeed, when we talk about suspended solids, we tend to think of something solid. The reality can sometimes be quite different. In many cases, part of what is defined as suspended solids is made up of rather amorphous matter, i.e. "soft", neither really liquid nor really solid. This kind of material can behave like a solid and be retained on a filter. But if the differential pressure across the filter becomes too big, it will deform like a liquid droplet and pass through the filter pores.

Suspended solids have two other characteristics that play an important role in regards to dissolved air flotation:

1. Their electrostatic charge. Almost every particle has an electrostatic charge. These electrostatic charges are located on the surface of the particles. It is obvious that in small particles these charges are more important than in large ones because the smallest ones have a larger developed surface. These charges, usually negative, are more or less strong and depend on the materials of which the particles are made, as well as on their interactions with water. Other factors such as the presence of colloidal particles and dissolved matter also influence the interactions caused by the electrostatic charges of SS. These unipolar charges cause repulsion between the particles, which opposes the forces of attraction. However, given the relatively large volume of most particles, the influence of electrostatic charges on the interactions between them is relatively small. In the absence of significant turbulence, even the particles constituting the fine fraction of TSS can agglomerate into larger flocs that are easily separated by gravity.
2. The interfacial tension with water. This is the cause of the "wetting" or "non-wetting" effect when talking about two dense media (two liquids or a liquid and a solid). For example, this phenomenon allows a dewdrop to remain in a ball on the surface of leaves without spreading. Or for a drop of water to keep an almost spherical shape on a wax surface. Wax is then said to be hydrophobic. Other materials are hydrophilic because the same drop of water would spread widely over their surface. If we are talking about this phenomenon between a liquid medium and a gas, we speak instead of surface tension. The interfacial or surface tension plays a decisive role in many interactions between different materials.

It is what makes two liquids mix or not mix (they are said to be miscible or immiscible). This is what gives rise to capillarity (surface tension between water and air), which allows trees, thanks to their very fine capillaries, to make water rise to a height of tens of metres. Or the coalescence of two drops of water into a larger drop. Or the coalescence of two air bubbles in the water to form a larger air bubble. In the last two cases, the two small drops (or bubbles) try to join together to form a larger drop (or bubble) because, for the same volume, this drop (or bubble) has a smaller surface area compared to the sum of the surface areas of the two small drops (or bubbles). This leads to a lower tension energy between the two phases. In the present case, we are actually dealing with a so-called triple line where three interfaces meet: a liquid (water), one or rather several different solids (SS) and a gas (air). The forces that interfere are then more complex. On the one hand, the molecules of each phase attract each other towards the inside of the phase. On the other hand, the molecules of the different phases can attract each other (wetting) or repel each other (non-wetting), which results in the formation of a greater or lesser contact (wetting) angle and, consequently, the appearance of greater or lesser adhesion forces between these phases. In practical terms, this is largely what will determine the ability of the different particles to form more or less stable flocs and the strength of adhesion of the air microbubbles to these particles and, therefore, greatly influence the efficiency of flotation clarification.

1.1.2 The Colloidal Materials

They form a homogeneous suspension of solid particles in a liquid medium. The size of the concerned particles is between 1 μm and 1 nm (0.001 μm). It is the intermediate phase between suspended solids and dissolved matter (true solutions) whose size is less than 1 nm.

The mechanical characteristics and behaviour of colloidal suspensions depend on similar phenomena to those described above concerning the fine part of the suspended solids. The main differences are, for the most part, only a matter of scale, but this is of importance.

Firstly, as with suspended solids, the particles forming colloidal material have electrostatic charges. Some have higher charges than others. Some may have positive charges, but the vast majority are negatively charged. Therefore, they can attract or repel each other. All these interactions also depend on other factors such as pH or temperature. Nevertheless, in the vast majority of cases encountered in water treatment, colloidal suspensions are negatively charged as a whole. These dominant negative charges keep the particles in stable suspension. Indeed, if the electrostatic charges are strong, then the particles repel each other like two small magnets that one tries to stick together by their two sides of identical polarity. In this case, the particles remain more or less in stable suspension and their ability to separate from water is diminished.

Secondly, the very small size of the particles gives them a very large developed surface area in contact with the water, which increases the importance of the interactions caused by their electrostatic charges, so that these forces dominate the forces of attraction (called Van der Walls forces) and the gravitational forces. Their behaviour becomes little or not at all influenced by attraction and gravity. Consequently, the slightest mechanical or even thermal agitation (Brownian motion) is sufficient to keep them in stable suspension in the water and prevent them from agglomerating or settling. This is also how micro-droplets of water remain suspended in the air to form clouds. It is the same phenomenon, except that, in this case, it is a liquid phase in a gaseous medium.

This is the main difference between suspended solids and colloidal matter. While suspended solids are more or less likely to precipitate, agglomerate and be separated from the water by simple settling or natural flotation, colloidal matter remains in stable suspension dispersed uniformly in the water. They cannot be separated by gravity. In some cases the presence of air microbubbles used for dissolved air flotation could modify certain equilibria and allow a small fraction of the colloidal matter to float, but the effect remains marginal and its use is generally not justified in industrial conditions.

The arrangement of electrostatic charges on colloidal particles is illustrated in more detail in Fig. 1.2. If the colloidal particle is negatively charged, it necessarily has negative charges on its surface. These negative charges strongly attract the (positive) cations present in the water. These cations form a dense and stable layer surrounding the particle. This layer, called the Stern layer, is composed exclusively of positive charges and is firmly anchored to the surface of the particle. However, it is rarely able to compensate, and thus neutralise, all the anionic (negative) demand of the particle.

On its side this fixed layer of positive charges attracts, on its outer side to the particle, negative charges, but given the still dominant anionic demand of the particle, positive charges (cations) are always attracted towards the surface of the particle by mixing with the negative charges. This second layer, called the Gouy layer, contains both negative and positive charges, but is always predominantly negative. It is not really firmly attached to the surface of the particle. It moves with the particle, but with a certain delay, with a certain flexibility, as if the particle were “floating” inside this second layer.

Despite the accumulation of positive charges in these two layers around the particle, the whole may remain negative if the positive charges are insufficient to completely neutralise the anionic demand of the particle. Thus, the repulsive forces between the particles remain dominant and the colloid remains stable. The medium is then said to lack cationicity.

The electrostatic potential at the surface of the particle is called *surface potential* (1). The potential at the surface of the Stern layer is called the *Stern potential* (2). The electrokinetic potential at the surface of the second Gouy layer is called the *zeta potential* (3). It is mainly this potential that determines the electrostatic charge of the particle, and thus, the strength of the interactions that this particle would have with other neighbouring particles. These interactions finally lead to a certain equilibrium

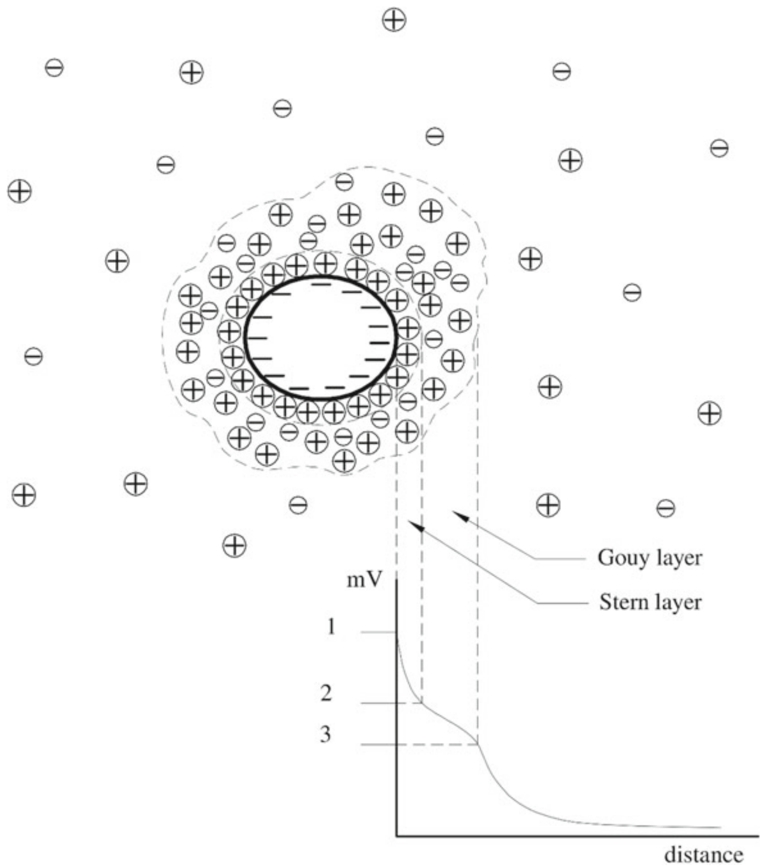

Fig. 1.2 Electrical potential of a colloidal particle, 1—surface potential, 2—Stern layer, 3—zeta potential

of the zeta potential of the different particles forming the colloid. It is expressed in mV and characterises the degree of stability of colloids—the higher it is, the more stable the colloid is. Below –10 mV the colloid is considered unstable and the particles can coagulate easily. Between –30 and –40 mV the colloid is relatively stable—this is for example the most common case for surface water. Above –40 mV the colloid is stable and above –60 mV it is very stable.

1.1.3 The Dissolved Materials

These are particles smaller than 1 nm. They are mostly molecules and agglomerates made up of several molecules.

While it is still possible to create conditions under which colloidal matter can agglomerate and form larger flocs (the size of SS) that can be separated by settling or flotation, it is not possible to agglomerate and thus separate dissolved matter from water simply by modifying the electrostatic balance. However, dissolved matter in water has an important influence on the properties and behaviour of colloidal matter. They can change the pH or provide electrostatic charges that can change the equilibrium of colloidal suspensions.

In summary, one can say that the "dimensional" classification of materials in water is not hazardous. The boundaries between SS and colloidal matter and between colloidal matter and dissolved matter respectively, correspond to a change of state and a change of behaviour from the point of view of water treatment. One can thus summarise as follows:

– SS has a large size and a small developed surface. The attraction forces between them (Van der Walls forces, depending on the mass) dominate the forces of electrostatic repulsion (increasing with the increase of the developed surface of small particles). They can agglomerate and be separated from water by settling, flotation or filtration on a filter media because their behaviour is influenced more by the forces of attraction and gravity than by their electrostatic charges.
– Colloidal particles have a small size and a large developed surface. The electrostatic forces on their surface dominate the gravitational and attractive forces. They remain in stable suspension and cannot be separated by gravity. However, it is possible, by physical means, to modify or neutralise their electrostatic charges to allow them to agglomerate and form larger flocs. Once agglomerated into flocs, they can be separated by sedimentation, flotation or filtration.
– Dissolved materials are so small that it is impossible to change their state by physical means and allow them to agglomerate into flocs. They can be agglomerated only by chemical reactions producing insoluble precipitates.

1.1.4 The Microbubbles

The air microbubbles are, of course, the key element of dissolved air flotation. They are generated, as described above, by depressurising (releasing to atmospheric pressure) water in which a certain amount of air has been dissolved beforehand at a pressure of typically 4–6 bar. Under these conditions, the vast majority of the "excess" air microbubbles produced after the pressure relief are formed almost instantaneously (from a few thousandths to a few tenths of a second, according to the different researchers) because the quantity of excess air is very large. If the amount of excess air is small, the complete formation of the bubbles may be slower and be completed in a few seconds, but this is a bad sign indicating a malfunction of the pressurisation system.

There are many scientific publications and research reports on the mechanism of formation of air microbubbles after the depressurisation, on their evolution in the seconds following their formation, on their size, on their stability and/or respectively their tendency to coalesce into larger bubbles. Some of these papers are mentioned in the bibliography at the end of this book. Even if some of the studies have been carried in rather sterile and somewhat artificial conditions (pure water) and therefore difficult to transpose directly into practice, it is very interesting and important to understand these mechanisms and the influence of different factors on this phenomenon and on the microbubbles properties.

On a practical level, the most important conclusions derived from the numerous publications on the subject, but also from direct observations easy to make on site, can be summarised as follows.

1. The size of the bubbles depends on the pressure at which the pressure relief occurs. One could say that the higher the pressure, the finer the bubbles, but this rule is only valid in a restricted range of pressures. Although this phenomenon is relatively easy to observe at pressures of 2 to 3.5–4 bar, it quickly fades above 5 bar. This is one of the reasons why in the vast majority of cases pressurisation is carried out at a pressure of between 4 and 6 bar. Under these conditions the size of the microbubbles generated is between 10 and 120 μm, with the majority being between 40 and 70–80 μm. It should be pointed out here that in many cases the finest bubbles (smaller than 20–30 μm) do not seem to be the most effective for flotation as their rising velocity is too low. This effect can be observed in a simple 500 or 1000 ml test tube in which a flotation test has been performed with pressurised water and water containing flocs. If the pressurised water contains very fine bubbles with a flotation velocity of 5 to 8–10 cm/minute, it is easy to see that almost all the visible flocs have already floated to the surface long before the last fine microbubbles have risen.
2. When formed, microbubbles are negatively charged. It is difficult to measure their zeta potential with the equipment used for measuring particle's zeta potential. It is generally estimated to be between –20 and –40 mV. The strength of the negative charges of the bubbles depends on the presence of dissolved salts in the water, the pH, the presence of surfactants and probably other factors. This electrostatic charge of microbubbles plays a very important role in the formation of aggregates between microbubbles and particles. It is logical to assume that negatively charged bubbles will not be attracted to particles that also have a negative charge. Instead, they will be more attracted to positively charged particles and will easily form stable clusters with them.
3. Bubble size is influenced by the presence of certain dissolved and colloidal matter. For example, salts present in seawater reduce the size of bubbles obtained at low pressure (up to 1–1.5 bar), but have little influence on their size if they are obtained at pressures above 4.5–5 bar. The presence of certain chemicals (some alcohols, flocculants, oils, proteins and other surfactants) results in smaller microbubbles. The presence of surfactants can help to form a film around the microbubbles and improve their stability. Depending on the electrostatic charges, other surfactants may have the opposite effect and lead to a decrease in the stability of the microbubbles, i.e. increase their tendency to coalesce and form larger bubbles.

4. The size of the bubbles depends on the design of the pressure relief device. This influence is very important, even crucial in some cases. It is less important in other cases. In general, the lower the content of dissolved and colloidal matter, the more important the role of the pressure relief device is for the size and especially the stability of the bubbles produced. On the other hand, the richer the water is in colloidal organic matter, the less the size of the bubbles is influenced by the pressure relief device. This phenomenon is related to the one described above. The more organic matter that can form a film around the microbubbles, the smaller and more stable the size of the bubbles and the less likely they are to coalesce. And conversely, the purer the water, the greater the effect of rapid coalescence after their formation. Hence, the importance of creating optimal pressure relief conditions to reduce coalescence as much as possible. The result of this sensitivity can reach impressive proportions. Many of the pressure relief devices widely used in wastewater would give very poor results in some cases of drinking water clarification. For example, it is possible to install pressure relief diaphragms with orifices of several centimetres in diameter in municipal wastewater treatment plants and obtain white water of decent quality. In drinking water, however, pressure relief orifices are rarely larger than a few millimetres in diameter. This is a very important topic and will be discussed in detail later.
5. The combination of the lack of surfactants to promote microbubble stability and the choice of an inappropriate pressure relief device can greatly promote coalescence of the bubbles and cause up to 40–50% of the air to be lost (and even more!), generating in just a few tenths of a second large bubbles which are not effective for flotation and which are even troublesome because they cause strong turbulence on the way up.

1.2 The Main Forces and Interactions Involved in the Relationships Between the Participants in the Implementation of Dissolved Air Flotation

What would be the ideal scenario for perfect clarification by dissolved air flotation? It's easy to define: particles and bubbles attract each other irresistibly and stick strongly and permanently to each other. Each small and very small particle attaches itself to the surface of a bubble, and each larger particle attaches several bubbles to its surface. Under these conditions all particles are associated with one or more bubbles. In this way, the bubbles would be able to fully perform their role of floating all the particles to the surface. In order to realise this scenario in the best conditions, several phenomena that influence this process must be taken into account.

1.2.1 Formation of Particle-Bubble Agglomerates

The various studies on the formation process of agglomerates between particles and bubbles have led to the definition of three models:

1. Collision between the pre-formed bubbles and the particles leading to their attachment to each other by electrostatic forces. For this to occur, the solid particle must approach the air bubble with sufficient force to thin and pierce the electrostatic charges ‘films’ surrounding the bubble and the particle. It is then possible for the bubble to cling to the hydrophobic particle by wetting effect.

Two sub-scenarios are possible in this case:

– The electrostatic charges of the two participants are different. For example, the bubbles have a negative charge while the particles are positively charged. In this case the force of attraction may be strong enough to cause a strong and stable attachment.
– The electrostatic charges are weak, at least those of one of the participants (most often it is those of the solid particle). In this case, simple electrostatic attraction is not enough to form an agglomerate. It is necessary to compensate for this lack of attraction by kinetic energy, in other words, by mechanical mixing causing multiple collisions. But under these conditions the attachment between the bubbles and the particles can be fragile. It depends on the degree of hydrophobicity of the particles, which determines the wetting angle between the bubbles and the particle (Fig. 1.3). Thus, the greater the wetting angle (3) (Fig1.3a), the better the attachment of the bubble (2) to the surface (1) of the hydrophobic particle. Conversely, the smaller the angle (Fig1.3b), the more fragile the bond between the bubble and the particle. It can break down if the turbulence is too strong and can be re-established further on if another opportunity arises under more favourable turbulence conditions.

2. Pre-formed bubbles are trapped inside an agglomerate of particles such as a floc. If the floc is strong enough, it’s perfect—the bubbles stay inside.
3. Formation and growth of bubbles from nuclei on the surface of a particle or floc—a rarer and less represented phenomenon.

In the most frequent practical cases, the three models coexist in parallel, because the particles present in the water are in fact different in size and properties. And, to a lesser extent, the same is true of bubbles. But this scenario can be disrupted by certain factors.

Firstly, suspended solids and especially their fine fraction (which often represents the majority in terms of weight) can have negative electrostatic charges, just like air bubbles. This is a problem, as they repel each other. This is less of a problem when the suspended solids have low or almost zero electrostatic charges. In this case, it is much easier to form bubble/particle agglomerates, although sometimes the attachment between bubbles and particles is more fragile under conditions of high turbulence.

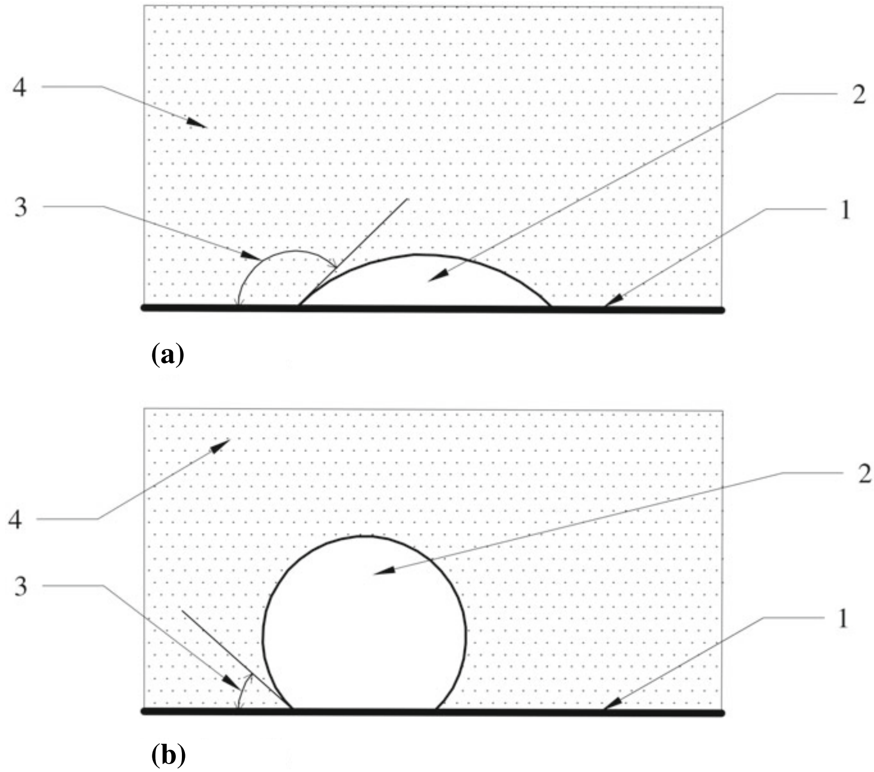

Fig. 1.3 Contact angle between an air bubble and a solid particle in water. 1—hydrophobic particle, 2—air bubble, 3—contact angle, 4—water

Secondly, there are cases, fortunately very rare, in which the particles are extremely hydrophilic and the air bubbles do not cling to them. There are cases where a perfect cloud of microbubbles rises among well formed and rather light flocs without clinging to any of them… And once the air is gone, the flocs remain dispersed in the water or settle slowly without any at the water surface. This is very frustrating. In some cases a change of chemical treatment may solve the problem, but in others it is possible that no treatment leading to an acceptable result can be found.

Thirdly, colloidal matter is even less accessible to bubbles because it is strongly charged; particles repel each other and in addition repel bubbles that have the same negative charge. Also, colloidal particles (1–0.001 μm) are much smaller than bubbles (40–70 μm) and can be fully trapped only if a very high number of particles succeed in attaching to a bubble, which reduces the probability of success.

It can therefore be concluded that for successful clarification by dissolved air flotation, it is essential to create the most favourable conditions possible for the formation of stable agglomerates between particles and bubbles. By the way, the problems of agglomeration of particles, especially colloidal particles, are more or less identical in the implementation of clarification by sedimentation. Here too, the electrostatic repulsion between fine particles prevents or at least disturbs precipitation and clinging between them, as well as the formation of flocs of greater density that settle easier. This floc formation is very beneficial for both clarification techniques as it allows, on the one hand, to obtain more concentrated sludge and thus a reduced sludge volume, and on the other hand, to better trap the finer particles, thus a better separation of the solids within the liquid and, finally, a clarified water of better quality.

There are two solutions to this, which are widely applied in practice:

- Use a long-chain flocculant with positive electrostatic charges that can bind negatively charged particles to their surface. Thus, the electrostatic charges of the particles are more or less neutralised. And at the same time, through these charges, the particles are attached to these long molecular chains which hold them, agglomerate them and allow them to form flocs.
- To modify the electrostatic equilibrium of the particles, especially that of the colloidal particles, by providing additional positive charges so as to favour their neutralisation and their agglomeration into flocs of greater size and density. In other words, transform colloids into suspended solids that can be easily separated from the water by flotation or sedimentation.

1.2.2 Coagulation and Flocculation

In reality, for municipal or industrial effluent, or even for more "pure" water such as surface water used for drinking water production, the importance of the size classification of the particles present in the water is, in a way, somewhat relative. Indeed, for our concern, the mechanical properties, the dimensions of the different particles and their electrostatic charges must be considered mainly from the point of view of their ability to be agglomerated into flocs. To achieve this, three methods are usually used:

- The use of organic flocculants,
- The use of mineral coagulants,
- The combined use of coagulants and flocculants.

Each of these treatments has broadly the same aim—to neutralise (or at least reduce) the zeta potential of the colloid and allow the formation of flocs.

1.2.2.1 The Use of Organic Flocculants

Flocculants are very long organic molecules with electrostatically charged molecular extensions attached to them. The "carrier" molecule is a polymer, i.e. a long molecule whose backbone is made up of the repetitive attachment of a base element. The most common "carrier" molecule is polyacrylamide, composed of acrylamide monomers.

Flocculants can be classified according to several criteria:

- The shape of the polymer molecule.—It can be linear or reticulated Fig1.4).
- The polarity of their electrostatic charges.—They can be cationic (with positive charges, thus attracting negatively charged particles) or anionic (with negative charges, thus attracting positively charged particles).
- The density of their electrostatic charges.—Thus, cationic flocculants can be weakly cationic (few positive charges along the polymer), medium cationic or strongly cationic (many positive charges along the polymer). The same is true of anionic flocculants—they can be weakly, medium or strongly anionic. They can also be non-ionic if the charge density is very low.
- Their molecular weight.—Polymers with an average molecular weight of less than 100,000 g/mol are said to be low molecular weight, between 100,000 and 1,000,000 g/mol—medium molecular weight, between 1 and 5,000,000 g/mol—high molecular weight and above 5,000,000 g/mol—very high molecular weight.

Flocculants used in water treatment come in two commercial forms:

- In powder, i.e. as a pure product, containing 100% active matter. To prepare the solution to be dosed, they must be dissolved in water. The dilution requires a certain amount of time (usually 10–20 min) and a certain intensity of mixing because the "deployment" of the very long polyacrylamide molecules in water is slow and requires prolonged mixing. It is important to respect these dilution conditions if one wants to have a product that develops its full effectiveness. For

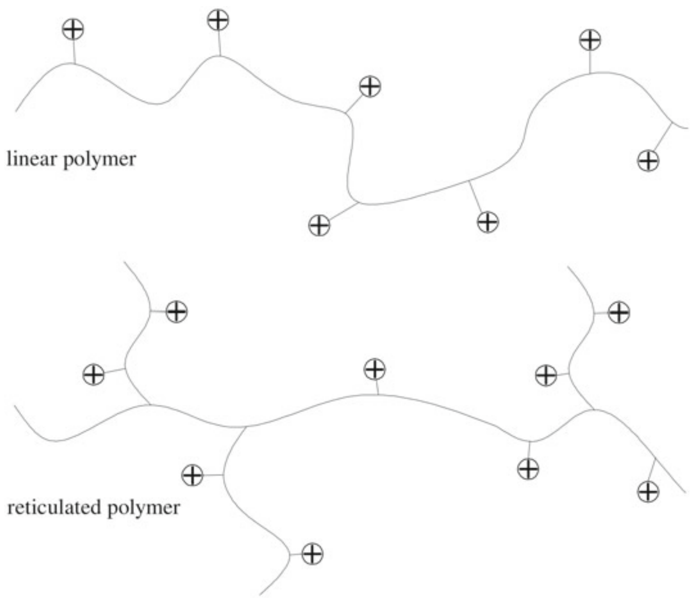

Fig. 1.4 Types of polymers

this purpose, automatic or sometimes manual (for small flow rates) dilution units are used.

- In aqueous emulsion in which the polymer is dispersed with emulsifying products. This form contains less active matter (usually 30–50%), but has two practical advantages over dry powder products. Firstly, the powdered product is sensitive to moisture and tends to lump or even freeze in a block on contact with water or even ambient humidity. It should be handled with care. Aqueous emulsions have fewer drawbacks in this respect. And secondly, the emulsion product is already "pre-diluted" and is easier to use. Nevertheless, it also requires dilution and a few minutes of mixing to obtain a high-quality solution. This form is mainly used for the treatment of small wastewater flows, as emulsifiers are generally not allowed for drinking water production.

In order to trap TSS and eventually lightly charged colloidal particles, a cationic flocculant can be used. It works in two ways. Firstly, its positive charges attract the negative particles and they cling to different places in its molecular chain. At the same time, it neutralises, at least in part, the electrostatic charges of the particles and reduces the repulsive forces between them. Secondly, these very large molecules can attach to several particles and form bridges between them. These bridges between the particles attached to their surface, now more or less electrostatically neutral, tangle easily and form stable, solid flocs that are easy to separate from the water. This technique, which is very widespread in water treatment, has its advantages and disadvantages, the most important of which are as follows.

Advantages

- The dosage required for flocculants is low—typically a few mg/l are sufficient to trap several hundred, sometimes even several thousand mg/l of TSS.
- They therefore produce very little additional sludge
- Flocculants produce concentrated, stable and mechanically strong sludge. This flocculated sludge is easy to separate from water and to dewater. In fact, a large part of the applications of flocculants are in the field of sludge dewatering.
- They are not toxic or corrosive

Disadvantages

- The strength of their electrostatic charges is limited. They may be sufficient to trap suspended solids and possibly some colloidal matter in unstable colloids. But in many cases they are too weak to lower the zeta potential of stable and very stable colloids sufficiently to allow flocculation.
- Although soluble in water, their very long molecules give them a certain clogging ability. In excessive quantities, flocculants can clog certain filter media and reduce their filtration capacity. They should be used with caution upstream of fine sand filters and with great caution upstream of microfiltration (MF) or ultrafiltration (UF) membranes. This applies especially to anionic flocculants as they are very stable and have a lifetime of up to several weeks. In comparison, especially in waste water, cationic flocculants are considered to degrade more or less within

48 h after dilution. For the same concentration of solution, anionic flocculants are also more viscous than cationic ones. They are more difficult to wash out and are therefore more clogging.

1.2.2.2 The Use of Mineral Coagulants

The use of mineral coagulants is necessary when very high and abundant cationicity is required to destabilise a colloid with a high zeta potential and/or a high concentration in the water. In these cases, a flocculant will not be sufficient, even at a very high dose.

The most commonly used coagulants in practice are:

- Aluminium sulphate—$Al_2(SO_4)_3$ 0.14 H_2O or $Al_2(SO_4)_3$ 0.18 H_2O
- Sodium aluminate—$NaAlO_2$
- The different forms of polyaluminium chloride (PAC)—$Aln{\cdot}(OH)m{\cdot}Cl_3n{-}m$
- Ferric sulphate—$Fe_2(SO_4)_3$, 9 H_2O
- Ferrous sulphate—$FeSO_4$, 7 H_2O
- Ferric chloride—$FeCl_3$, 6 H_2O

All these products are marketed in the form of:

- Powders or granules to be diluted on site. Storage and dilution facilities are sometimes expensive and complex, but the product delivered is 100% pure, which limits transport costs. This form is economically advantageous for sites that are far from production facilities and consume large volumes.
- In ready-to-use solutions. The solutions usually contain between 40 and 60% water, which increases the cost of transport, but the use and the operation are much simpler.

What these products have in common, apart from their low production cost, is that they are all based on alumina or iron—two trivalent cations, thus very strongly cationic and therefore very effective. In fact, generally speaking, trivalent cations are much more efficient than bivalent cations, which are much more efficient than monovalent cations. This phenomenon is described by the Schulze-Hardy theory.

The action of these coagulants, once introduced into water, takes place in two stages. The first is hydrolysis, producing intermediate positive polycharged molecules that neutralise the zeta potential. These molecules have been shown to be the main coagulating form and are even more efficient in terms of neutralising electrostatic charges and destabilising colloids than Al^{3+} and Fe^{3+} cations. The second step is the formation of hydroxides—$Al(OH)_3$ and $Fe(OH)_3$ respectively. These hydroxides are insoluble and precipitate, thus contributing to the agglomeration of destabilised colloidal particles and the formation of flocs—this is the flocculating form (C. Cardo—Le Traitement des Eaux). This coalescence of the particles around the hydroxides is called sweep coagulation.

While the first stage occurs very quickly, the second is slower. It is therefore important to ensure very intense mixing when the coagulant is injected in order to ensure rapid and homogeneous dispersion of the product in the water, which is essential for the first stage to take place before the hydroxides are formed in the second stage. On the contrary, once the hydroxides have formed, their agglomeration into flocs requires a much slower and more extended mixing. Indeed, it takes time for a maximum of collisions between particles to occur to form flocs. At the same time, these flocs are fragile and too violent mixing would prevent them from growing sufficiently. There are two other factors that play an important role in this process.

The first one is the pH on which the solubility of the hydroxides depends. The pH of the lowest solubility of aluminium hydroxide $Al(OH)_3$ is between 6 and 6.7. For iron hydroxide $Fe(OH)_3$ these values are between 5.5 and 8.3 respectively. It is therefore important to maintain the pH in these ranges so as not to lose the effectiveness of the coagulation. In these pH ranges the dissolved forms of Al^{3+} and Fe^{3+} are also at their minimum, which is very important in drinking water treatment, especially for dissolved Al^{3+} whose solubility is much higher than that of Fe^{3+}. Dissolved iron is also a parameter to be closely monitored, for example in seawater pre-treatment, as it is not well supported by ultrafiltration (UF) membranes and especially by reverse osmosis (RO) membranes. Depending on the pH, the coagulation mechanism may vary slightly. If the pH is close to neutral or slightly higher, particle coagulation occurs mainly by entrapment and the zeta potential may remain negative. If the pH is in the acidic range (pH 5–6), then neutralisation of electrostatic charges is favoured and the zeta potential may ideally be neutralised.

The second factor is related to alkalinity. When introduced into the water, mineral coagulants also react with the carbonates usually present in it. As a result, some of the alkalinity is consumed by the coagulant with the production of CO_2, which lowers the pH. As each coagulant consumes a given amount of alkalinity, the lower the alkalinity of the water and/or the higher the dose of coagulant, the greater the drop in pH. On the other hand, if the water is strongly "buffered" (high alkalinity) and the dose of coagulant is low, the drop in pH would be lower. Therefore, this phenomenon should also be taken into account and the pH should be artificially raised (e.g. with soda) to keep it in the right range. For more details on this subject see Chap. 9.5.

The advantages and disadvantages of using mineral coagulants are different compared to organic flocculants.

Advantages

– Very efficient in terms of colloid destabilisation. In many cases it is the best solution applicable in industrial conditions that one has.

Disadvantages

– The dosage is higher and can reach more than a hundred mg/l of iron or aluminium for certain industrial effluents. This means a large quantity of coagulant and significant operating expenses.
– They often require a pH adjustment, and therefore more chemicals.
– They are toxic and corrosive and require great care in their handling.
– Coagulants produce sludge (hydroxides).

- Hydroxide flocs are small and fragile. Therefore, their complete separation from water is sometimes difficult.
- Hydroxide sludge is not very concentrated and therefore has a large volume.

In practice, the use of mineral coagulants alone is becoming increasingly rare because of these last two disadvantages.

1.2.2.3 The Combined Use of Coagulants and Flocculants

This is the most “complete” treatment combining the high colloid destabilization capacity of mineral coagulants with the rapid formation of large, stable, solid flocs obtained with flocculants. The treatment is usually carried out in two separate stages.

The first coagulation stage involves flash mixing for about 30 s when the coagulant is added, followed by slower mixing, the duration of which can vary greatly depending on the characteristics of the water being treated. In most cases, the more polluted the water, the shorter the time required for good coagulation, as the probability of collision between the particles increases with their concentration in the water. And vice versa—the lower the concentration of particles, the longer the time to achieve good coagulation. Nevertheless, it sometimes happens that the second phase of coagulation of even heavily polluted water is rather slow.

The second stage is flocculation, which is achieved by adding a flocculant. It also requires sufficiently sustained agitation to ensure good mixing and a high probability of collision between the micro-flocs formed by coagulation. At the same time, the mixing should not be too turbulent to avoid breaking the flocs formed and allowing them to grow. The flocculation time can vary from a few tens of seconds to several minutes, depending on the case.

In many cases, the cationicity brought by the coagulant, in its action, makes the electrostatic charge of the mixture switch to the positive. This depends on the dosage of the coagulant. A correct dosage would be to cancel the zeta potential and possibly tilt it slightly to the positive side. An overdose would usually be useless as it would very rarely bring about a significant improvement. Under these conditions, it is therefore more advantageous to use an anionic or non-ionic flocculant that would better “catch” the positive flocs than a cationic flocculant that would only add more cationicity. Not that a cationic flocculant would not work at all, but it would act more by bridging than by electrostatic clinging. In addition, the dosage required is likely to be higher, as the product would only act with reduced effectiveness. Considering that cationic flocculants are generally more expensive than anionic flocculants, the price of the treatment can increase significantly.

This rule of always using an anionic flocculant after coagulation with a mineral coagulant is reliable, but it does not apply in 100% of cases, at least with regard to flotation clarification. It can be seen that in some cases (e.g. in the treatment of effluents containing latex or certain paints) a cationic flocculant works better than all the anionic flocculants tested. Contrary to expectations, in these cases the cationic flocculant mainly improves the attachment of air microbubbles to the flocs.

1.2.2.4 The Use of Organic Coagulants

It should be mentioned here that there is also a large family of synthetic organic coagulants. The most common ones are:

- Melamine formaldehyde.
- Epichloridrine dimethilamine (Epi DMA).
- Polydiallyldimethylammonium chloride (Poly DADMAG).

These organic coagulants have many applications, especially for colloids with low Zeta potential and very fine suspended solids. They have the advantage, among other things, of having very little influence on the pH and of producing denser sludge, hence of smaller volume. These products can be used alone or in combination with a mineral coagulant.

Finally, it is important to note that none of the methods described above can achieve perfect coagulation of all of the colloidal matters. The efficiency of the treatment depends on the pollutants present in the water and their heterogeneity. Even if in optimal conditions the majority of the particles are destabilised and flocculated, some may, on the contrary, be "overloaded" with cationicity and remain in the colloidal state. In general, the more homogeneous the particles, the more efficient the coagulation if the coagulation conditions are optimal. And vice versa—the more different the materials in the water, the more difficult, if not impossible, it is to create ideal coagulation conditions, as what is favourable for one type of material may not be for others.

1.3 Issues and Challenges in Implementing Dissolved Air Lotation

A question that is often asked when faced with a clarification or sludge thickening problem is "how to do it? Which technology to choose?" And it is important to weigh up all the pros and cons before making a decision, because the choice is not always clear-cut. There are many examples of cases where there is serious hesitation. Typically, there are three solutions—decantation, dissolved air flotation and filtration (remember that this technique remains a competitor to flotation, so its advantages should not be overlooked). The cases of lighter-than-water TSS clarification seem to make us lean quickly towards flotation or filtration, but these cases are not very frequent. And the same is true with cases of TSS that are frankly heavier than water and very easily settleable—one does not hesitate for long to choose settling. But there are many examples of TSS with a specific weight almost identical to or slightly higher than that of water, whether it is natural water or municipal or industrial effluent. These TSS can settle at a high or at least "acceptable" settling velocity in the context of the project, and in some cases this is the chosen solution. It has its advantages and disadvantages:

Advantages

– Low energy consumption.
– Relatively simple operation.

Disadvantages

– If the settling velocity is low (less than 1.2-1.5 m/h), the facilities are voluminous and the installation takes up a lot of space which is not always easy to find.
– Reliability of operation is sometimes relative because, on the one hand, settling can be sensitive to variations in water quality, and on the other hand, under certain conditions two fractions of TSS can occur—one that settles and one that floats naturally. Of course, most settlers are equipped with devices to collect a small amount of floating material, but these devices are soon out of date, if this floating fraction becomes more abundant.

In cases where the specific weight of TSS is close to that of water, dissolved air flotation is increasingly the chosen solution, especially when space is limited and/or when it is particularly advantageous to obtain, in parallel with clarification, a high sludge concentration.

Advantages

– Clarification velocities are much higher than sedimentation—between 6 and 25 m/h. Consequently, the facilities are smaller and take up much less space.

Disadvantages

– High energy consumption (for the pressurisation system).
– The equipment is slightly more complex to operate.

Filtration also has its advantages, especially when the TSS content is low (less than 10–15 mg/l for wastewater and less than 6–8 mg/l for natural water).

Depending on the application, the advantages of each of the technologies are more or less in evidence than those of the others. For example, for surface water, for colour or algae removal, dissolved air flotation is often the technology of choice. This makes sense—not only does it usually give better results in terms of clarification, but it operates at hydraulic loads of between 12–15 and 25–30 m/h, compared with 0.2–0.6 m/h in non-assisted sedimentation. It is obvious that in this case the flotation plant would require a much smaller space than that occupied by a sedimentation plant. Conversely, for high TSS concentrations, such as activated sludge clarification in biological treatment plants (3–5 g/l TSS), the use of dissolved air flotation is limited to the rare cases of low and very low flow rates (rarely more than 20–30 m^3/h) of very high COD industrial effluents and for sites where space is at a premium. In these cases, to reduce the volume of the aeration tanks, it is possible to operate them with a biological sludge concentration of 8–10 g/l for which secondary clarification by sedimentation is almost impossible. Or in the case of thickening of excess biosludge where the concentration of floated sludge and its maintenance in an "aerated" state (biological dephosphatation) are important factors—see Chap. 9.4.

If the choice of flotation technology is made in general, there are still several possibilities concerning the type of device (circular or rectangular, horizontal or vertical configuration), the construction material of the tank (concrete or metallic) and the floated sludge extraction method (scoop, scraper, overflow). Not all solutions are equal in terms of performance, investment and operation in a specific application. For example, circular units are cheaper and very suitable for biological sludge thickening. However, their use in the clarification of large flows of drinking water is less advantageous, as they take up more space and, above all, require external coagulation and flocculation tanks, which considerably complicates the layout of the works and the water transfers.

Once the type of clarifier has been chosen, attention must be paid to the details. As mentioned earlier, dissolved air flotation separates only suspended solids. It has little or no effect on colloidal particles. If the aim is to remove colloidal pollution, it must first be coagulated and flocculated into flocs. Flotation works well with smaller flocs than those sought for clarification by sedimentation, but it is still better to have flocs of a size visible to the eye, i.e. at least 300–500 μm. If coagulation/flocculation or simple flocculation is required, the most suitable devices should be selected taking into account the coagulation and flocculation times required and the site conditions.

The implementation of dissolved air flotation includes the following main elements:

- Dissolving air in water for pressurisation.
- The pressure relief of the pressurised water generating the microbubbles.
- Mixing the pressurised water containing the microbubbles with the raw water, with or without prior coagulation/flocculation.
- Flotation of the TSS.
- Discharge of the floated sludge.
- Bottom sludge removal.
- Clarified water collection.

Each of these elements plays an important role and contributes to the good operation of the installation. Its design must meet several requirements that are sometimes contradictory.

1.3.1 Dissolving Air in Water for Pressurisation

The production of compressed air and, most of all, the dissolving of air in water is the main energy consumption part of the flotation installation. It is therefore important to determine how much air bubbles, i.e. what pressurisation rate is needed in each case. On the one hand, insufficient or too tight pressurisation would be dangerous, as it would result in incomplete or fragile clarification (and therefore unreliable, sensitive to almost inevitable variations in water quality and capricious to operate) and/or poorly concentrated floated sludge forming an unstable floated sludge blanket. On the other hand, oversized pressurisation would not only be expensive in terms of electricity, but would also create useless turbulence in the contact and flotation zones, which one would gladly do without. Not to mention the hydraulic overload caused by the pressurisation flow rate (in the case of pressurisation with recycled water, i.e. in almost all cases…) which must be taken into account when sizing the DAF clarifier.

There are of course sizing methods and recommendations on the values of certain parameters, but they hardly take into account an important factor, which is the strength of the bonds between the flocs and the bubbles. In some cases, the bubbles cling firmly to the flocs and it does not take much to produce excellent flotation. In other cases the bonds are more difficult, more fragile, are made and broken by turbulence, and more air is needed to achieve a good result. It is also necessary to take into account the fact that only a fraction (often very small) of the bubbles is really associated with the flocs. If one reasons only on this quantity of air "linked" to the flocs, one risks to be mistaken, because for the clashes between bubbles and flocs to occur, many collisions are necessary, which will occur efficiently only in the presence of a large quantity of bubbles in water. However, bubbles not associated with flocs are not really lost. During flotation they accumulate under the floated sludge blanket and, as it forms, mix with it and hold it firmly to the water surface because, by reducing its density, the air trapped in the floated sludge increases its buoyancy. Therefore, as the floated sludge blanket increases in thickness, the upper part of the sludge rises above the water. This drains some of the water contained in this surface part of the sludge layer and increases its concentration considerably. This effect is very important in the case of sludge thickening by flotation and part of the air supplied is dedicated to it.

The choice of air dissolving device is also important. The most efficient devices in terms of saturation (packed saturators) are not suitable for wastewater because they are sensitive to clogging of the packing. The operation of some devices, although efficient, requires a relatively complex set of instrumentation which is not always appropriate for small wastewater treatment plants for which rustic and reliable equipment in all circumstances is to be preferred.

1.3.2 The Pressure Relief of the Pressurised Water Generating the Bubbles

The pressure relief conditions also sometimes play a major role in the bubbles' generation. Under all other equal conditions, depending on the pressure relief device, it is possible to produce almost exclusively very fine bubbles that hold together and spread evenly in the water, or to lose a lot of air that coalesces almost immediately to form large bubbles. In fact, the most efficient pressure relief devices, giving the finest and most homogeneous bubbles in terms of size, use very small pressure relief orifices. They give excellent results in drinking water, but are inapplicable in wastewater treatment because they clog very quickly. Conversely, a simple globe valve or a calibrated diaphragm would be much more reliable in this respect. But such an pressure relief method would make some of the air be lost in coalescence even on effluents containing enough organic matter to ensure a good stability of the remaining bubbles produced. Between these two extreme examples, there is a whole range of possibilities to choose from depending on the application and the type of DAF clarifier to be fitted. Compromises are often made, with the emphasis on reliability of operation rather than on the quality of the pressure relief.

1.3.3 The Mixing of Pressurised Water Containing Bubbles with Raw Water, with or Without Prior Coagulation/ Flocculation

Here again, there are several constraints that are difficult to reconcile. Firstly, it is obvious that there is much to be gained by producing the bubbles as close as possible to the point of use, i.e. directly inside the contact zone, to minimise coalescence before the formation of floc/bubble aggregates. For this purpose, the injection of pressurised water is usually done over a large area, and to ensure a good mixing it would be necessary to have many pressure relief points. This means several pressure relief devices with small orifices that are sensitive to clogging. In addition, the contact zone is often difficult to access (as is the case with most circular DAF clarifiers) Secondly, there is also the issue of mixing the white water with the effluent to be treated. On the one hand, it is better to mix the effluent as quickly and as homogeneously as possible, but on the other hand, this should not be done by creating too much turbulence, which could destroy the flocs that have been carefully grown in the previous flocculation stage. And thirdly, in all cases it would be advantageous to keep easy access to the pressure relief device(s) which are sometimes one of the sensitive points in terms of operation and maintenance.

1.3.4 Suspended Solids Flotation

This step must be carried out with care and a good sense of compromise, as its implementation must reconcile technical constraints, construction constraints, transport and installation constraints and, finally, budget constraints. Firstly, it is obvious that the quality of flotation clarification (indeed, just like sedimentation clarification) is highly dependent on turbulence in the clarification zone. This should be minimised, even though in the large majority of cases dissolved air flotation is much faster and less sensitive to turbulence than sedimentation. It is in your interest to have low flow velocities and therefore a large cross-sectional area and surface area in this zone. Or to find tricks to improve the separation conditions, such as the use of lamellae. Secondly, the water must enter this zone “ smoothly “.But at the same time not too slowly, because free air bubbles rise quickly and the parts furthest away from the entrance of the flotation zone may end up beyond the microbubble mat which is very beneficial for the maintenance and concentration of the floated sludge layer. Thirdly, the flotation zone must be sized to reconcile conflicting requirements:

- Have sufficient flotation area and residence time to ensure a low level of turbulence for good clarification.
- At the same time, avoid oversizing the tank, as this will increase its cost and, sometimes, the difficulties of implantation.
- Take into account the constraints of transport and onsite erection.

1.3.5 Floated Sludge Disposal

The choice of floated sludge disposal device is important for several reasons. Firstly, it must be suitable for the application and the requirements of the installation. How much floated sludge will be produced and what will be the requirements for it are questions whose answers may suggest different choices. For rectangular DAF clarifiers the answers to these questions may direct the choice to a simple overflow with closure of the clarified water outlet or with raising of the level by an adjustable weir. Or to a mechanical device such as a surface scraper or pedal wheel. Secondly, the floated sludge removal device must be sized according to the amount of floated sludge produced, its concentration and its specificities. Thirdly, it must be simple, robust and reliable, but not out of price, as it is a relatively expensive component. Fourthly, it must take into account the selected floated sludge extraction mode, i.e. continuous or periodic extraction. Finally, the selection of the construction materials for certain components can vary significantly from case to case, and it is important not to make a mistake as this can be very costly.

1.3.6 Bottom Sludge Disposal

Although it is hoped that all solid particles will float to the surface of the clarifier, it should be kept in mind that no clarification technology is perfect and that a very small fraction of flocs, or other impurities, may settle out. This amount is certainly very small, but within a week or a month, these settled particles will end up forming a real deposit at the bottom of the clarifier and, ultimately, create problems. It is therefore important to have a means of collecting and removing them as they occur. The mechanical bottom scraper option offers a reliable solution, but is expensive and requires some maintenance. Conical or pyramid bottoms are simple, but the choice of the slope angle is important. If the slope is steep, it is perfect, as it will make the sludge slide properly to the bottom. But a steep slope would require a deeper tank, which is problematic in terms of construction and transportation for metallic clarifiers. Conversely, a shallow slope forming shallow pyramids (or cones for circular units) is easier to build, but will sometimes be insufficient to make the sludge slide to the bottom of the pyramid, and ultimately will not serve its purpose.

1.3.7 Clarified Water Collection

This includes the clarified water collection elements and the device for regulating the water level in the tank. The collection of the clarified water can be done in several ways. The choice should be made as to which is most appropriate for the type of unit, the geometry of the tank and the method of controlling the water level in the tank. In general, one should try to meet the following requirements as best as possible:

– Collect the clarified water in such a way as to avoid the carry-over of bottom sludge and, of course, of floated sludge.
– Do this by avoiding preferential currents that create short circuits and turbulence.
– The collection should be as homogeneous as possible, without leaving dead zones.
– Flow velocities in the different points of the collection system should avoid deposits as much as possible.
– Minimise variations in water level caused by changes in flow rate. Alternatively—vary the water level slightly with flow to ensure proportionality of floated sludge removal. To be considered on a case by case basis.
– Ensure accessibility for easy cleaning from time to time (as for all other parts of the installation).

In conclusion, it can be said that there are always several possible ways to build an installation. It is important to take into consideration all the specificities of the project and to make the choices that are best suited to the site, the application, the type of installation and even the skill levels of the operators (because in an industrial environment the operation of the wastewater treatment plant is sometimes entrusted to technicians occupying other positions and the managers do not always take care to train them properly…). But to make the right choices, one still needs to be able to choose from a range of different clarifiers and components suitable for different applications and configurations. And this is one of the problems often encountered in the market. Many manufacturers have one single type of clarifier that they try to place almost everywhere, arguing that this clarifier is perfectly suited to the situation. If these arguments are combined with a very optimistic performance guarantee and an attractive price, many customers may be tempted to buy an installation that would cause them problems in the short or medium term. One should not hesitate to study several solutions before deciding.

1.4 Main Parameters Characterising the Process

This chapter deals with the main design and performance parameters of the various components of a flotation plant.

The most important ones are the following:

For Pressurisation

- Air characteristics and solubility of gases in water
- Air-to-Solid ratio
- Saturation rate in the saturator
- Pressurisation rate
- Saturation pressure.

For Clarification

- Hydraulic load
- SS loading
- Capture rate.

1.4.1 Air Characteristics and Solubility of Gases in Water

Table 1.1 shows the solubility of some gases commonly used in water treatment as a function of temperature. Table 1.2 shows the density of air at different temperatures. Table 1.3 shows the variation of air density with altitude.

For maintaining a given volumetric concentration of bubbles after pressure relief in fresh water, all other conditions being equal, two design factors must be considered:

Table 1.1 Solubility of gases in water—litres of gas per litre of water at atmospheric pressure P = 1013 hPa

Gas	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C	35 °C
Air	0.0255	0.02268	0.02048	0.0187	0.0172	0.0161	0.0150
H_2	0.0204	0.0195	0.0188	0.0182	0.0175	0.0170	0.0167
O_2	0.0428	0.038	0.0341	0.031	0.0284	0.0261	0.0245
N_2	0.0208	0.0185	0.0166	0.0154	0.0143	0.0134	0.0125
CO_2	1.424	1.194	1.019	0.878	0.760	0.665	0.592
CH_4	0.048	0.0417	0.0269	0.0338	0.03	0.0276	0.0254
C_2H_6	0.0803	0.0656	0.0550	0.0472	0.0410	0.0362	0.0323

Table 1.2 Density of dry air as a function of temperature at atmospheric pressure P = 1013 hPa

Temperature	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C	35 °C
Mass, kg/m^3	1.269	1.247	1.225	1.202	1.184	1.164	1.146

Table 1.3 Density of dry air as a function of altitude at 15 °C (for other temperatures it is possible to compensate proportionally according to the values in Table 2)

Altitude, m	0	200	400	600	800	1000	1200	1500	1800	2000
Mass kg/m^3, at 15 °C	1.225	1.202	1.179	1.156	1.145	1.112	1.090	1.058	1.027	1.007

altitude and temperature. If the installation is at high altitude, the volume of air to be injected into the water for pressurisation must be adapted, as the air is less dense at altitude. Thus, a larger volume of air can be dissolved in the water than at sea level. For example, the mass of air at sea level is 1,202 kg/m^3 at 20 °C, whereas at an altitude of 1000 m it is only 1,091 kg/m^3. In other words, to obtain the same volumetric concentration of air bubbles after expansion, the pressurisation rate (or the pressure in the saturator) can be reduced proportionally by a coefficient of 1.091/ 1.202 = 0.907 (i.e. a 1.1 times reduction).

As can be seen from *Table 1.1*, the solubility of air in water decreases significantly with increasing temperature. This should be taken into consideration when sizing the air flow to be injected for pressurisation. For example, if the tests determining the quantity of air required are carried out at 20 °C, but the installation is going to operate at 30 °C, to maintain the same volumetric concentration of air bubbles after pressure relief, the pressurisation flow rate (or the pressure in the saturator) should be increased proportionally, i.e. 0.0187/0.0161 = 1.16 times.

However, with regard to altitude, the lower density of the air must also be taken into account when sizing the compressors supplying the air for pressurisation. These are volumetric devices, so the density of the air at intake is an important factor, as they draw in a volume and not a mass of air. However, the air flow rate for pressurisation remains constant, because in practice, air flow meters are used for dosing air in saturators with continuous air injection. These devices are usually calibrated in Nm^3/h at sea level. If the compressors provide a minimum pressure of 7 bar and the pressure is then stabilised at 6 bar by a pressure reducer (this is almost always the case, as without a pressure reducer the air flow rate would vary with compressor starts and stops), then the air flow rate is measured under pressure (the pressure in the saturator). The effect of the lower density of the air at the compressor inlet due to altitude disappeared when passing through the compressor, which compensated this difference in density. The conditions for dissolving the air in the saturator therefore remain unchanged. However, the volume of air available for flotation, which is released when the same volume of pressurised water is expanded, will be greater at altitude than at sea level.

1.4.2 Air- to-Solid Ratio (A_s)

This parameter has been present in scientific research on dissolved air flotation for many decades. It specifies the quantity of air needed to float a quantity of solids in water. It is expressed in mg of air per mg of SS. In some cases, for practical reasons, it can also be expressed in litres/kg or Nm^3/kg. Indeed, for air, it is easier to think in terms of litres or Nm^3, because the measuring devices (flow meters) measure a volume and not a mass. This parameter is used for sizing the pressurisation system. It is used to calculate the amount of air needed to ensure a sufficient volumetric concentration of bubbles to guarantee good clarification of a specific water or good thickening of a particular sludge. Normally it is specific to each application, i.e. to each type and concentration of SS. As an indication, for the thickening of biological sludge, the values of A_s most often recommended are between 0.015 and 0.025 kg/kg, i.e. approximately 0.0125 to 0.02 Nm^3/kg at 20 °C. In drinking water clarification the reported A_s is around 0.2–0.3 kg/kg for relatively high TSS concentrations and up to 0.4–0.5 kg/kg for clean water containing only a few mg/l of TSS.

Example: if 20 m^3/h of biological sludge with a concentration of 5 g/l is to be thickened and the A_s *value is 0.015 kg/kg TSS, then the quantity of air to be dissolved would be 20 × 5 = 100 kg of sludge per hour × 0.015 kg/kg = 1.5 kg/h of air, i.e. 1.25 Nm^3 of air per hour at 20 °C.*

While the concept of this parameter seems logical and sensible from a scientific point of view, its definition and use remain rather difficult in practice. Indeed, the values proposed in different studies vary over a wide range—from simple to double or even more for quite similar cases. The same applies to the values found in different installations operating in very similar applications (if we refer to the usual basic parameters). Between drinking water clarification and sludge thickening, the range in terms of TSS concentration is vast. As values vary from 0.02 to 0.4 (i.e. by a factor of 20) and it is difficult to choose the right value for intermediate concentrations.

It seems obvious that the value of the Air to Solids ratio cannot vary linearly with the concentration of TSS in the water. It cannot be the same for a concentration of 10 mg/l of SS and for 1000 mg/l of the same SS. Because if one divides the value for 1000 mg/l of SS in proportion, i.e. by 100, the concentration of bubbles in the water will decrease 100 times. Under these conditions, the probability of collisions between flocs and bubbles would be so low that it would be somewhat naive to hope that the rare bubbles will all find the rare flocs. In reality, even for a very low SS concentration, it is necessary to have a sufficient concentration of bubbles in the raw water +white water mixture to ensure sufficient collisions. In practice, between a concentration of 10 and 1000 mg/l of the same SS, the difference between the amount of air needed for good flotation would be more in the range of 2 to 3 times rather than 100 times.

Secondly, the 'optimum' air to solids ratio can vary considerably depending on the attraction between the bubbles and flocs, and also on the stability of the agglomerates formed. The stronger the attraction and the more stable the agglomerates, the less air is needed for good flotation. And vice versa. In this respect, a well-chosen chemical treatment can considerably modify these two parameters and allow an excellent flotation with little air.

Finally, many feedbacks from similar installations show a clear dependence of this parameter on the hydraulic load of the DAF clarifier, which seems easily understandable. As turbulence increases with hydraulic load, more air is needed to create a sufficiently abundant cushion of bubbles to compensate for the stalls caused by this turbulence.

In conclusion: without disputing the logical sense of this parameter for the sizing of a pressurisation system, it would be more suitable to define it with a pilot or at least with a flotation test on site, case by case, whenever possible. At least for large installations with a high-energy stake. And it would be wiser to rely more on experience than on values recommended by various sources for "similar" cases. Because we rarely know the exact details of the conditions under which this parameter has been defined (what variations in TSS concentration and characteristics does the recommended A_s cover, with what chemical treatment etc.).

For more or less "standard" applications, such as drinking water clarification, recommendations on the amount of air to be used are often expressed in ml/l (or l/m^3) of raw water, which makes much more practical sense than As. Typical values for drinking water range from 6 to 8 ml/l (J. Haaroff, Van Vuuren, 1995—Design parameters for dissolved air flotation in South Africa) or 7–9 ml/l (J. E. Edzwald and J. Haaroff—dissolved air flotation for water clarification), with the higher values being for high hydraulic loading DAF clarifiers. This presentation of the required air quantity seems preferable as it ensures a sufficient bubble concentration without considering eventual (relatively small) variations in the TSS concentration. For example, in surface water clarification, it is common to have raw water containing a few mg/l of TSS for most of the year and peaks of 30 or even 50 mg/l for a short period of algae bloom. Indeed, going from 5 to 50 mg/l TSS at the inlet should not make a significant difference in terms of the amount of air required, as a sufficient concentration of bubbles must be maintained in the water anyway to ensure good flotation even for the 50 mg/l TSS. In other words, for these low TSS concentrations, there is no need to increase the amount of air even if the SS load increases several times. Nevertheless, to reach the end of such a resonance it would be legitimate to ask the question "where is the limit"? If one considers that there should be practically no difference between 5 and 50 mg/l of TSS at the inlet, what would be the maximum TSS concentration that can be clarified with a given amount of air? It is difficult to give a precise answer to this question, as it depends on several factors mentioned earlier. Although it is difficult to define the exact maximum value, there are of course ways to take precautions. One can go through a piloting campaign, but peak concentrations are not available on demand and sometimes one can wait for years to test. Or consider a safety measure such as frequency inverters on the pressurisation pumps that allow to increase the saturation pressure, for example, from 5 to 6 bar and thus gain 20% more dissolved air.

Finally, there is another way of defining the amount of air required for certain applications and for non-assisted clarification units. This is the amount of air per square metre of flotation surface per hour. However, this is a different presentation of the same thing—the amount of air per unit area ultimately receiving a certain volume of water or a certain amount of sludge to be floated.

1.4.3 Saturation Rate in the Saturator

This parameter characterises the capacity of the saturator to approach the maximum possible saturation rate at a given pressure and temperature. It is expressed as a % of the maximum saturation rate and is used to calculate the pressurisation flow rate as a function of the quantity of air to be introduced into the water to be treated.

In a saturator, water is continuously injected at a certain pressure. Air is also injected at the same pressure, continuously or intermittently, depending on the design of the saturator. The efficiency of the dissolving process depends mainly on two factors:

– The contact area between water and air inside the saturator. The larger the area of exchange, the faster and more efficient the dissolution of the air in the water.
– The contact time. The longer the contact time, the more air ends up dissolving in the water.

Depending on the type of saturator, saturation rates vary between 40 and 90%. However, this percentage needs to be clarified because it can be considered from two different points of view. The dissolution of the air in the water and the later pressure relief of the pressurised water (to produce the air bubbles) leads to a change in the composition of the air inside the air-cushion saturators, which is the case for the majority of the saturators available on the market. What happens? It is known that atmospheric air contains essentially 21% oxygen and 79% nitrogen. When this mixture is injected into the saturator, these proportions change because the solubility of oxygen is more than twice that of nitrogen, so it is absorbed in priority by water. Thus, the fraction of nitrogen will gradually increase and that of oxygen will decrease. Equilibrium will be reached when the ratio of the concentrations of oxygen and nitrogen in the pressurised water leaving the saturator reaches that of the air entering the saturator. At this point the air cushion in the saturator will contain about 88% nitrogen and 12% oxygen. This air inside the saturator (called saturator air) will be about 9% less soluble in water than atmospheric air. This would mean that the maximum rate a perfect saturator could achieve would be 91% in terms of atmospheric air. Of course, this rate will be 100% in terms of saturator air.

It should also be pointed out that during the pressure relief process, the air carried by the pressurised water will not necessarily come out completely in the form of bubbles. If the raw water is not saturated with air (at atmospheric pressure of course), some of the air carried by the pressurised water would make up the deficit to the point where the raw water is saturated with air. Thus, only the "remaining" excess air will be able to form bubbles. For a pressurisation rate of 10% typical for drinking water clarification this phenomenon can take on significant proportions, especially if the water comes from a borehole. To solve this problem, some authors go as far as to propose a pre-aeration of the raw water, for example on a waterfall. If the raw water is pumped, such a solution is not necessarily cheaper in terms of energy consumption than a slight increase in the pressurisation rate, but the comparison is worth making.

Knowing the saturation level of a saturator is like knowing its performance. The higher the saturation level, the better the performance, as it will be able to dissolve the required amount of air in a smaller pressurisation flow. The saturation rate of a saturator does not depend on the pressure inside. Under all other equal conditions, it will normally provide the same performance regardless of the pressure.

How to measure the saturation efficiency of a saturator? For saturators with continuous air injection one can stabilise the water level inside, then measure the flow rates of the pressurised water and of the air consumed by the saturator in stable operation. Thus, one can simply calculate how much air it consumes per m^3 of pressurised water and compare this value with the corresponding air solubility at the temperature and pressure in the saturator. For example, for a saturator operating with a flow rate of 100 m^3/h of water at 20 °C at a pressure of 5 bar, which can absorb a maximum of 6 Nm^3/h of air, without the water level inside starting to drop, the calculation of the saturation rate would be as follows:

The maximum solubility of air at 20 °C and 5 bar would be $0.0187 \times 5 = 0.093$ m^3/m^3 *of water. The saturator absorbs a maximum of 6* Nm^3/h *of air for 100* m^3/h *of water, i.e. 0.06* m^3/m^3*. The ratio between the maximum possible absorption and the actual absorption would be* $0.06/0.093 = 0.64$*. The saturation rate achieved is therefore 64%.*

Of course, this method is not very accurate, as it does not take into account all the factors influencing the process, but the result obtained is sufficient from a practical point of view.

For saturators with intermittent air injection (aiming to maintain the water level inside the saturator between two setpoints) this method is not usable because, while the water flow rate is constant and easily measurable, it is more difficult to have an accumulation of the injected air flow rate, unless one has a flow meter recording an accumulated flow over several hours. In this case, it is possible to use the device shown in Fig. 1.5. The cylinder (1) with a volume of at least 2 l is filled completely with water and plugged with the removable plug (6) comprising the diffusion tube (2) with the isolation valve (4), the diaphragm (3) with a diameter of about 1 mm and the outlet pipe (5). The cylinder is then turned upside down and connected to the pressurised water inlet and the receptacle (8) as shown in the sketch. The isolation valve (4) is gradually opened and the pressurised water expanded by the diaphragm (3) begins to replace the water in the cylinder (1) at the same time as the expanded air begins to form the air cushion (10). When the air cushion (10) is sufficiently filled, the isolation valve (4) is closed. The volume of the air cushion (10) and the volume of the water in the receptacle (8) are measured. Then, with these two values and the same calculation as above, the saturation rate reached by the saturator can be calculated.

For a simple quick test of a saturator's operation that can be done easily on site without setting up a sophisticated and cumbersome device, a simple 1000 ml laboratory flask can be used—Fig. 1.6. All that is required is a sample point for the

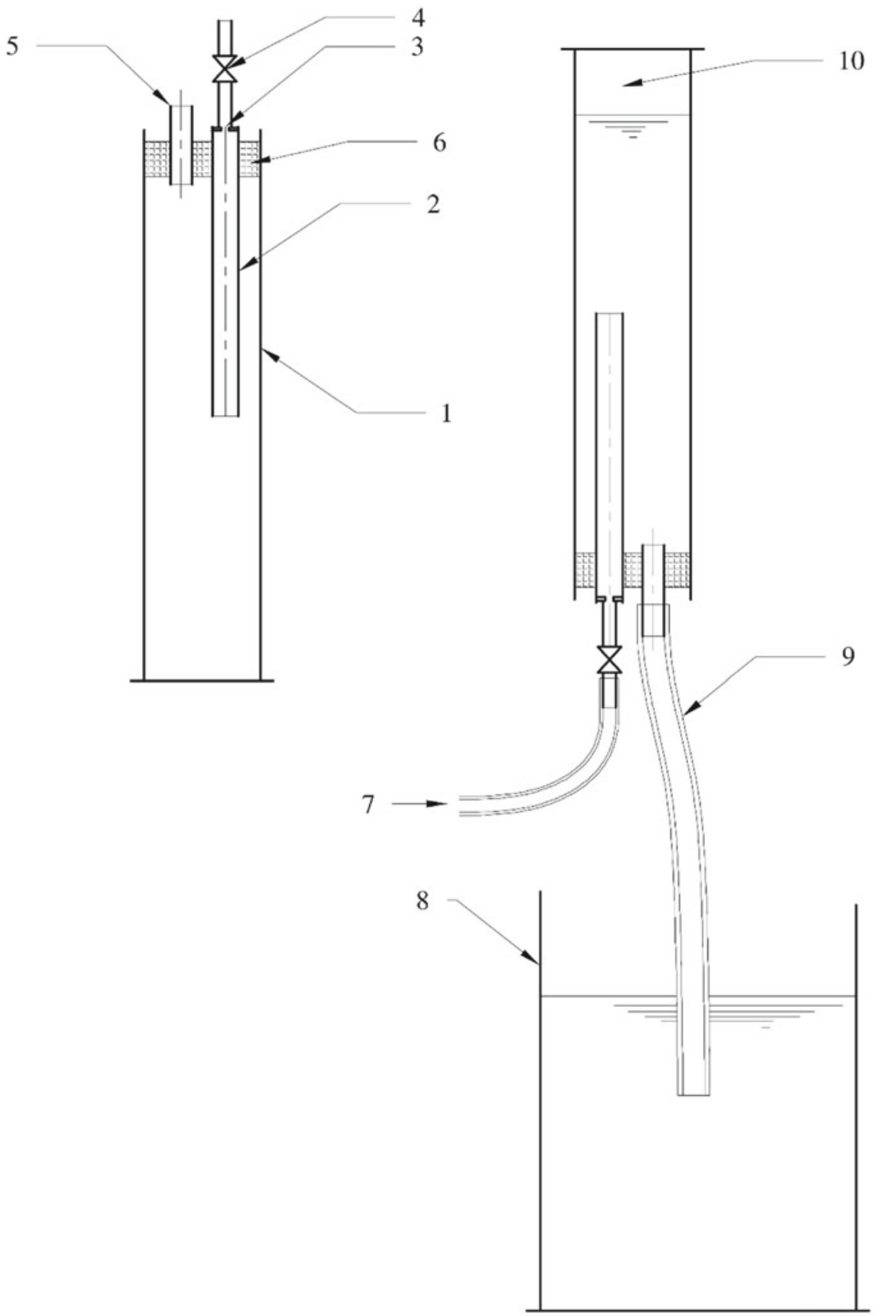

Fig. 1.5 Dissolved air measurement device, 1—glass cylinder, 2—diffusion tube, 3—diaphragm with calibrated hole, 4—isolation valve, 5—outlet pipe, 6—removeable plug, 7—presuurised water inlet, 8—receptacle, 9—flexible hose, 10—accumulated air cushion

pressurised water with a piece of 6/8 mm flexible tube, ideally with a valve so that the pressure relief can be made as close to the flask as possible. By introducing the pressurised water into the bottom of the flask as shown, simply fill it as quickly as possible to overflowing, leave it to overflow for 20–30 s so that the volume of water is exchanged once or twice and then remove the tube gradually in reducing progressively the flow without cutting it off completely so that the flask continues to overflow until the tube is completely out after 8–10 s. In this way the flask will be full of pressurised water "to the brim". Then simply let the air out and measure the drop in water level in the throat of the flask. Knowing the diameter of the throat, one can easily calculate the volume of air that the water has lost.

Of course, this measurement is not accurate because it is not done under the best conditions. Firstly, air is lost during the filling of the flask. Secondly, the pressure relief under these conditions is not optimal—one can easily see the immediate formation of large bubbles in the flask. Therefore, some air is lost before the beginning of the observation, but if the result of the calculation shows that the water has lost even 3.8–4% of its volume, the saturator is working approximately properly. Therefore, this method should only be used as an indication to get an idea and to easily spot any significant malfunction of the saturator. However, it has another advantage. It allows

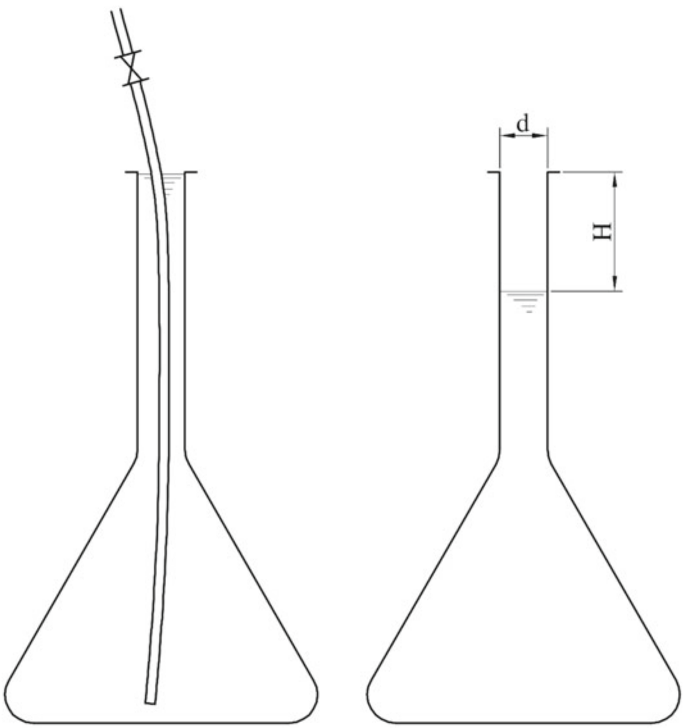

Fig. 1.6 Quick measurement of dissolved air with a laboratory flask

you to see if a film of floated sludge has formed on the surface of the water in the throat of the flask after the air has left. If the pressurisation is done with recycled water (which is almost always the case), then its presence indicates a flotation malfunction, as it shows that there are still remnants of floatable material in the clarified water. If, on the contrary, the surface of the water in the throat is perfectly clean after such abundant pressurisation, then the DAF clarifier has performed its role honourably and has separated all the floatable material.

It is worth drawing the reader's attention to a few details regarding the analysis and perception of this parameter. It is logical to assume that the higher the saturation rate of a saturator, the better it performs in terms of bubble production. This is not always true, as bubble production also depends on the pressure relief conditions, which will be discussed in detail later in Chap. 3.3. In general, if the pressure relief is not done under the best conditions, the higher the saturation rate, the more bubbles would be produced at high concentration at the pressure relief and would tend to coalesce faster to form a larger number of larger bubbles, which are less efficient for good flotation. For example, the multiple pressure relief nozzles used in drinking water essentially favour the formation of fine bubbles. In this case, a high saturation level is beneficial and a saturator giving 80% saturation will certainly be of value. But for pressure relief modes used in wastewater (e.g. a pressure relief valve on a pipe) this benefit is less, because at high saturation some of the air would be lost uselessly in large bubbles, which makes a saturator giving 80% saturation not really valued. It can be deduced from this that for wastewater it is probably not very beneficial to have a saturation level above 60–65%. Saturation tests carried out on a test stand show that above 70–75% saturation the white water produced by pressure relief with a seat valve starts to become greyish and the bubbles—visibly larger. The most likely explanation would be that in such conditions the pressure relief would favour an increase in coalescence inside the pressure relief valve itself. Once the saturation level was lowered below 60%, at the same flow rate and pressure, the white water returned to its milky white appearance. For reference, the same test carried out with a multi-orifice diffuser used in a drinking water pressure relief system did not show any variation in the quality of the white water. These values should be considered as a guide, as on the test stand the fresh water supply to dilute the white water after pressure relief was probably insufficient, but this experiment illustrates the tendency of what can happen when there is too high a concentration of microbubbles in a restricted space, even for a very short period of time.

1.4.4 Pressurisation Flow Rate

The pressurisation flow rate is defined according to the quantity of air to be dissolved, the saturation rate of the saturator and the saturation pressure.

To return to the example started above (thickening 20 m^3/h of biological sludge at a concentration of 5 g/l with the value of the selected As of 0.015 kg/kg of TSS), if 1.25 Nm^3 of air per hour is to be dissolved in a saturator with a saturation efficiency *of 60%, at sea level, in water at 20 °C and at a pressure of 5 bar in the saturator, the pressurisation flow rate will be calculated as follows:*

Air solubility at 20 °C at 5 bar—0.0187 × 5 = 0.0935 Nm^3/m^3, if saturation is 100%. For an efficiency of 60% we would have 0.0935 × 0.6 = 0.056 Nm^3/m^3 of pressurised water actually dissolved. To provide 1.25 Nm^3/hr we therefore need 1.25/0.056 = 22.32 m^3/hr of pressurised water.

If one always works at the same saturation pressure and uses the same type of saturator, then sizing for the most common water temperature range (i.e. 15–20 °C) is practically reduced to the choice of the "pressurisation flow rate". This parameter is usually given as a % of the raw water flow rate at the inlet to the plant. Depending on the application and the TSS concentration, this rate can vary from 8–10% (generally for less than 100 mg/l of TSS at the inlet) to more than 200% (biological sludge at 10 g/l). The pressurisation rate can be determined by a pilot test or at least by flotation test on site. But when it comes to a project involving an installation that does not yet exist, the only way to choose is based on experience.

In some cases the tender specifications give indicative ranges of 'recommended' pressurisation rates. A frequent ambiguity to be cautioned against is the lack of precision on the saturation pressure and the definition of the pressurisation rate which can be defined in two different ways:

- The pressurisation rate as a % of the raw water flow.
- The percentage of pressurised water of the total flow entering the flotation zone, where the total flow includes the raw water flow plus the pressurised water flow.

For example, 20% pressurisation on an inflow of 100 m^3/h is 20 m^3/h. But to have 20% pressurised water of the total flow into the flotation zone, you need 100/0.8 = 125, and 125—100 = 25 m^3/h.

It is important to choose the pressurisation flow rate carefully, as the most important part of the energy consumption of the installation is that of the pressurisation pump. This is certainly true for pressurisation rates above 10–15 m^3/h. For very small wastewater plants (cases with only a few m^3/h of raw water to be treated), it is not advisable to choose a pressurisation rate of less than 3–4 m^3/h. This is for the following reasons:

- The savings in terms of energy consumption are negligible, as very small pressurisation pumps of 2–3 m^3/h at 5.5 bar often have very low efficiencies.
- These very small pumps often have impellers with passages of only 3–4 mm, which present a risk of clogging.
- The pressure relief device for 1.5 or 2 m^3/h (valve or calibrated diaphragm) will be quite small and will also present risks of clogging.
- Finally, an excess flow of 2–3 m^3/h will hardly change the size and therefore the price of the DAF clarifier.

Finally, a few reminders of two trivial but sometimes mismanaged details

- Some installations are equipped with flow meters on the pressurised water loop and the flow rate is easily readable directly. On other installations, this flow rate is

calculated according to the pressure drop in the saturator inlet injector, which is displayed as the differential pressure between the pressures upstream and downstream of the injector. If the pressure relief is done with one or more valves or, more generally, with one or more regulators, it should be remembered that what is being regulated is a flow rate and not a pressure. In other words, it is not the upstream or downstream pressure of the injector that counts, but the difference between the two pressures.
- The pressurisation pump is usually centrifugal. Therefore, every change in the pressurisation flow rate results in a change in the saturator pressure and therefore in the air flow rate. The air flow rate must be readjusted after each modification of the pressurisation flow.

1.4.5 Saturation Pressure

As already mentioned, pressure relief at a pressure below 3–4 bar sometimes produces bubbles of poor quality, especially in drinking water. For this reason, pressurisation is usually done at a pressure of over 4 bar. From there, the choice of saturation pressure may depend on other factors:

- The available pressure of the compressed air that will be used for pressurisation. In industrial effluent treatment plants, it is common to use the plant's own compressed air network to supply the pressurisation system. In this case, the minimum pressure that this existing network can provide must be taken into account. It seems useful to recall here some simple common sense details that are sometimes neglected:
- For reasons of reliability and stability of the air flow measurement, it is recommended to have a saturator supply pressure reserve of at least 0.5 bar higher than the pressure in the saturator. The closer these two pressures are to each other and the more the control valve has to be opened, the more its sensitivity decreases and the more unstable the air metering becomes. And when they are the same, it is no longer possible to inject air into the water—on the contrary, it is the water that could go back into the air circuit, if the pressure in the saturator becomes higher than the pressure at the air pressure reducer outlet.
- Sometimes the minimum pressure available is more than enough (6.5 or even 7 bar), so one can choose to pressurise at 5.5 or even 6 bar. But sometimes the minimum pressure available is only 5.5 bar. In this case the pressure in the saturator should not exceed 5 bar.
- If the defined pressurisation flow rate is at the limit of the hydraulic capacity of a standard saturator size and the available air pressure allows it, the dissolving pressure can be increased slightly to be more hydraulically comfortable and to avoid using a larger saturator size.
- As a safety reserve, one can choose to operate, for example, at 5 bar under normal conditions and then increase to 6 or even 6.5 bar if necessary. This option is particularly interesting for large drinking water installations with pressure relief nozzles where the flow rate is relatively little influenced by the pressure above

5.5–6 bar. Thus, a simple way to increase the amount of dissolved air is to increase the dissolving pressure.
– The operating point offering the highest efficiency of the pressurisation pump can also influence the choice of the dissolution pressure.

1.4.6 Hydraulic Load

The hydraulic load is defined as the flow of treated water per unit of flotation area. It is expressed in $m^3/m^2.h$, or in other words in m/h. There are several ways of presenting this parameter. It can be given in relation to the incoming flow (the raw flow) or in relation to the total flow, i.e. the incoming flow + the pressurisation flow. The latter presentation is more logical because the pressurisation flow rate brings a non-negligible and sometimes even quite substantial hydraulic load. Secondly, in calculating the flotation area, the area of the contact zone may or may not be included, if the DAF clarifier has such a zone. The small details of the definition of this parameter should therefore be clarified.

The hydraulic load, together with the definition of the air requirement and the pressurisation flow rate, is one of the main parameters for sizing a DAF clarifier. It concerns the surface area and dimensions of the tank of the clarifier. Therefore, it has a direct influence on the cost of the unit and possibly on the installation and civil engineering costs.

It is obvious that the most appropriate hydraulic load for each specific case would be the maximum load reasonably possible, minus a safety margin to cover possible unforeseen events and contingencies. In this way, the DAF clarifier would be the most compact and therefore the cheapest possible, but without excessive risk. It depends on most of the factors influencing flotation clarification described so far, namely:

– The stability of air bubbles in this water
– The attraction between the bubbles and the SS
– The stability of the agglomerates between the SS and the bubbles
– The bubbles' concentration, i.e. the amount of air per m^3 of raw water
– TSS concentration—above a certain limit the SS loading must also be taken into account, not only for the amount of air to be used, but also for collection and floated sludge extraction reasons.
– The chemical treatment (coagulant, flocculant) which may not only influence, but sometimes completely change all the above mentioned parameters.
– The specificities of the DAF clarifier and its hydraulic concept.

As an indication, for DAF clarifiers with non-assisted clarification (lamellae or other tricks such as "U" shaped elements), the total hydraulic load in wastewater (municipal, food processing effluents etc.…) is typically between 5 and 8 m/h, sometimes up to 10 m/h. For drinking water applications where the amount of TSS is low and the chemical treatment—in general—quite efficient, most modern flotation plants are designed for hydraulic loads ranging from 15–20 to more than 30 m/h. For such very high hydraulic loads, the pressurisation system is sometimes slightly oversized to provide a sufficiently thick bubble blanket over the entire surface of the flotation zone. For assisted clarification DAF clarifiers, each manufacturer has its own sizing methods based on its technology and experience. For some vertical DAF clarifiers, the term hydraulic load, in relation to the surface area of the water mirror, becomes meaningless and the design is based on other specific criteria.

To determine the hydraulic load, it is strongly recommended that a test be carried out whenever possible, as the variations from case to case can be significant, even for apparently similar applications. Of course, a test is not always possible. Then comes the temptation to use "usual" values, as this is easier and safer for everyone. This starts with the sales people who make offers all year round and who do not have the means, and sometimes the qualification, to organise a proper on-site flotation test, especially with a well-chosen chemical treatment. This also includes consultants and sometimes even end-users who use values given in commercial brochures to get an idea. In short, everyone would like DAF clarifiers' sizing to be simple, but alas, it is not. There are so many cases where DAF clarifiers work well at twice the maximum capacity given in the sales brochures. And vice versa—sometimes they 'stall' well below these values which are in fact given only as an indication, without this being made clear.

1.4.7 Solid Load

The SS loading is defined as the amount of TSS entering per unit area of the flotation zone. It is usually expressed in kg/m^2.h. This parameter is an important design parameter in the same way as the hydraulic load. Both should be considered in parallel because, beyond certain values, one or the other becomes decisive for the sizing of the flotation surface. For example, for clarification of biological sludge in a non-assisted clarification DAF clarifier, the hydraulic load will remain predominant up to a concentration of about 1500–2000 mg/l (for clarification with 2–3 mg/l of cationic flocculant). Above these values the sizing could be done rather in relation to the SS load of 6 to 10 kg/m^2.h not to be exceeded depending on the characteristics of the sludge and the degree of sludge thickening sought. For other applications, for example in the paper industry, this limit would be in the range of 2,500–3,000 mg/l of TSS or even more for certain paper effluents.

The acceptable SS load depends on the same factors as the hydraulic load mentioned above. Of course, certain applications have their own specificities according to the different cases.

The two most common applications where SS loading is important are clarification and thickening of biological sludge. Indeed, these are probably the "common" applications for dissolved air flotation where the TSS concentration of the raw water is the highest. Moreover, the Air-to-Solid ratio is fully relevant as a sizing parameter. In the literature, there are many publications about the biological sludge thickening suggesting values for the different design parameters, especially the Air -to-Solid ratio and the SS load. But it is more difficult to find information on the simultaneous influence of these two parameters on the design and subsequently on the operation of the DAF clarifiers. If one wishes to study this application in depth, one must add another important factor, but rarely considered in combination with the first two: the Sludge Index (Mohlmann Index). This parameter characterises the capacity of sludge to compact. It can significantly influence the recommendations for SS loading and other design parameters to be retained in this application.

All this leads to the conclusion that design parameters such as hydraulic load, solid load and Air-to-Solid ratio have to be considered as a whole and with care, as they in turn depend on other, sometimes quite influential factors. Separating them from each other could give an incomplete and misleading picture. A value for the Air-to-Solid ratio only makes practical sense if one knows the mass and hydraulic loads of the DAF clarifier, the characteristics of the TSS to be floated and the characteristics of the clarified water and floated sludge required.

1.4.8 The Capture Rate

It defines the proportion between the concentration of a pollutant contained in the clarified water compared to its concentration in the raw water. In other words, it defines the efficiency of the clarification. It is expressed in % and can concern any pollution parameter—TSS, COD, BOD, TOC etc. Technically speaking, this parameter certainly makes sense. But it must be well defined on a case-by-case basis. Otherwise, out of a clearly defined context, it can become quite ambiguous. For example, a TSS capture rate of 98% for a clarification of water containing 1000 mg/l of TSS may be achievable (this means 20 mg/l of TSS in the clarified water), whereas for the same water containing only 50 mg/l of the same TSS this figure does not make much sense. Indeed, it would mean that the clarified water would contain 1 mg/l of TSS, which is a concentration that is (very) difficult to achieve and difficult to measure, as at this level the measurement is likely to be perturbed by colloidal matter. It is therefore advisable to handle this parameter with care, as it appears in many specifications, without the details that should govern it.

Chapter 2
The Main Equipment of a Dissolved Air Flotation Plant

2.1 Coagulation and Flocculation Equipment

The specific features of dissolved air flotation make this clarification technology almost always used in combination with chemical treatment. The few exceptions are mainly biological sludge thickening and some applications in food processing such as the removal of particulate grease (non-emulsified). The reason for this is mainly that this technology can clarify very quickly and very well if it is used under the best conditions. Well, a chemical treatment by flocculation or by coagulation + flocculation ensures the most favourable conditions from several points of view. It is also true that chemical treatment is beneficial and even indispensable in a large number of cases of clarification by sedimentation, as it improves the efficiency of separating polluting materials. In sedimentation, it certainly makes it possible to significantly increase the sedimentation velocity, but in flotation its importance can be even more significant, because it favours not only the trapping and agglomeration of micro-flocs and the quality of liquid/solid separation, but also the quality of the adhesion of micro air bubbles to the flocs.

As mentioned, flocculation, and especially coagulation + flocculation upstream of flotation may, in some cases, have some specificities compared to clarification by sedimentation. The possible differences can be essentially two:

1. Settling often requires large, compact flocs that settle better because they create less turbulence around them as they settle into the water, which in turn rises to take their place. In the case of flotation, the bubbles make the flocs rise very efficiently and the turbulences caused by their rising influence the process relatively less than in sedimentation. Therefore, it is not always necessary to have large flocs for flotation to work well. Often small flocs of a few hundred microns in diameter float perfectly well and at very high velocities as for example in drinking water treatment. The advantage of this is threefold. Firstly, the flocculant dosage can be reduced. Secondly, this reduction in flocculant dosage, apart from the cost aspect, will be beneficial in cases where flotation is followed by filtration, as

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
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the residual flocculant remaining in the water (there is always some left, as it is difficult to expect all of it to be trapped in the flocs.) will have less of a clogging effect on the filter media. And thirdly, the flocculation time, and therefore the volume of the flocculation tank, will be smaller.

2. The electrostatic charges of the air bubbles will sometimes impose different requirements on the electrostatic charges of the flocs. Therefore, sometimes it is necessary to adapt the chemical treatment to flotation, especially in cases of coagulation + flocculation. Sometimes the flocculant that gives the best results in sedimentation is not the most suitable for flotation. Therefore, it is always best to validate the selection made with Jar tests (in view of sedimentation) with a flotation test to ensure that the coagulant/flocculant combination selected with the Jar test also gives the best flotation results. Most often, this concerns the selection of the flocculant. Sometimes, even often, after coagulation with a mineral coagulant, a cationic flocculant gives the best results in settling, whereas in flotation an anionic flocculant would perform better. Of course, one might consider that the cationic flocculant somehow "finishes" the job of the coagulant, and therefore the dosage of coagulant would be less, at least in theory. Whereas, to use an anionic flocculant, the dosage of coagulant must be sufficient to neutralise the electrostatic charges of the particles as much as possible and even slightly shift the charge of the medium to the positive. Consequently, one could deduce that more mineral coagulant is needed. In reality, this assessment is questionable, as the cationicity of cationic flocculants is much lower than that of mineral coagulants and, to have a real additional cationicity contribution by the cationic flocculant, a significant dosage is required. There are many examples of this type of case where a change in flocculant can completely change the performance of the DAF clarifier. One such example is a particleboard mill in Finland with a DAF clarifier sized for a contractual capacity of 80 m^3/h to treat 60–70 m^3/h of log debarking pond effluent. According to the customer, the unit had difficulty treating more than 40 m^3/h without starting to lose flocs. The treatment originally chosen by the mill's water treatment chemical supplier was PAC + cationic flocculant. The resulting flocs were bulky and solid, but the customer complained that the flotation was malfunctioning. The only remedy he could find was to increase the flocculant dosage to 40–70 mg/l (!!) depending on the day, to be able to treat his 40 m^3/h as best he could. Finally, he called for help. Once on site it was clear that the flocs were quite large and well formed, but tended to remain dispersed in the water and floated only very poorly. Changing the flocculant type showed that with the same PAC dosage and only 1.5 mg/l of anionic flocculant the DAF clarifier was easily treating up to 116 m^3/h (the maximum flow rate of the DAF clarifier feed pump) providing a clarified water quality never before achieved, whilst saving almost €300 per day in flocculant costs.

2.1.1 *Influence of the pH*

It has already been mentioned that pH plays an important role in the performance of coagulation with a mineral coagulant, and even flocculation with a flocculant. The pH optimisation is an integral part of the chemical treatment set-up prior to clarification. Sometimes there are two possibilities for coagulation with the same coagulant at different pH values with quite different results. An example is a plant producing vegetable oils and several kinds of oil-based condiments in Croatia where, during commissioning, the dose of $FeCl_3$ needed to obtain contractual guarantees turned out to be significantly higher than in the preliminary tests and produced a lot of sludge. This high dosage of $FeCl_3$ reduced the pH to about 5.5–5.8 (usually around 6.2–6.8 before treatment). It was found that acid breaking with hydrochloric acid (HCl) at pH 4.6–4.8 prior to coagulation reduced the required dose of coagulant by 2–3 times while also achieving better COD and oil reduction. The flocs produced were small and compact and their volume decreased several times. In addition, the sludge produced was dewatering better. In short, the configuration was beneficial in all aspects. Two additional tanks were required—one before coagulation to acidify and one after the DAF clarifier to raise the pH to the standard required for discharge to the sewer, but the result was well worth the investment. Operating costs were reduced overall, as the cost of acidification and neutralisation was more than offset by the savings in coagulant and sludge treatment costs…

The adjustment of the pH is usually done in two ways. The first is to use the coagulation tank directly, in which both treatment steps are carried out at the same time. The coagulant dosage is kept fixed and the acid (or soda) dosage is regulated to obtain the desired pH. This method allows a stable pH to be obtained at the tank outlet. On the other hand, the mixing of the water in the tank and, above all, the injection points of the products must be carefully studied to ensure that the coagulant is not dispersed in a zone where the pH may still be far from the optimum value for coagulation. The second way is to use a separate pH adjustment tank upstream of the coagulation tank. A stirred tank with a residence time of 2–3 to 8–10 min is sufficient and allows the pH to be adjusted properly before coagulation. In this configuration, automatic regulation of the pH is often simpler and more reliable, but for low-buffered waters, significant variations in the dosage of the coagulant can modify the pH a posteriori. In this case the pH will probably not be optimal for coagulation. It is therefore advisable to test and choose the most appropriate method on a case-to-case basis.

The pH adjustment in drinking water treatment is also very important not only for the quality of the coagulation, but also to keep the amount of residual iron and especially alumina dissolved in the water as low as possible. In general, it should be done before coagulation. CO_2 is very often the preferred acidifier, as the drop in pH is limited to around 5.5 at the lowest, which gives a certain security in the event of a dosing incident. For more details on this application see Sect. 9.5.

For flotation plants, the pH should be raised (when necessary) if possible with sodium hydroxide rather than lime. Low doses of lime (as for remineralisation) are not a problem, but high doses of lime can make the flocs heavier and more aerophobic, thus disturbing the adhesion of air bubbles.

2.1.2 Static Mixers

Static mixers are devices that allow a rapid and homogeneous dispersion of a continuously dosed chemical in water. They can be installed on a pipe or in a canal. The operating principle is simple: it uses one or more baffles that deflect all or parts of the flow in different directions inside the pipe (or channel), in order to create turbulence and disperse the dosed product homogeneously in the stream. The product is dosed in one or more points upstream or at the beginning of the static mixer where the stream passes in a narrow section. Then, depending on the size and design of the mixer, this flow containing the metered product is dispersed throughout the flow section. Small diameter tubular static mixers generally have a single injection point for the product to be dispersed. Large diameter tubular and channel static mixers usually have several injection points for the product to be dispersed.

The energy required for mixing is provided by the stream. Therefore, static mixers inevitably create pressure losses. For tubular static mixers these pressure drops range from one or two tens of centimetres to more than 1 m, depending on the size, type and sizing. Such a pressure drop is not really acceptable for channel static mixers. This is why the latter are more complex and have several product injection points so as to limit pressure drops to less than ten centimetres in most cases.

There are numerous static mixer types on the market. Each manufacturer has its own peculiarities, dedicated application areas and specific advantages. For more information on the design and detailed specifications of the existing devices, the reader may wish to look on internet—suppliers and documentation are easily found there. For the application area of interest, the following points should be highlighted:

1. Static mixers are a good solution for mixing chemicals in water that is free of or at least low in SS. The very presence of bulky bodies, fibres or filaments is an eliminating factor for these devices, as they may clog the baffles of the mixer. Alternatively, screening should be provided upstream of the mixer.
2. Static mixers are a good solution for mixing the flocculant. It should be remembered that a good dispersion of the flocculant in the water upstream of the flocculation tank (or tubular flocculator) is essential for an optimal result. This detail is often overlooked either through negligence or a misplaced concern for cost reduction. Many cases can be seen in the practice where the flocculant flows directly over a corner of the flocculation tank. This is the ideal concept to make the mixing of the product with the water as slow and inefficient as possible… This also applies to cases of soda or acid injection in a pH correction tank. A good mixing of the chemical to be injected, whatever it is, at the entrance of the tank can allow to reduce significantly its volume and also, sometimes, to reduce the dosage, due to a more efficient use of the product.

3. Static mixers can be a good solution also for coagulant injection. However, in terms of mixing energy and shear forces transferred to the water, they cannot always compete with good dynamic mixing. There is also the problem of flow variation. If, for some reason, the flow rate becomes significantly lower than the design flow rate of the mixer, its efficiency in terms of mixing energy will be slightly reduced.
4. For coagulant injection, it would always be preferable to select a static mixer that creates intense mixing, even if this would result in significant pressure drops. This is not always possible if the piezometer line is tight.

2.1.3 Pipe Coagulators/Flocculators

These devices are in reality simple long pipes ensuring a certain mixing and contact time between the water and the dosed reagents upstream or along the pipe. They consist of several sections of straight pipes connected by elbows to form a compact spiral of significant length and are widely used for almost all chemical treatments. Coagulation, flocculation, but also pH adjustment are entrusted to tubular coagulators/flocculators, especially for the treatment of small flows of industrial effluents. A schematic diagram of such a device is shown in Fig. 2.1.

Usually pipe coagulators/flocculators are adapted on a case to case basis depending on the application and site conditions. They can be equipped with different options such as:

– A bypass with isolation valves—always useful!

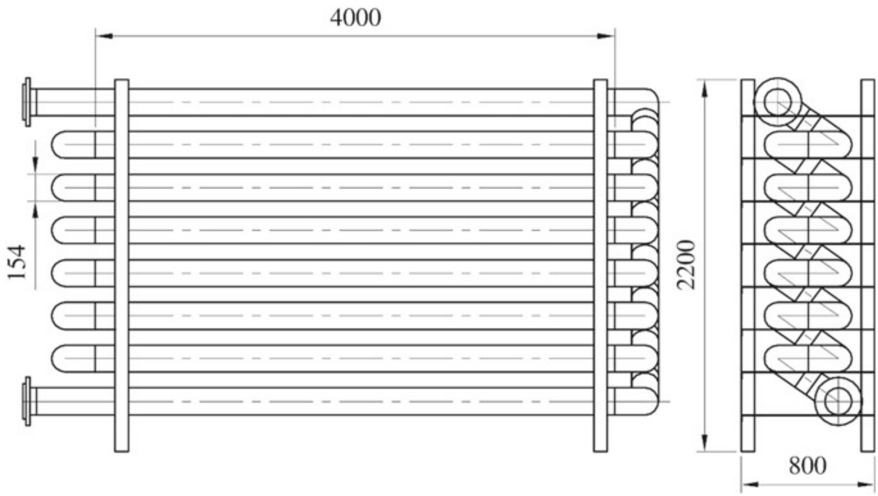


Fig. 2.1 Pipe flocculator

- One or more static mixers placed at locations corresponding to the different reaction times required. In the most complete case, a pH corrector can be injected, then a coagulant and finally a flocculant. But this is an extreme example, as it is often difficult to do all three things properly in a single device because of reaction time limitations (see below).
- One or more chemical injection points arranged according to the same principle.
- One or more sample points—always very useful!

These devices work well and are often preferred to separate, mechanically mixed tanks as they have some important advantages:

- They have no moving equipment (like the dynamic mixers in mixed tanks). Therefore, no maintenance is required, except in rare cases of clogging.
- They are powered directly by the feed pump which provides all the energy required for the various mixtures.
- There is no water surface, therefore no odours, no possible foams to clean, no possible overflows…
- Compared to mixed tanks, they can sometimes be cheaper in terms of investment, but in general, this is rarely the case.

The main disadvantage of these devices is their small volume. If one looks at the device shown in Fig. 2.1, one can see that this sketch shows a pipe coagulator/flocculator consisting of 14 straight sections in DN 150. The cumulative length of the straight pipes is 56 m and the total length is about 65 m. Its volume is about 1150 l. It is built with stainless steel pipes, but the preferred (and dominant) construction material for these devices is PVC because it is cheaper, easier to build and more resistant to corrosion. Assuming a residence time of at least one minute, this device would be suitable for a maximum flow rate of 65 m^3/h. The flow velocity in the DN 150 would be 1 m/sec. And the pressure drops could approach 1400–1600 mm excluding those created by optional equipment like static mixers.

Of course, each device is designed on a case-by-case basis, but it would seem that the optimum design velocity offering both sufficiently sustained mixing and reasonable residence time would be between 0.5–0.6 and 0.8 m/sec. On the other hand, it can be seen that with a diameter of more than DN 200 the size of the apparatus becomes disproportionate and difficult to defend compared to a mixed tank of equivalent volume. As a reference, the device shown in Fig. 2.1 has the volume of a tank with a diameter of 1100 mm and a water height of 1200 mm (thus 1400 mm with the edge).

This leads us to the conclusion that this type of device is well suited for relatively low flow rates—maximum 80–100 m^3/h with a residence time not exceeding 60 s. Or 120 m^3/h with a residence time of 50 s. But in both cases this results in an impressive device of about 6–7 m long, 2.2 m high and 1 m wide, which is quite large compared to a 2 m^3 mixed tank, i.e., as an example, a diameter of 1.4 m and a height of 1.5 m including the edge. And of course, the device will be significantly more expensive compared to the mixed tank, regardless of the price of the mixer to be supplied to agitate the tank.

In current practice, these devices are used for diameters between DN 65 and DN 150, which means that the flow rate does not exceed 50–60 m^3/h. Of course, this is only an indication—there are always exceptions. Some manufacturers offer units in DN 300 and even DN 350, with a pipe length of up to 36 m and a velocity of up to 1.3 m/sec. The unit is 5.5 × 1.2 ×2.8 H m. This is the equivalent of a 3500 l stirred tank, or only 1.7 m in diameter and 1.8 m high with the edge. But after all, why not?

Continuing with this thought, we can return to the idea mentioned above, i.e. to make a pH correction + coagulation + flocculation in the same apparatus. It is obvious that even with a design velocity of 0.4 m/sec (almost too low a limit to avoid deposits at a lower flow rate than the maximum design flow rate, and also too low a limit in terms of mixing energy…), at least 70 m of pipes are needed to ensure even three short minutes of residence time, which seems to be a minimum to carry out the three operations successfully. It is certainly possible, but for a flow rate not exceeding 15–20 m^3/h.

In conclusion, one can say that tubular coagulators/flocculators are good devices that work very well in many cases, but which, nevertheless, must be used in appropriate applications and after validation of the reaction times necessary to obtain the desired result. Systematic use of standard devices of this type should be avoided.

2.1.4 Coagulators/Flocculators with Dynamic Mixers

These tanks, equipped with one, or sometimes several mixers, are the most common devices for pH adjustment, flash mixing, coagulation or flocculation. They can be adapted to all flow rates and sometimes provide up to 40 min of residence time for specific cases of flocculation of particularly cold and low mineralized drinking water.

Depending on the size and application, the tank can be made of stainless steel, plastic (polyethylene or polypropylene), polyester or concrete for larger sizes. Glass fused to steel tanks is also an option. The volume of the tank is determined by the residence time required for the reaction to be carried out. For rapid mixing of coagulant the recommended residence time is usually 30–45 s. For coagulation the residence time can vary considerably. In general, the more polluted the water, the faster the coagulation, but unless proven by on-site testing, it is wise to allow at least 2–3 min. For drinking water the time required for good coagulation can be up to 15 min or even longer. The same applies to flocculation. In many cases of industrial or municipal effluents, flocculation is very fast (about 10 s) and an in-line injection of flocculant is sufficient. In drinking water treatment the flocculation time can, in some cases, be as long as 20 min.

The optimal time of reaction for a pH correction depends on several factors such as:

– The stability of the pH of the incoming water—the more stable the pH is, the easier it is to stabilise the control system. Conversely, the more the pH of the incoming water varies greatly, the longer it will take for the control system to react to deliver a stable pH at the outlet. Usually, a well-sized buffer tank upstream of the plant allows the pH and, more generally, all the water characteristics to be homogenised and smoothed out properly.

– The same philosophy applies to the inlet flow. If the flow is stable, regulation is easier and more reliable than if it is not.
– The buffering capacity of the water, in particular its sensitivity to acids or bases (the water is said to be weakly or strongly buffered respectively). In the case of weakly buffered water, a small variation in the dose of acid or soda will strongly modify the pH, hence the additional sensitivity of the adjustment.
– The degree of change in pH required. Going from pH 7.5 to pH 7 or to pH 5.5 does not require quite the same time to stabilise the regulation, especially if the water is not very strongly buffered.

As an indication, in the treatment of industrial effluents, the time required for a good pH correction is around 5 to 10 min. Reaction times can be estimated by experience, but experimental confirmation on site is always preferable, as the variations can be quite significant, even for cases that are "similar" at first sight.

2.1.4.1 Circular Tanks

Stainless steel, plastic or polyester tanks are usually circular. This shape is more suitable for these construction materials than the rectangular shape which requires reinforcement. The maximum diameter that can be transported on the road is 2900 mm, but if one opts for glass fused to steel tank, one can have any desired diameter.

The most important points to consider when designing circular tanks are:

1. The ideal proportion from the point of view of mixing efficiency is a volume whose diameter equals the depth. Of course, this is only a recommendation. One could deviate by 20% from this rule, either way, without creating a real problem for the mixing. Of course, mixer manufacturers can adapt to shapes that deviate from this ideal proportion, but it is better to respect it, if possible, without creating other problems.
2. Each circular tank agitated with a vertical axis mixer must be equipped with anti-rotation baffles. Otherwise, the mixer rotates the entire volume of water in the tank like a homogeneous block, which creates two significant problems:

– The mixing is almost impossible because the water rotates with the mixer.
– This rotation causes an oscillation of the water in the tank which is transmitted to the propeller and makes the shaft oscillate. Most often the shaft or even the blades of the mixer break in the short term.

The schematic diagram in Fig. 2.2 shows two variants of baffles. As a guide, the recommended width of the baffles should be 15–20% of the tank radius. The baffles can be made as 60 or 90° angles (for plastic or polyester tanks) or as a single flat (for stainless steel tanks). The baffles extend almost the full height of the tank, but stop

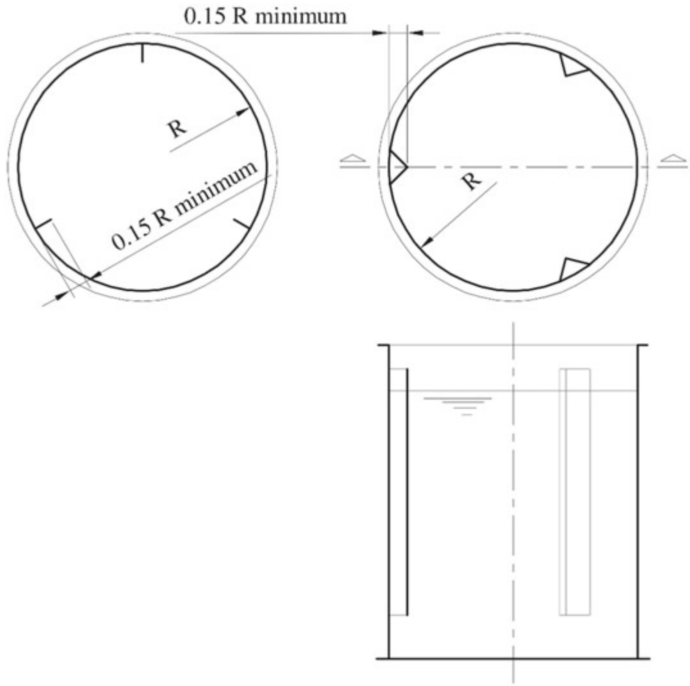


Fig. 2.2 Circular coagulation/flocculation tank with baffles

15–30 cm from the bottom to allow good cleaning of the bottom corner by the flow. In general, a minimum of three or four baffles are required, depending on the diameter of the tank. Above 2900 mm diameter it is preferable to have four, especially if the mixer has four blades.

Baffles can be avoided in two ways:

- Install an off-centre mixer with an inclined shaft—this is a good solution for small tanks, as there are mixers that attach directly to the edge of the tank and direct the flow diagonally towards the centre of the bottom.
- Install a mixer with a vertical shaft, but off-centre by about 25% of the radius. In this way, the propeller creates different speeds of water on the near and far side of the wall, which prevents the water from rotating as a block at the same speed.

Nevertheless, it is easy to see by simple observation that the baffles create additional turbulence in the flow towards the periphery that is not observed with an off-centre vertical mixer or an inclined shaft mixer.

There are two ways to maintain the water level in a coagulation or flocculation tank upstream of a flotation unit—see Fig. 2.3.

1. Connect the tank with the DAF clarifier in a communicating vessel—Fig. 2.3a. The level in the tank will be the same as that in the DAF clarifier plus the small

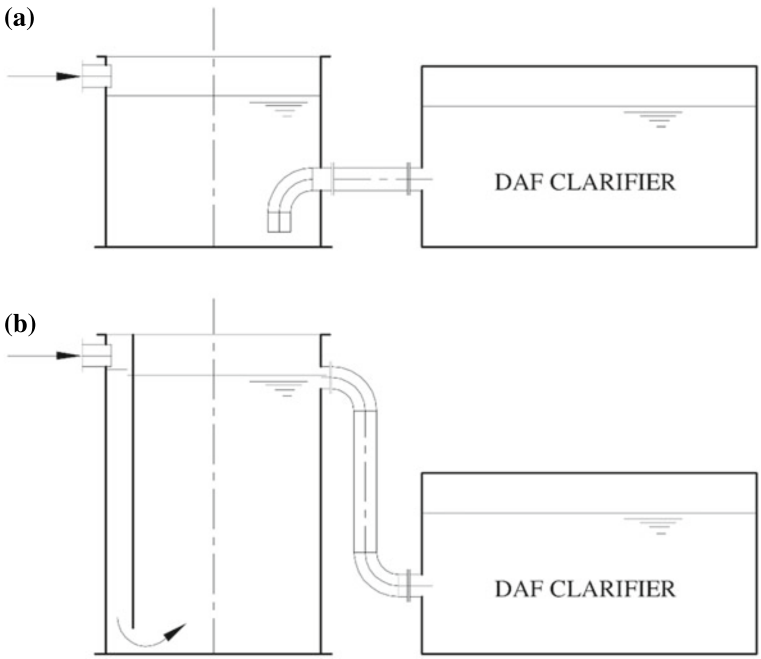


Fig. 2.3 Modes of maintaining the level in a coagulation or flocculation tank

head loss in the connecting pipework which should be sized with a velocity of less than 0.8–1 m/sec, if possible. In this case, the inlet to the coagulation or flocculation tank will be at the top and the outlet at the bottom. This configuration allows to shorten the connection pipe, to install a bigger pipe and to avoid any air suction and any destruction of the flocs if it is a flocculation tank outlet. This method of feeding the flotation tank is perfect from a technological point of view, but has the disadvantage of having the two water surfaces at the same level. If the volume of the tank allows its height to be adjusted in relation to the level of the water in the flotation tank, it is perfect. If not, the tank should either be raised on legs if it is too small, or the DAF clarifier should be raised if the tank is too high.

2. Through a weir or a simple outlet pipe at the top of the water surface—Fig. 2.3b. In this case, the entry to the tank will be at the bottom. This solution allows the water level in the tank (and therefore its volume) to be fixed precisely, but has a disadvantage that is often overlooked. If the difference between the water level in the tank and that in the DAF clarifier is significant (more than 40–50 cm), and, taking into account the "standard" sizing of the connecting pipes which consists in choosing a diameter giving a velocity of about 0.8–1 m/sec, it happens that the fall of the water in the outlet pipe sucks air and pushes it down into the DAF clarifier. As the water inlet to the DAF clarifiers is almost always submerged, the air coming out of the supply causes severe turbulence in the contact zone of the

DAF clarifier. The contact between the air and the white water also affects the quality of the white water, as some of the bubbles are lost on contact with the air. This type of outlet should be avoided unless the vertical part of the outlet pipe is sized for a velocity of less than 0.3–0.4 m/sec, which will allow the air to flow up the pipe without being sucked down further. It does have one advantage, however: it allows the coagulation tank to be much higher than the DAF clarifier. This is not ideal, but sometimes it is the only way to fit a large (and transportable) tank into a small space. If it is a coagulation tank, if the outlet pipe is large enough to ensure a maximum velocity of 0.3–0.4 m/sec and if the flocculation behind it is done in-line, then this could be acceptable. In this case the water fall in the outlet pipe could be used to mix in the flocculant, if this is of interest given the type of DAF clarifier behind. If it is a flocculation tank, this solution is not recommended, as the falling water will break the flocs. In this case a slight excess of flocculant will allow to reconstitute them more or less in the contact zone of the flotation tank, but this solution remains a compromise to be avoided as much as possible.

It is recommended to keep the outlet velocity of a flocculation tank low in order to avoid breaking the flocs that have been carefully grown in the tank. The most severe recommendations suggest a maximum velocity of 25 cm/sec (for drinking water), but in general one should try not to exceed 40–50 cm/sec even for flocculated effluents.

2.1.4.2 Rectangular Tanks

This type of tank is mainly reserved for concrete constructions. Exceptions are made when several successive tanks are grouped together in a compact rectangular block. In these cases, they can be made of stainless steel or plastic, with the necessary reinforcements on the flat walls. The optimum proportions follow the same rule discussed earlier—the optimum volume for mixing remains the cube. For very large drinking water clarification plants, a rectangular tank can have two and sometimes three mixers. In this case, ideally, each mixer mixes a cubic volume.

2.1.4.3 Dynamic Mixers

Once the dimensions of the tank have been defined, the selection of the mixer is made according to the mixing intensity required for the function to be performed (pH correction, flash mixing, coagulation or flocculation). This intensity expresses the energy that the mixer must dissipate in the water, which then defines the power consumed by the motor and its nominal power.

The two most common ways of calculating motor power express more or less the same thing in two slightly different ways. The first is to simply define a power per m^3 of volume depending on the application. It is expressed in W/m^3 of volume of the tank to be mixed. The second way is to calculate the power as a function of the velocity gradient G (expressed in sec^{-1}), adopted for each application. This method has the advantage of taking into account variations in the viscosity of water as a function of temperature. It is therefore considered to be more accurate, although on the other hand it should be remembered that the choice of the values of the velocity gradient is ultimately made rather empirically and on the basis of experience.

The velocity gradient *G*, also known as the *G* factor, is equal to:

$$G = \sqrt{\frac{P}{V \cdot \mu}} = K\sqrt{\frac{P}{V}}$$

G Velocity Gradient, (s^{-1})
P Dissipated power, (W)
V Volume of water in the tank, (m^3)
μ Dynamic viscosity, (Pa s)
K Constant expressing the dependence of viscosity on temperature.

$$K = \sqrt{\frac{1}{\mu}}$$

Temperature °C	0	5	10	15	20	30	40
K	23.6	25.6	27.6	29.6	31.5	35.4	38.9

Table 2.1 shows recommended values of *G* for different applications as a guide. In practice, it is recommended that the velocity gradient *G* is chosen taking into account the specific characteristics of the mixer. This is because there are several types of mixers and propeller shapes that are more suitable for some applications, shapes and sizes of tanks than for others. And the mixing performance can differ significantly for the same power dissipation, i.e. for the same velocity gradient *G*. Each manufacturer has its own sizing methods and calculation software which also take into account other factors such as:

Table 2.1 Recommended *G* values for different applications

Application	G, s^{-1}
Flash mixing	400–1000
Coagulation	260–400
Neutralisation, pH correction	240–300
Flocculation	60–100
Drinking water flocculation first stage	70–100
Drinking water flocculation second stage	40–60

– The level of agitation
– The shape of the tank
– Peripheral speed of the impeller—this should not exceed 2 m/sec, and even 1.5 m/sec for flocculation, so that the shear forces caused by the blades do not destroy too much of the nearby flocs
– The speed of rotation of the impeller
– The circulation flow rate
– The pumping flow rate

It is therefore recommended to consider the mixing problem as a whole and not to focus only on one parameter such as the velocity gradient G or, even less, the power dissipated per m^3 of water. The values shown in Table 2.1 are indicative and are mainly used to control the sizing of the mixer, which is ultimately done by the manufacturer.

Finally, a few words should be said about the power supply to the mixer motors. If the small mixers of the neutralisation or coagulation tanks can be powered directly, it is recommended to use frequency inverters for the flocculation tanks, especially those of large size (more than a few dozens of m^3). This allows the speed of the mobiles and the mixing intensity to be adjusted to optimise flocculation as well as possible. Frequency inverters in these power ratings are not very expensive and in addition offer good protection of the motors against possible overload. In fact, more and more manufacturers are offering motors with on-board frequency inverters in their product range.

2.2 Air Dissolving Devices

Before going into the details of the different types of saturators, a few important points should be made:

1. Apart from pressure and temperature, the efficiency of dissolving air in water depends on two factors: the contact area and the contact time between air and water. As already mentioned, the main purpose of each saturator is to bring water and air into contact as efficiently as possible, in order to obtain the highest possible saturation rate, and do this in the shortest possible time in order to limit the volume of the apparatus. It is obvious that there is a contradiction between the two effects sought. On the one hand, a very long contact time between a gently agitated water surface and an air cushion above it could lead to a very high saturation rate, but the volume of the vessel would be immense. And vice versa—very violent mixing, combined with a large exchange surface between water and air, even for a short contact time, could be very efficient and allow to have very compact apparatus. Most often, there is a compromise to be made between the volume of the apparatus (affecting its cost and size) and the energy devoted to mixing the two phases (affecting the operating costs). Each saturator offers “its” solution in the search for this balance.

The temperature has a double influence on the dissolution process. On the one hand, the solubility of air increases with decreasing temperature. It would therefore be logical to expect a better dissolution of air at lower temperatures. But on the other hand, the diffusion of dissolved gases in water becomes slower with decreasing temperature, which slows down the dissolution process. These two phenomena partially balance each other by reducing somewhat the influence of temperature on the amount of dissolved air. Therefore, it can be said that:

– The exchange surface between water and air and the intensity of water mixing inside the saturator are of great importance.
– While the amount of air dissolved by the saturator is relatively less influenced by temperature, the rate of saturation will, under all other equal conditions, be higher at higher temperature than at lower temperature. Thus, if a saturator can achieve, for example, 70% saturation at 30 °C, it would probably have some difficulty exceeding 50–55% at 10 °C. Admittedly, the solubility of air at 10 °C is about 30% higher (in mol/m^3) than at 30 °C, but the saturator will have some difficulty in really dissolving 30% more air with the same contact surface and the same mixing energy. Therefore, when talking about the saturation rate of a saturator, it would be correct to specify also at what temperature.

2. In general, there is no really precise method of sizing these devices. The values of some parameters such as the molar (mol/m^3) or mass (mg/m^3) concentration of atmospheric air as a function of altitude and temperature and the solubility of each of the air components in water at different temperatures, altitudes and pressures are known. This could allow a relatively accurate calculation of the transfer rate of each of the air constituent gases into the water at the dissolution pressure. However, it is more difficult to estimate the values of other key parameters such as the area and contact time between air and water and the influence of the hydraulic conditions created inside a saturator. Therefore, in practice, the choice of most design parameters is based on the results of tests carried out on each type of saturator and on experience.
3. It seems logical to assume that the saturator with the highest saturation rate will always be the most efficient for flotation. This is not always so obvious and the race for maximum performance at all costs is not always justified. At the risk of being controversial, it could be said here that 'more' is not necessarily 'better' in all cases. In other words, a very high saturation rate does not necessarily provide a substantial advantage in all applications. It has already been mentioned that the pressure relief conditions have a great influence on the fineness and stability of the microbubbles produced. But in most wastewater treatment plants the choice of pressure relief devices is based more on reliability than on efficiency. This means that a moderately efficient pressure relief device will quite often produce a certain portion of large bubbles and only a part of the bubbles generated will remain fine and therefore really effective for flotation. However, it can often be seen that a more "coarse" pressure relief under less "perfect" conditions of very highly air-saturated water produces mostly more coarse bubbles and ultimately

not so much more fine bubbles than if the pressurised water was less air-saturated. It should be noted, however, that this opinion is based on visual observations and not on precise measurements. To give an order of magnitude, it can be said that in wastewater treatment, given the most common pressure relief devices used in these applications, a saturation rate above 60–65% seems to be relatively unbeneficial.

2.2.1 Pressurisation Pumps

It seems worthwhile to devote a few lines to this subject, even if it seems irrelevant at first sight. After all, a pump is a pump… But there are three things that deserve some clarification.

The first is the choice of pump type. Any volumetric pump is to be avoided absolutely. The reason is simple—the slightest clog in the pressure relief or closure of the pressure relief valve results in an immediate and dangerous pressure build-up.

The most suitable pumps are centrifugal pumps, if possible single-stage. This is not to say that multi-stage pumps should be avoided in all cases—they often offer better efficiencies than single-stage pumps, especially for smaller sizes. But they have the disadvantage of having narrower gaps in the impellers, which are easily clogged even by small objects accidentally dragged into the pressurisation circuit. Multistage pumps can be used for drinking water applications or, in any case, for water that is almost free of SS. For other applications, the single-stage pump is the safest solution.

The choice of impeller type is also important. Although the so-called "closed" impellers offer the best energy efficiency, in wastewater treatment they present risks of clogging, especially for small sizes—up to 10–15 m^3/h. A vortex impeller is, of course, a little more energy-intensive, but will be almost impossible to clog. It is the best solution for the treatment of food processing effluents, which are often the most difficult in this respect.

The second concerns the materials of construction and the standards to which the pump is built (also called the pump construction code). With the exception of seawater applications and some rare cases of specific industrial effluents, the most common materials of construction are:

- Cast iron body and impeller
- Cast iron body and stainless steel impeller
- Stainless steel body and impeller

The materials of construction must, of course, be compatible with the characteristics of the water being pumped, but the most important element is the standard to which the pump is build. Construction standards for centrifugal pumps are tailored to different operating conditions, levels of robustness and reliability. They specify the design and sizing of the main components of each pump, such as shafts, bearings, seals, couplings, body and impeller wall thicknesses, etc. Depending on the construction code, for the same characteristics, a pump may weigh 25 kg (stamped stainless steel pump for clean water) or 250 kg (chemical process pump, oil industry). It is obvious that the two pumps will not have the same robustness, the same durability and … the same price. It is therefore important to choose not only the construction materials that are suitable for the application, but also the type of construction. Although drinking water does not pose any particular problems for pumps of "light" construction, certain industrial effluents and applications can cause even the strongest pumps to suffer (abrasive particles, filaments, corrosive products, deposits, cavitation, etc.).

The third is the pump curve. For a better understanding, let us take a real-life example. Let us look at the two pressurisation pump curves shown in Fig. 2.4. In both cases the expected operating point is 80 m^3/h at 60 m. The first shows a so-called "flat" curve and the second—a so-called "steep" curve.

Let's assume that during operation it happens that a plug generating 6 m of pressure drop is formed somewhere in the circuit downstream of the pump. This can be caused, for example, by a slight clogging of the pressure relief device by a large object reducing the water throughput, which results in a pressure increase.

In the first case (Fig. 2.4a) this 6 m pressure drop will reduce the pump flow rate from 80 to 48 m^3/h, which will have a serious impact on the operation of the saturator (the saturation rate will drop for most saturators) and, consequently, a serious impact on the amount of air supplied, since the flow rate of the pressurised water will be reduced. This will result in a degraded saturation level and a reduced pressurisation flow rate. In other words, there will be a double loss—on both the saturation rate and the pressurised water flow rate. The small plug will be sufficient to create a problem.

In the second case *(*Fig. 2.4b*)* the same 6m pressure drop will reduce the pump flow rate from 80 to 73 m^3/h. The impact will therefore be much less. From experience, one could even say that nothing that serious will probably happen, since only 9% of the pressurisation flow is lost, compared to 40% in the first case.

This example highlights the advantage of "steep" curve pumps over "flat" curve pumps. Flat curve pumps are more sensitive to partial clogging and the pressurisation flow rate is more difficult to regulate when the pressure relief device is adjustable (manual valve or automatic purge valve). Therefore, when choosing a pressurisation pump, especially for small flows and wastewater treatment, it is best not to assume that the DAF clarifier will always work as intended and that the clarified water used for pressurisation will always be of excellent quality. Because during the long life of an installation, incidents are bound to occur that can cause clogs in the pressure relief devices. And if the flotation system has to operate under these conditions for even a few hours, a night or a weekend, a pressurisation pump with a "steep" curve will limit the damage by providing, as far as possible, a more stable pressurisation flow.

Finally, some pumps even have flat curves with a rising "hump" at low flow. This means that the pump's flow rate can jump deliberately between two very different values since there are two operating points corresponding to the same pressure. This is called an unstable pump. To be avoided at all costs…

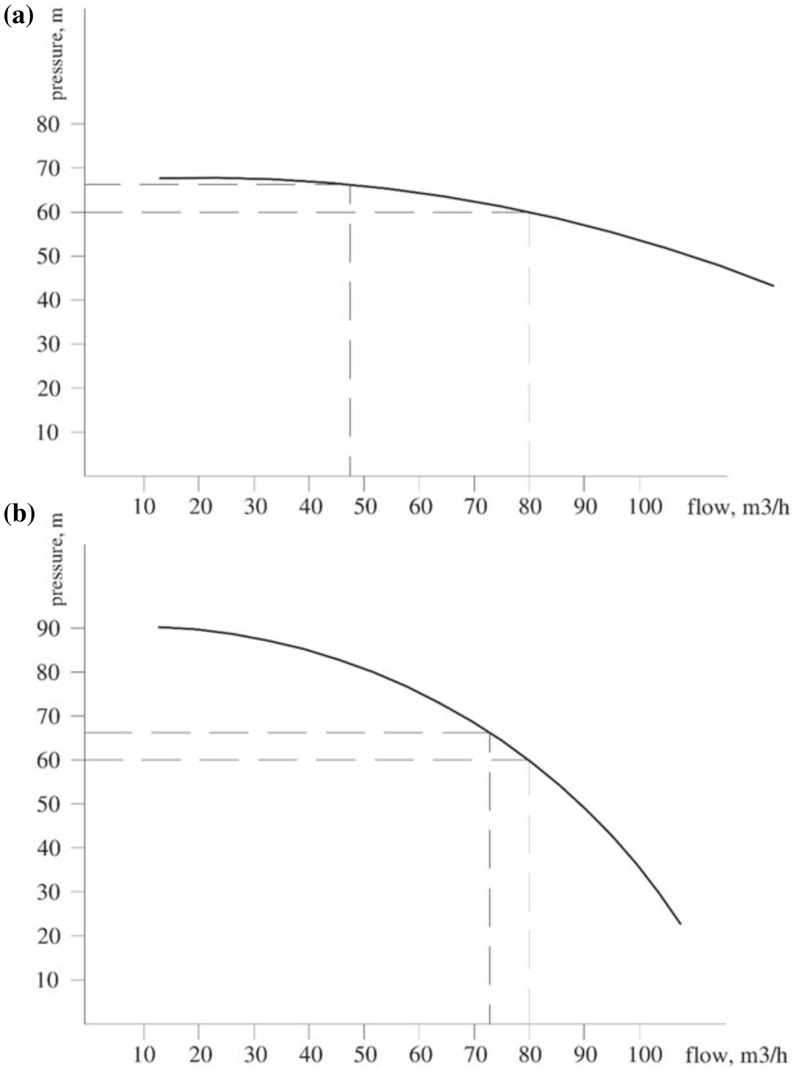


Fig. 2.4 Centrifugal pump curves

2.2.2 Unpacked Saturators

This is the most common type of saturators. The dissolving process consists of bringing water and air into contact at a pressure generally between 4 and 6 bar, so as to ensure maximum transfer of the air into the water as quickly as possible. The aim is to achieve a high saturation rate (to provide a large volume of air bubbles after pressure relief) in a small volume saturator (to reduce its cost and size), and of course at the lowest possible energy cost. These requirements are obviously contradictory and always lead to a compromise that each manufacturer orientates according to his design, the application and the technological constraints.

For the saturators considered in this chapter, the volume selected generally represents the equivalent of 40–90 s of pressurised water flow. But some devices go up to the equivalent of 120 s and even more. The nuance hidden in the expression "equivalent of" is important, because in reality the water stays less long in the saturator, because part of the volume is occupied by the air cushion. Depending on the construction of the saturator, the actual volume of water in the tank can vary significantly.

This group of devices includes vertical and horizontal cylindrical saturators. There are three types of unpacked saturators on the market:

- Saturators without air recirculation.
- Saturators with internal air recirculation performed by the incoming flow. There are two versions: with internal injector(s) and with external injector(s).
- Saturators with internal air recirculation provided by an external pump.

2.2.2.1 Saturators Without Air Recirculation

Typical sizing of the saturator volume is 60–90 s of pressurisation flow. The principle of operation is simple—see Fig. 2.5. Water is dispersed in an air cushion to obtain a maximum contact surface. The more efficient the water dispersion and the larger the volume of the air cushion, the better the result. The energy for the dispersion of the water in the air cushion is provided by the pressurisation pump. Dispersion can be done in several ways. Figure 2.5a shows dispersion by a perforated plate forming a kind of shower. This concept is outdated and is hardly ever used nowadays, because the contact surface between air and water is not very high. Indeed, to increase this surface, the diameter of the holes would have to be reduced and their number increased, but, for the same flow rate, this would reduce their diameter, which would increase the risk of clogging, especially in wastewater.

A more recent version of this concept (Fig. 2.5b) uses a single nozzle dispersing water into the air cushion. This solution does not present a risk of clogging, but to provide good dispersion the nozzle requires a relatively high driving pressure, which increases the energy costs.

Figure 2.5c shows a dispersal device projecting water onto the walls of the saturator tank, using nozzles or through simple holes as shown. This concept allows the water to be spread out in a thin film, thus increasing the contact area and therefore the efficiency of the exchange. The spray velocity is in the order of 6–8 m/sec, which represents a pressure drop that can be calculated according to the formula $H = v^2/2g$, i.e. approximately 0.2–0.33 bar pressure drop. This is the energy cost of this concept.

The volume of the saturator is divided between a volume of water in the lower part and an air cushion in the upper part. The water level in the tank is maintained automatically by self-regulation or artificially by external intervention, depending

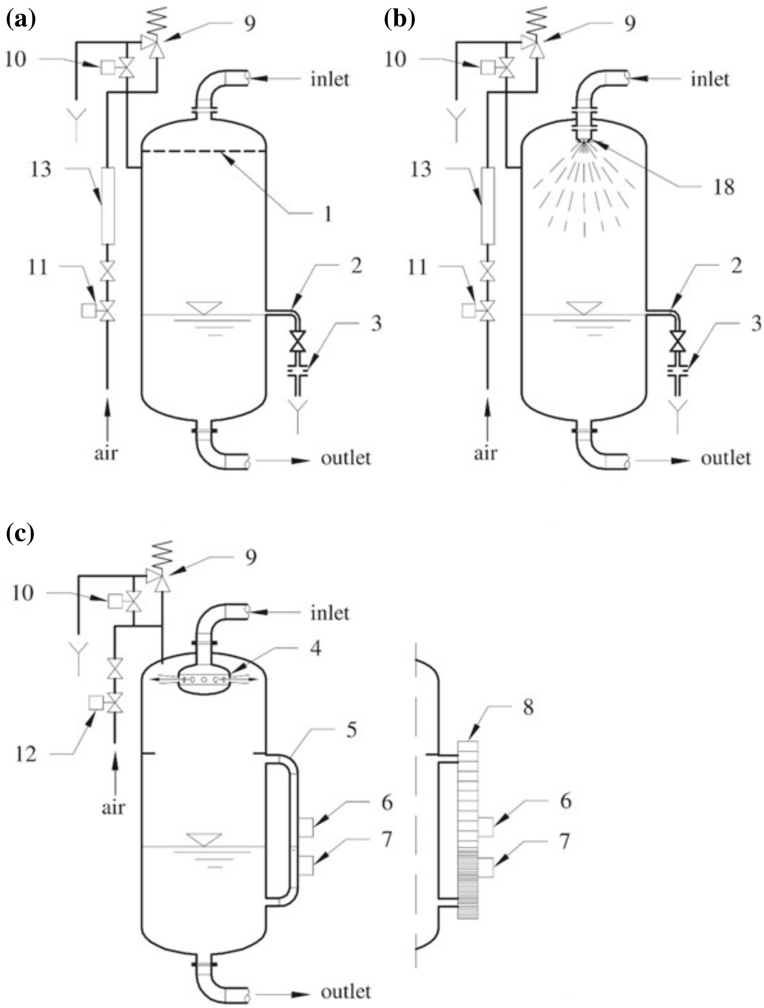


Fig. 2.5 Saturators without recirculation. 1—perforate plate, 2—air bleed-off, 3—calibrated diaphragm, 4—dispersion head, 5—level indication pipe, 6, 7—level sensors, 8—magnetic level indicator, 9—safety valve, 10, 11, 12—solenoid valve, 13—air flow-meter, 14—dispersion nozzle

on the way the installation is operated. Self-regulation means that if the amount of air added to the saturator is less than its maximum dissolving capacity, the water level will tend to rise because the air cushion will be progressively consumed by the dissolution of the air that forms it. This will result in the creation of a natural equilibrium between the amount of air injected and the dissolving capacity of the device. Obviously, this works well if the amount of air injected remains below the maximum dissolving capacity. This mode of operation is reliable, but does not allow the full dissolution capacity of the saturator to be used. If the amount of air injected increases and approaches the maximum dissolving capacity of the saturator, the water level will drop and the volume of the air cushion will tend to increase, fed by the excess air. This increase in air cushion volume could, in some cases of especially designed devices, improve the dissolving capacity of the saturator and the water level could stabilise at a lower level. This mode of operation approaches the maximum dissolving capacity of the saturator, but the closer one gets to the maximum dissolving capacity of the saturator, the more sensitive the pressurisation system will become. The water flow and air flow must be monitored very closely and care must be taken to ensure that one is always on the right side of the equilibrium, i.e. keeping the air dosage below the maximum dissolving capacity. It should be noted that the range of self-regulation that can reasonably be used in practice depends very much on the design of the saturator and it is important to know this and not to approach the limits too closely to avoid the risk of malfunction.

If, on the other hand, the amount of air injected becomes greater than the maximum dissolving capacity of the saturator, the water level will drop and the volume of the air cushion will increase until it fills the entire volume of the device and exits into the DAF clarifier through the pressure relief system. This mode of operation allows the full dissolving capacity of the saturator to be used, but requires the water level in the saturator to be regulated by external intervention.

The saturators shown in Fig. 2.5 operate as follows: The water input is supplied by the pressurisation pump and its flow rate is known. Air is supplied by a compressor at a pressure at least 0.5 bar higher than the pressure in the saturator. The amount of air injected is measured on the air flow meter (13). The water level in the saturator is self-regulating, if the amount of air injected is less than the maximum dissolving capacity of the saturator. If the amount of air injected is higher than the maximum dissolving capacity of the saturator, the level is regulated by the non-dissolved air blead-off (2) located at a level that ensures a maximum volume of the air cushion and at the same time a sufficient depth of water to prevent air from being drawn towards the pressurised water outlet. The device is normally equipped with a calibrated diaphragm (3) limiting the flow rate of the blead-off. Air, being much less dense than water, always passes first, and at a much higher rate, thus maintaining the water level at the blead-off level. This method of regulation is reliable and has only one fear: a clogging of the diaphragm hole. To limit water loss, it is better to have a small hole. The diameter of the hole is usually in the range of 3–3.5 mm, but it is easy to clog if one treats wastewater that may still contain large particles. Obviously, if a 10 mm diameter hole is used, the risk of clogging will be much lower, but about 8 m^3/h of water would be lost through the drain, compared to only 0.6–0.7 m^3/h for a 3 mm hole.

However, there is a way of solving this problem by reintroducing the ‘lost’ pressurised water from the blead-off into the clarifier. In some cases, for example:

– If the pressure relief is done by a simple valve or calibrated diaphragm
– If the clarifier has a contact zone (separate from the flotation zone) in which it would be acceptable to have some turbulence caused by purged air
– If the pressurisation rate is relatively high (more than 30–40 m^3/h)

– If the calibrated diaphragm can be installed (while remaining accessible) in the immediate vicinity of the clarifier, it would be possible to opt for a larger orifice (5–6 mm diameter, therefore less sensitive to clogging) and to introduce the bleed water into the DAF clarifier after the pressure release valve, so as not to lose the pressurised water. However, this solution remains a delicate compromise to implement, as the turbulence caused by the purged air can quickly become annoying.

For this type of saturator, attention must be paid to one detail—the management of the air cushion at the time of shutdown. If the solenoid valve (11) shuts off the air when the pressurisation pump is switched off, the air cushion in the saturator remains under pressure, because the water supply is always equipped with a non-return valve preventing air from flowing back into the pressurising pump. Unless there is an automatic valve on the pressurised water pipe at the outlet of the saturator (not recommended as delicate to implement), the air cushion will push water out of the saturator, downstream of the pressurisation circuit, until the pressure in the saturator drops to atmospheric pressure. If the pressure in the saturator at the time of shutdown is 5 bar, then the expansion of the air cushion will be about 5 times its volume. Therefore, depending on the initial volume of the air cushion, it will expel some or all of the water from the saturator. In this second case, the remaining air will come out in the flotation tank causing a geyser which is not appreciated by the operating staff… This problem has two possible solutions:

– Have an air cushion occupying only a small volume, insufficient to expel all the water from the saturator, i.e. less than 20% of the volume of the saturator if it operates at 5 bar. This can be a handicap because of the reduced contact surface between water and air.
– Have a solenoid valve (10) that opens when the pressurisation pump is stopped, simultaneously with the closing of the solenoid valve (11), to let the expanding air escape from the top rather than from the bottom.

The saturator shown in Fig. 2.5c works on the same principle, although the way the water is dispersed is different. In this figure, a regulation of the water level in the saturator by external intervention is shown. In this case, the saturator is equipped with a pair of liquid/gas interface sensors (6) and (7). When the sensor (6) is in contact with a liquid (water), the solenoid valve (12) is opened, sending an air flow rate greater than the maximum dissolving capacity of the saturator, which lowers the water level until the sensor (7) is in contact with a gas (air). The air flow is then cut off by closing the solenoid valve (12). This cycle is repeated continuously to regulate the amount of air consumed by the saturator and to maintain the water level between the levels of the two sensors (6) and (7).

The sensors (6) and (7) most often used are of the ultrasonic or inductive type. They are reliable and do not come into contact with water. This is the preferred solution for wastewater treatment. The only potential sources of problems are:

– The formation of a plug (a floating crust) in the level tube (5). This can be remedied by providing a system for purging the level tube (5), which should be done manually from time to time.
– The formation of foam in the level tube (5) which can "mislead" the sensors.

For drinking water or water with a low TSS content, a magnetic level indicator (8) can be used instead of the level tube (5) (shown on the right in Fig. 2.5c). The advantage of this device is that it gives a direct view of the water level in the saturator, which is very useful for routine operation. Level sensors (6) and (7) corresponding to the chosen device can be fitted and the saturator operated as described above. Alternatively, a magnetic level indicator can be fitted, providing an analogue signal, and this signal can be used for regulation. The only disadvantage of these devices is that their operation is based on a magnetic floater that slides in a vertical tube and tilts the indicator bars. This is not really suitable for dirty water or water that is likely to create deposits that could block the floater.

It is also possible to use a simple pressure measurement instead of sensors (6) and (7). Or a differential pressure measurement, as this avoids the cumulative inaccuracies of the two pressure sensors. This measurement of pressure above and below the liquid level would give the exact position of the liquid level. Nevertheless, attention should be paid to the accuracy of the measurement offered by the chosen pressure sensor(s). For a pressure of around 6 bar, one would tend to choose devices calibrated for 0 to 10 bar. However, they are often accurate to within 0.3–0.5% of the measured pressure, i.e. ± 15–25 cm water column at 5 bar, which in some cases may be too wide.

Experience shows that the maximum saturation rate of saturators without air recirculation rarely exceeds 60%, and is even lower if they are used in self-regulating mode. But this is only an author's estimation based on observations and approximate measurements made in real site conditions.

Saturators of this type are almost always vertical. The cylindrical height is in the range of 1.5–3 times the diameter, but there is no real rule determining this proportion.

Their main advantage is the simplicity of construction. Operation in self-regulating mode seems simple, but requires a good knowledge of the operation of the saturator and regular monitoring, which is not always the case in reality. Automatic water level control can maintain maximum efficiency and reliable operation of the saturator, provided that the level sensor system is well adapted to the application and also well serviced.

2.2.2.2 Saturators with Internal Air Recirculation Performed by the Incoming Water

There are two versions—with internal injector(s) or with external injector(s).

Figure 2.6a shows a vertical saturator with internal air recirculation, achieved with an internal hydroejector. The hydroejector (14) is fed by the pressurisation pump. It sucks the air from the air cushion and returns it to the bottom of the saturator, creating a high internal air flow that provides efficient mixing and a significant contact surface.

As an indication, an injector of this type, even if made with standard pipes, i.e. with a somewhat relative precision, can easily suck in an air flow representing (in volume of compressed air at 5 bar) up to 50% of the flow of the motive water.

The advantageous shape for this type of saturator is rather elongated in height, so that the injector can send the air as deep as possible into the water volume. The height of the cylindrical part is usually 1.8–3 times the diameter of the saturator, depending on its size. In large units the outlet of the injector can be more than 2 m deep. The water velocity in the injection nozzle (15) is about 12 m/sec, which results in a pressure drop of 7.3 m + immersion depth of the injector. This is the energy

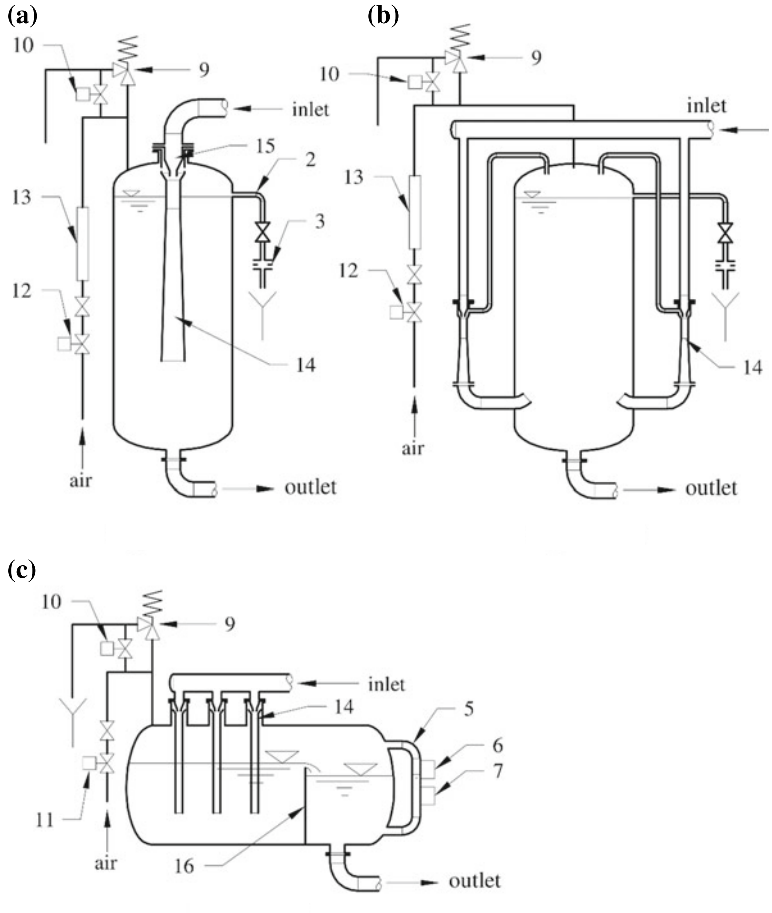


Fig. 2.6 Saturators with circulation. 2—air bleed-off, 3—calibrated diaphragm, 5—level indication pipe, 6, 7—level sensors, 9—safety valve, 10, 11, 12—solenoid valve, 13—air flow-meter, 14—hydroinjector, 15—inlet nozzle, 16—partition

"loss" of this concept. This is significant, especially if the saturator is operated at low pressure.

Level control in the saturator is shown with an air bleed-off, but can also be done with level sensors and solenoid valves as shown in Fig. 2.5c.

Figure 2.6b shows a saturator working on the same principle, but with one or, more often, several (3–4 units) external hydroejectors. This concept allows the use of smaller and more readily available off-the-shelf hydroejectors, which could avoid the construction of a custom ones.

Figure 2.6c shows a horizontal saturator. In this case recirculation is provided by one or more relatively small hydroejectors (max. 50–60 m^3/h of motive water per hydroejector). The outlet of the hydroejectors can be above the water surface or below the water surface at depth (as shown in the figure). In the first case the water depth will be 1.1–1.2 times the radius of the tank to ensure maximum contact surface between the water surface and the air cushion. In the second case the amount of air drawn in will be slightly reduced, but the mixing will be improved, especially for tanks with a diameter greater than 1.4–1.6 m. The depth of the water in the dissolving compartment will be in the range of 1.4–1.6 times the radius of the tank.

In both cases the ratio between the length of the cylindrical part and the diameter is in the range of 1.5–2.5. The device is often equipped with an internal baffle (16) to maintain a constant water level in the dissolving compartment, in order to regulate only the water level in the outlet compartment. This partition also prevents air bubbles from being carried towards the outlet.

The main advantage of this type of saturator is that it can recycle a large volume of air and thus ensure a large contact surface. A well-designed hydroejector can ensure a saturation rate of more than 70% and even up to 80%, if the volume of the tank is more than 80–90 s of pressurisation flow. Another advantage, especially for vertical saturators, is the small volume of the air cushion, which does not cause any problems during shutdowns.

The disadvantage is that they must always work at a fixed water flow rate, because the operation of the hydroejectors is sensitive to the motive water velocity. It is therefore difficult to vary the pressurisation flow rate significantly. If the pressurisation flow rate is significantly higher than the design flow rate, this could still be acceptable, as the injector will work well, and, despite the additional energy losses, the result will be relatively correct, even if the residence time of the water in the tank will decrease. The problem arises especially in the case of a significant decrease in the pressurisation flow rate due, for example, to a clogging of the pressure relief system. In this case, in addition to the decrease in pressurisation flow, the injector will suck less and the flow of recirculated air may decrease significantly. A visible change in pressurisation quality can be observed after a drop in pressurisation rate beyond 20–25% on a vertical saturator of this type. Of course, it is relatively easy to detect the problem quickly by installing a flow meter in the pressurisation circuit. But unclogging the pressure relief devices can be more difficult to achieve. In this respect, saturators equipped with several (3 or 4) hydroejectors have the advantage of allowing the isolation of one of them to maintain the driving velocity on the others and maintain the quality of the pressurised water, even at reduced flow rates. This is a good solution for cases where it is necessary to vary the pressurisation flow rate according to the incoming flow rate or the quantity of SS in the raw water. Provided, of course, that there is an adjustable pressure relief device or several non-adjustable pressure relief devices with the possibility of isolating a certain number corresponding to the reduction of the pressurisation flow.

2.2.2.3 Saturators with Internal Air Recirculation Performed by an External Pump

Figure 2.7 shows conceptual drawings of a vertical saturator with multiple external ejectors and a horizontal saturator with internal ejector. Both are equipped with an external recirculation pump. In this case the driving force of the hydroejectors is not provided by the incoming water flow, but by a recirculation pump (17) providing a pressure of about 8–10 m. This "luxury" concept is admittedly more expensive than the one with hydroejectors fed by the pressurisation pump, as it requires a second pump in addition to the saturator feed pump. Nevertheless, it has two important advantages:

– The recirculated air flow rate is no longer limited by the incoming water flow rate. The recirculation pump (17) can have a much higher flow rate than the pressurisation flow rate and, therefore, provide more abundant aeration, as long as the water/air interface inside the saturator remains relatively stable. This would allow a very high saturation rate to be achieved. It can be estimated that a saturation rate of more than 80% could be easily reached, provided that the volume of the saturator is sufficient.
– It allows the pressurisation flow rate to be reduced at will without affecting the quality of the pressurised water. On the contrary, reducing the pressurisation flow rate would logically lead to an increase in the saturation rate because the water residence time would be increased.

Depending on the design and flow rate of the recirculation pump selected, the sizing of the saturator volume is usually equivalent to 80–120 s of pressurisation flow rate for vertical saturators and up to 150 s for horizontal saturators requiring a sufficiently high air cushion to protect the air intake of the hydroejector, i.e. at least 300–500 mm depending on the size of the saturator.

2.2.3 Packed Saturators

These are the best performing saturators in terms of saturation rate—see Fig. 2.8. They are always vertical. The water to be pressurised is dispersed over a layer of packing material (20) supported by a perforated floor (21). The water is dispersed homogeneously on the packing layer usually by a perforated plate (1), as shown

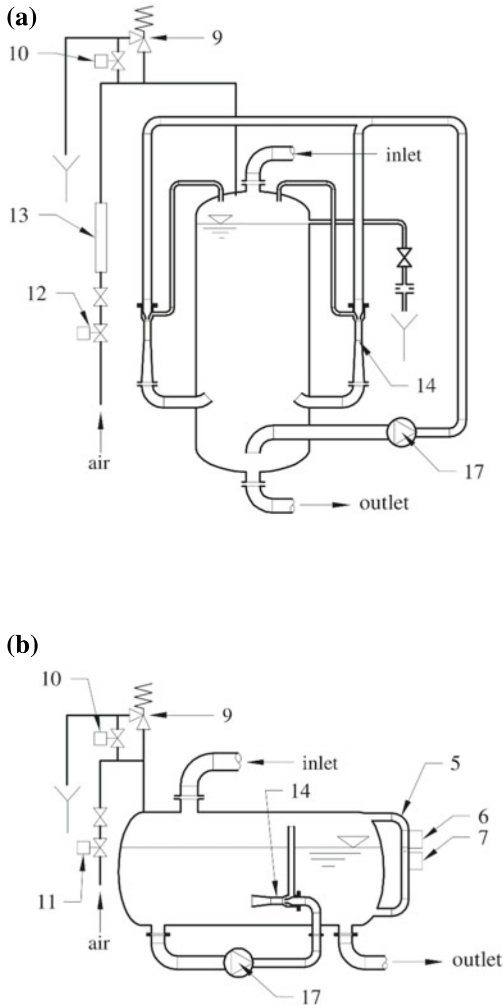


Fig. 2.7 Saturators with external recirculation pump. 5—level indication pipe, 6, 7—level sensors, 9—safety valve, 10, 11, 12—solenoid valve, 13—air flow-meter, 14—hydroinjector, 17—recirculation pump

in Fig. 2.5a, or, as shown as an example *in* Fig. 2.8, by a series of pipes (19) with dispersion nozzles covering the entire surface of the saturator. For small saturators a single dispersion nozzle (18) (see Fig. 2.5b) may be sufficient.

The packing material consists of cylindrical or spherical plastic elements with dimensions in the range of 30–80 mm. The elements are simply poured in bulk. They are highly openworked and are designed to have a very large surface area—from 100 to over 250 m^2/m^3, depending on the different types available on the market. This ensures a very large contact area between the air and the water that flows over the packing elements and allows a saturation rate close to 90% to be achieved, which means almost full saturation.

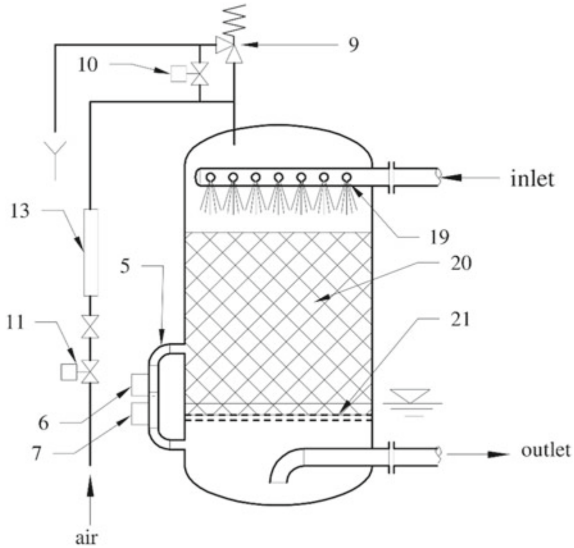


Fig. 2.8 Packed saturator. 5—level indication pipe, 6, 7—level sensors, 9—safety valve, 10, 11, 12—solenoid valve, 13—air flow-meter, 19—water distribution device, 20—packing, 21—packing support floor

The water level in the saturator is maintained below the floor (21) supporting the packing material (20), if the selected hydraulic load is low. If the selected hydraulic load is high, it is recommended to keep the water level just above the floor (21) to avoid possible turbulences that could cause air escapes through the water outlet, especially if the depth of the outlet compartment located under the floor (21) is low. In any case, the packing layer is kept completely or almost completely in the air cushion.

Here the hydraulic loading of the packing layer plays an important role and deserves further analysis. Intuitively, one would tend to think that a low hydraulic load would be beneficial for air transfer, as water would flow slower and in thinner layers over the packing elements. In reality this is not really the case, as at low hydraulic load the water does not manage to wet homogeneously the entire developed surface of the packing elements and part of this surface remains "dry" and therefore inefficient. In fact, a more "sustained" hydraulic load would be beneficial, as it would allow a better "wetting" of the packing elements. At the same time, too high a hydraulic load would create too high a pressure drop and lead to partial or complete flooding of the packing. It should be noted that the packing material is a mechanical barrier that creates pressure losses when water flows through it. These pressure losses depend on the empty space between the packing elements and their developed surface. If the packing is assumed to be a loose granular material, the void space between elements of the same size will be of the range of 20% in almost all cases. The developed surface and the voids within each element therefore play an important role for the pressure losses in the packing. For example, elements with large openings will create less pressure drop and carry a higher hydraulic load.

In practice, therefore, the hydraulic load depends essentially on the properties of the packing material and varies from 80 to 200 m/h with a dominant average around 140–150 m/h. Many tests have been published on this subject. There are also some methods for modelling the mass transfer of air into water for which the authors consider that the exchange surface between water and air is approximately equal to the developed surface of the packing elements. Even though these methods, the most accomplished of which seems to be the one proposed by Edzwald and Haarhoff in "Dissolver Air Floatation for water clarification", it is still difficult to find a simple, practical and reliable method of evaluating the dissolution kinetics of air in a packed saturator. There are several reasons for that:

- Even if the developed surface of the packing material and the transfer parameters are known, the estimation that almost 100% of the developed surface of the elements is evenly and laminarly wetted is an unlikely approximation.
- As the water passes through the packing, it becomes enriched with dissolved air, which reduces the rate of transfer obtained in the lower layers.
- The amount of dissolved air during the dispersion of water in the air cushion above the packing remains difficult to evaluate.

From a practical point of view, the hydraulic load has relatively little influence on the dissolution of air, provided that the packing is not flooded. Smaller elements give a slightly better result compared to larger elements, but the effect seems to be minor.

On the other hand, the height of the packing block has an important influence on the performance of the saturator. The higher the packing block, the longer the water stays in contact with the air, because ultimately the hydraulic load has little influence on the velocity of the water through the packing, since it is a simple free fall of the water through the packing. A higher packing will definitely perform better. In most cases the height of the packing block is between 800 and 1600 mm, but heights up to 2000 mm are often used as well.

The dimensions of the packed saturators are determined mainly by the hydraulic load selected in relation to the type of packing material and the height of the packing layer. The water dispersion space is relatively small and depends on the dispersion system design. If the distribution is done by a perforated plate, it will occupy very little height. Nozzle distribution will require more height, which will depend on the angle of the nozzle jet and its density.

The depth of the outlet volume under the floor (21) must be sufficient to avoid the formation of vortexes that can suck in air, if the water level is maintained under the floor.

Finally, given the large volume of the air cushion, it is very useful to have a system for discharging air in the event of shutdown (such as the solenoid valve (10) shown in the previous figures) to prevent it from entering the flotation tank.

The main advantage of packed saturators is their excellent performance and low energy loss for the distribution of water over the packing. This is because it is possible to achieve good water distribution with a pressure drop of less than 1 m, whereas saturators with a hydroejector require a pressure drop of over 7 m. The disadvantage is in the packing—it is very sensitive to clogging, either by all kinds of bulky particles or by biomass that develops in the packing itself. After all, it is nothing else but a variant of biofilter packing used as a biomass carrier for biological wastewater treatment. Therefore, it would not be wise to use this type of saturator for wastewater, even if it is free of TSS, because even low levels of organic pollution will eventually lead to biomass growth and cause clogging and preferential currents within the packing. Therefore, it is only used in drinking water.

2.2.4 Compact Saturators

Over the years and as technology has developed, some manufacturers have developed low volume, low cost saturators that are still good enough for many applications. It is virtually impossible to obtain accurate information on all the designs available on the market. Some are perplexing, but others deserve attention. Three can be mentioned, probably the most common in this category.

2.2.4.1 The Air Dissolving Tube (ADT)

This device was developed and marketed in the early 1980s by Krofta. The applications of flotation in the treatment of paper effluents were relatively easy and the large vertical saturators were too expensive and almost too efficient. The ADT was originally developed mainly for the paper industry, but it has found great success in many other applications and has become a standard device in thousands of flotation plants.

Figure 2.9 shows a schematic diagram of the ADT. It is a simple horizontal tube into which air is diffused by one or more panels (20) arranged horizontally on one or both sides of the tube depending on the size of the unit. The air is blown through a porous material giving fine bubbles. Water is introduced tangentially through an injector (22) at a speed of about 10 m/sec and progresses in a spiral, vigorously mixing the air bubbles diffused by the panel(s) (20). There is no air cushion in the ADT. The entry of water creates a vortex at the beginning of the tube which "sucks up" most of the undissolved air and allows it to be purged through the bleed-off (21). Of course, some of the undissolved air escapes the vortex and is discharged through the outlet, along with the pressurised water. This outlet can be located at the top or bottom of the tube. In the first case the undissolved air leaves the device freely. In the second case, an additional vent must be provided at the top of the tube to prevent the formation of an air cushion in the event of the vent (21) becoming blocked.

The residence time of water in the ADT is only 10–12 s. Its volume is therefore very low.

The advantages of this device are as follows:

- Low construction cost due to its low volume and simple design.
- Reliability of operation, which is very important in difficult operating conditions. There is virtually no regulation as there is no air cushion to maintain and

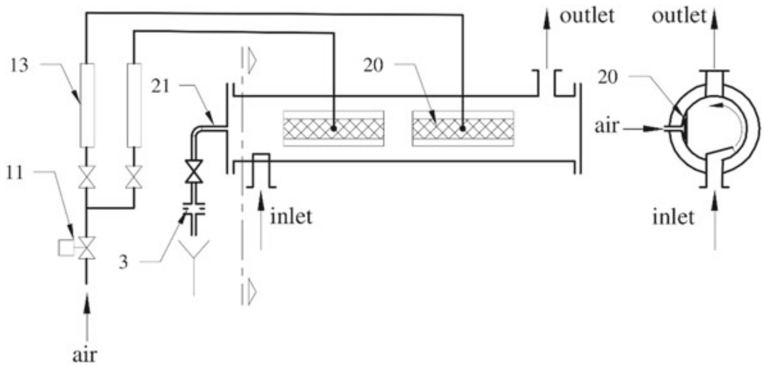


Fig. 2.9 Air dissolving tube (ADT). 3—calibrated diaphragm, 11—solenoid valve, 13—air flowmeter, 20—air diffusion panel, 21—undissolved air bleed-off

manage. If the water flow and the air flow are correct, the unit works without a hitch. A small weak point in this respect is that the calibrated hole (3) of the undissolved air drain (21) can (and often does) become clogged in wastewater. In this case the undissolved air is completely discharged through the outlet. This causes some turbulence in the DAF clarifier, but the ADT continues to work properly and provides almost the same quality of pressurised water. (Compare this with the saturators described above, which all need regulation to operate at maximum capacity. Unless one runs them in a self-regulating mode, but then their performance is more or less reduced).

Its weaknesses are:

- Relatively low saturation rate—around 35–40% at 20 °C. But, as has already been pointed out, a saturator that is less performing in terms of saturation rate is not necessarily much less efficient, at least not proportionally, in terms of air bubbles produced and actually available for flotation. In other words, a saturator at 60% saturation will not always actually produce 1.5 times more effective microbubbles than a saturator at 40% saturation. The conditions of pressure relief and injection of the pressurised water are important. In wastewater its performance can be sufficient, especially in industrial effluent applications where the pressure relief is done in pipes, which leads to a lot of coalescence. And, in the limited space of a pipe, the higher the air concentration after pressure relief, the more effective microbubbles are lost through coalescence.
- It always loses some air, which can be a problem for some high-rate DAF clarifiers, especially those with a homogeneous distribution of the water to be treated under the whole flotation surface. In this case undissolved air bubbles can cause turbulence. However, if the DAF clarifier has a contact zone separate from the flotation zone, there is less of a problem, as the air bubbles are evacuated there without disturbing the flotation too much.

– It requires an air flow meter for each air diffusion panel, which multiplies the flow meters.
– Air diffusion panels should be replaced from time to time—usually every 2–3 years.

2.2.4.2 The Air Dissolving Reactor (ADR)

Developed and marketed by KWI (Krofta Waters Inc.) since 2010, this saturator combines low volume and high performance. The volume is equivalent to 15–18 s of residence time of the pressurised water flow and its saturation rate reaches 60% at 20 °C in self-regulating mode and up to 65% in regulated mode.

Figure 2.10 shows a schematic diagram of the ADR. The tank is made of two parts—an upper cylindrical part below which is a second conical part. The cylindrical part is equipped with a set of deflectors (23) designed to provide maximum water dispersion. The water is introduced tangentially through the inlet nozzle (22) and dispersed by the deflectors into the air cushion. This dispersion provides a very large contact area between the air and the water, so that the dissolution of the air occurs directly in the air cushion. This configuration allows a high flexibility in the self-regulating regime. Thus, if the air dosage is lower than the maximum dissolving capacity of the device, the water level will stabilise itself (self-regulating level located somewhere in the cylindrical part). The higher the air dosage, the more the air cushion tends to increase in volume. Thus, the water level is pushed down, exposing more deflectors (23) above the water, which ultimately improves dissolution. In order to push the ADR to its maximum capacity, it is possible to switch to a regulated mode by opening the undissolved air bleed-off (21). In this case the air dosage can be increased beyond the dissolving capacity of the saturator and the undissolved air will be discharged through the bleed-off (21). The water level will remain towards the inlet of the trap tube (regulation level on the diagram), i.e. towards the base of the cylindrical part leaving all the deflectors in the air cushion exposed.

The water level can be visualised by a magnetic level indicator (as shown on the diagram), if the water quality allows it. But, most of the time this function is given to a simple transparent tube.

The role of the conical part is to attenuate the turbulence at the outlet of the cylindrical part, to reduce the downward velocity of the water and to avoid the departure of air bubbles through the outlet.

The main advantages of this saturator are:

– Highly reliable operation in self-regulating mode, whose flexibility allows easy adjustment close to maximum capacity. There is no instrumentation, no regulation. If the water and air flow are approximately correct, the unit will work without fail.
– Very good saturation rate for a compact saturator.
– Low volume.

Disadvantages:

– The larger ADRs are quite high and require a minimum ceiling height of 3.5 m.

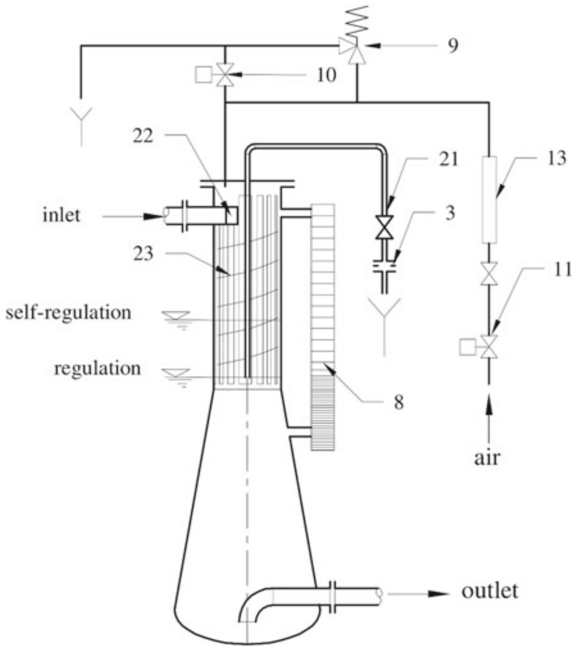


Fig. 2.10 Air dissolving reactor (ADR). 3—calibrated diaphragm, 8—magnetic level indicator, 9—safety valve, 10, 11—solenoid valve, 13—air flow-meter, 21—undissolved air bleed-off, 22—inlet injector, 23—dispersion baffles

– The volume of the air cushion is quite large, especially at maximum capacity with regulation. It is therefore recommended to equip the saturator with a solenoid air release valve (10) for the shutdown phases.
– In regulated operation, the air bleed-off valve (21), and especially the calibrated diaphragm (3), is at risk of clogging with wastewater. This leads to the gradual filling of the entire volume of the device with air and ultimately to air leakage into the DAF clarifier. For this reason it is recommended that this operation mode is only used in clean water.

Finally, it can be mentioned that it is quite possible to achieve water level regulation by intermittent air dosing as shown in Fig. 2.5c. It is only necessary to fit the ADR sight glass (or magnetic indicator) with sensors (6) and (7) (from Fig. 2.5) and the air circuit with a solenoid valve (12). This method of control has been used in a few installations in the oil industry.

2.2.4.3 Inclined Saturators

Several manufacturers use this type of saturator. Thus, it is difficult to find the origin of this device.

Its operation is based on the same principle as the saturators shown in Fig. 2.5b,c. The specific point is the inclination of the tube, which increases the surface area of the water table and at the same time the surface area over which the water spreads, thus ensuring a relatively large exchange surface for a small tube—see Fig. 2.11. The water is sprayed through a simple dispersion tube (24) at a speed of a few m/sec onto the emerging wall of the tube. The angle of inclination of the tube is about 15 to 20°, but there are saturators of this type inclined at 45°, in which case the water enters tangentially. The volume corresponds to about 15–30 s of pressurisation flow, but this value varies significantly between manufacturers.

This device requires a regulation of the water level. This is done by a bleed-off (21). The manual valve of the bleed-off or the calibrated diaphragm (3) regulates the bleed rate.

The main advantages of this device are:

– Very low construction cost.
– Simple to operate.

Disadvantages:

– Due to the (usually) small dimensions of the saturator, the contact area remains small. In order to obtain a decent saturation level, this saturator must be operated in regulated mode, as the self-regulating mode seems to be fragile to maintain.
– As with all devices with water level regulation by means of a bleed-off valve, the latter tends to clog up in wastewater. Unless one has a large orifice and is prepared to lose a lot of pressurised water if it cannot be reintroduced into the DAF clarifier.

In conclusion, one can say that all these compact saturators, in spite of their relatively low saturation rate compared to the "big" pressurisation tanks whose volume is the equivalent of more than 60–90 s of pressurised water flow, are finally well adapted to wastewater. They are used in a significant number of flotation systems in these applications. Nowadays, large pressurisation tanks are more and more often dedicated to two applications:

1. Drinking water installations where their high saturation rate is particularly emphasised for the following reasons:

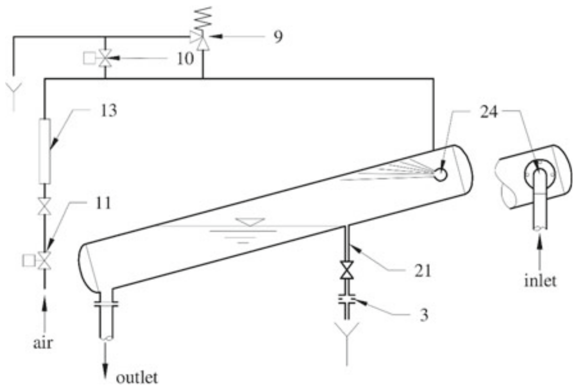


Fig. 2.11 Inclined saturation tube. 3—calibrated diaphragm, 9—safety valve, 10, 11—solenoid valve, 13—air flow-meter, 21—undissolved air bleed-off, 24—water dispersion slot

– To really take advantage of all the dissolved air at a high saturation level (70–80% and more), it is almost mandatory to have fine pressure relief devices with small, evenly distributed orifices far from each other. However, this is only reasonable in clean water where the risk of clogging of the pressure relief holes is low. (A coarser pressure relief through valves or large orifices will cause some of the air to coalesce into large bubbles).
– Drinking water treatment plants usually treat large flows. Consequently, the energy costs associated with pressurisation become significant. It is therefore essential to reduce the pressurisation rate as much as possible, trying to optimise the value of each kWh of energy spent.

2. To the oil industry. Technically speaking, it is difficult to find a clear reason for this, other than the notorious conservatism of some of the major players, who are very tied to their construction standards and specifications, some of which date from the 1960s. As for some specifications based on flotation devices from another era (but still present in many new projects), discussions with decision-makers in this sector suggest that installing 'known' devices has the advantage of not involving risks that no one would want to take… And yet, those who have taken the plunge express no regrets about having done so.

Apart from these three devices, there are multiple 'scaled down' versions of the 'large' pressure vessel concepts shown in Figs. 2.5, 2.6, 2.7 and 2.8. For example, driven by the need to reduce construction costs, some manufacturers have simply reduced the volume of the saturator shown in Fig. 2.6a to the equivalent of 20–25 s of pressurised water flow. The saturation rate is indeed somewhat reduced, but the construction cost is even more so. And, with a well-made injector, the result is quite satisfactory for the small industrial effluent plants that are the main market for small flotation systems.

2.2.5 Air Dissolving Pumps

The air dissolving pumps are an alternative to the "classic" pressurisation set composed of a pressurisation pump, a compressor and a saturator. Their objective is to combine the three functions (water pressure rise + suction of air to be dissolved + dissolution of the air sucked in) in a single piece of equipment that makes it possible to eliminate the compressor and especially the saturator from the pressurisation system, which is often the most costly and cumbersome piece of equipment.

The first trials in this field were conducted in the late 1960s/early 1970s with simple centrifugal pumps, single stage or (often) multi-stage. A small part of the pumped water was diverted to a hydroejector sucking in ambient air and the air/water mixture was introduced upstream of the pump. The results were more or less mitigated because:

– The air caused cavitation which quickly wore out the pumps.

- An air flow rate exceeding approximately 3–3.5% of the water flow rate could lead to a destabilisation of the pump's operating regime.
- The dissolution efficiency was still relatively modest compared to that of a saturator.

Later attempts were made to improve this result by moving the air injection point from the pump inlet to the inside of the volute, at a sufficient distance from the shaft, so that the pressure at the inlet point was already positive and to avoid too much cavitation caused by the vacuum at the impeller inlet. This concept has also been combined with the use of a disc impeller by injecting air between the two discs through a rotary joint rotating with the pump shaft. Other manufacturers use, for the same purpose (to avoid cavitation), a multi-stage pump and inject the air into the second stage. Most often, these concepts require compressed air.

However, some manufacturers have perfected their research and adapted some of their pumps specifically for the function. Today, this niche market is shared between a few brands, each of which has adopted its own particular technique. The most common and perhaps most successful concepts are three.

The first is based on a multi-stage side channel pump. These pumps come in two versions shown schematically in Fig. 2.12. The first is equipped with side channel stages only (Fig. 2.12a). In this case the inlet and outlet are on top of the pump. The second version (Fig. 2.12b) has a "standard" first stage with a closed impeller and the following stages are side channel type. In this case the inlet is on the front of the pump like a standard centrifugal pump. The first stage consists of a closed centrifugal impeller (1) which provides an initial build-up of water pressure and possibly an initial dispersion of air, if the latter is injected at the pump inlet. After this stage, the water/air mixture passes through several successive side channel stages (3) equipped with open impellers fitted with radial fins (2) which stir the mixture very effectively and at the same time drive it by vortex effect into the side channel, thus increasing the pressure at each stage and accelerating the dissolution of the air.

The second one is based on a multistage pump whose main feature is that it has impellers fully open on both sides. A conceptual sketch is shown in Fig. 2.13. The inlet to each stage is towards the centre and the outlet—towards the periphery of the impellers, as in a standard multistage pump. Air is injected at the pump inlet and is dissolved rapidly by the turbulence created between the impeller blades and the volute openings.

The third design uses a single-stage pump with an impeller fitted with relatively short radial fins—see Fig. 2.14. The water enters at the periphery of the volute, goes around and also exits at the periphery of the volute right next to the inlet. In this way, the impeller can make several turns of some portion of the water in the volute. At the outlet of the volute, the water can possibly pass through a more or less spherical volume integrated in the pump, in which a vortex is created that further improves the mixing and dissolution of the remaining air.

For all three concepts, air can be injected under pressure or sucked in by the pump. This air suction is achieved by a simple partial closure of the suction valve, which creates a vacuum at the pump inlet.

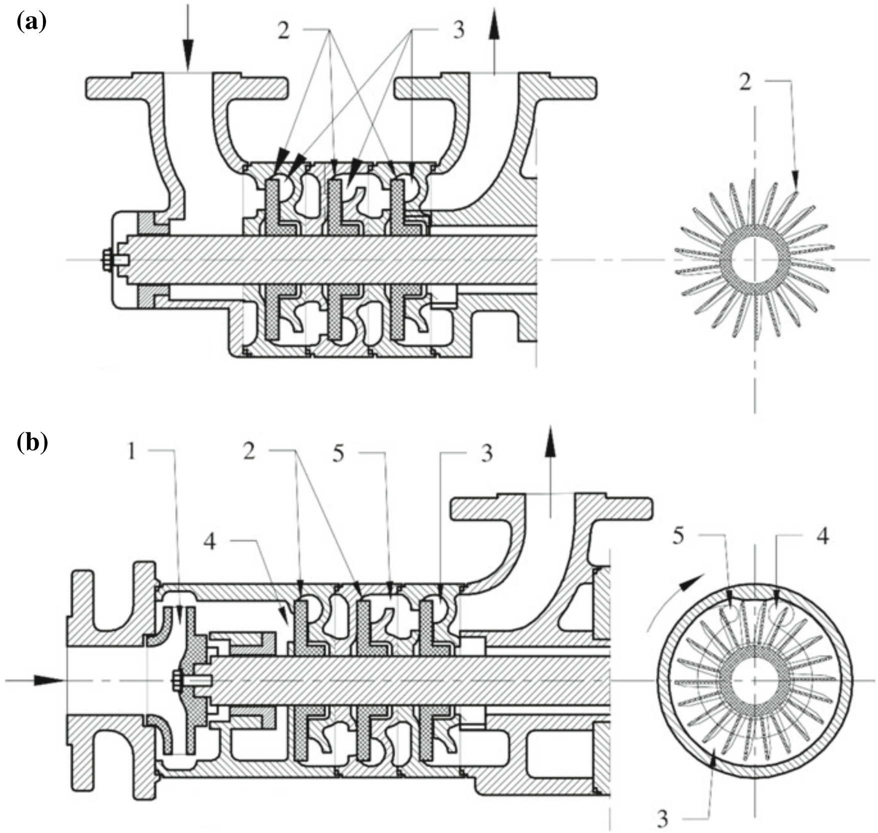


Fig. 2.12 Side channel pump. 1—closed impeller, 2—paddle impeller, 3—side channel, 4—side channel inlet, 5—side channel outlet

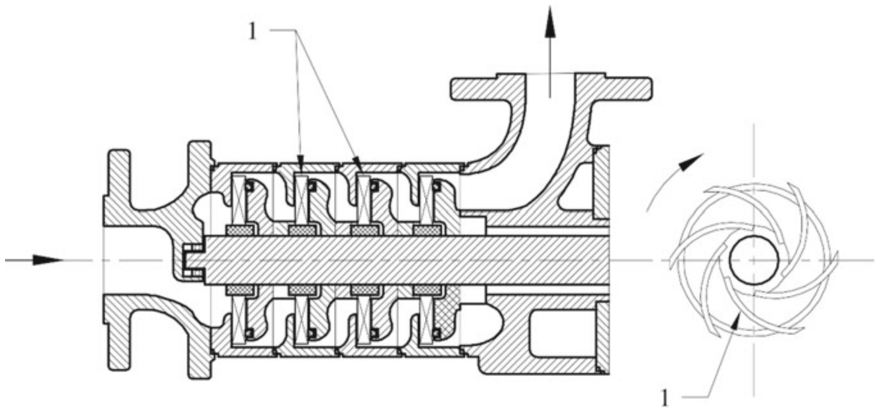


Fig. 2.13 Multistage pump with open paddle impellers. 1—open paddle impeller

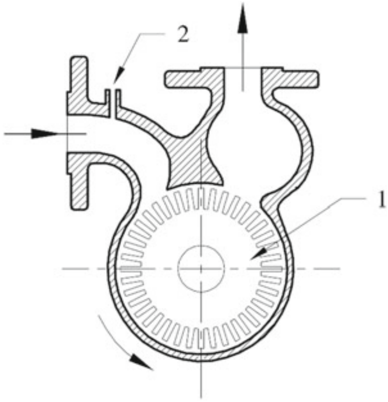


Fig. 2.14 Mono-stage pump with paddle impellers. 1—paddle impeller, 2—air inlet

Of course, manufacturers have not developed these gas dissolving pumps only for flotation applications. They are also used for dissolving other gases in a wide range of industrial applications, e.g. for dissolving nitrogen, carbon dioxide, ozone etc.

When used for flotation, these pumps have certain characteristics in common. They have a relatively small flow range—up to about 40–60 m^3/h for most manufacturers. They can operate with a gas-rich mixture without unpriming—some manufacturers say they can handle up to 20 and even 30% gas in the water at the inlet. At a constant flow rate, the power input and water delivery pressure decrease as the proportion of gas in the inlet increases.

It is difficult to find reliable information about the saturation rate that these pumps can achieve in real operating conditions. In their commercial documentation, some manufacturers announce saturation rates of more than 90% and even 100% (!) and promise a bubble size of 30 to 50 μm, even though the size of the bubbles has nothing to do with the way air is dissolved. It can be assumed that the best pumps (of these), when properly tuned, offer a decent saturation rate—probably in the range of 40–50%, but this is only an estimation.

Generally speaking, the main advantages of an installation with air dissolving pump compared to a conventional installation (single-stage centrifugal pump + compressor + saturator) are the following:

- Simple implementation with fewer components—no need for a compressor and instrumentation on the air circuit in most cases.
- These pumps offer a compact solution, which is advantageous for small spaces and skid mounted installations.
- This concept is normally cheaper than a conventional installation, although these dissolution pumps are relatively expensive compared to a single-stage pump providing the same flow rate and pressure. Provided, of course, that they are installed under operating conditions that ensure a decent mechanical life. But this comparison is somewhat relative, as everything depends on the size of the installation, the type of pump chosen, whether or not a deaerator or a contact tank is

installed after the pump, the cost of the saturator with which the comparison is made, the construction materials, etc.

The use of this type of pump for a flotation installation also entails some constraints. Generally speaking, at the same flow rate and pressure, these pumps consume more energy than a single-stage centrifugal pump. Comparing their power consumption at a dissolving pressure of 5 bar with that of a single-stage centrifugal pump supplying 5.5 bar (0.5 bar of pressure loss possibly provided to serve as a driving force for the mixture at the inlet of a saturator), one can see an over consumption of around 20–25% for the most "economical" pumps and up to more than 50% for certain side channel pumps. Of course, these differences depend on the flow rate (i.e. the size of the pump) and the amount of air injected into the pump. If one also add the "performance" criterion, i.e. for the same amount of air actually dissolved, it is difficult to find a simple and workable correlation. But it is safe to say that, for the same amount of dissolved air, the energy consumption of a pressurisation system using an air dissolving pump will always be at least 20–25% higher than that of a saturator and single-stage centrifugal pump, including the energy consumption for the production of the compressed air used by the saturator.

The vast majority of these pumps are sensitive or very sensitive to the presence of solid particles in the water. The installation of a basket pre-filter upstream of the pump is recommended. Some manufacturers of flotation equipment use them for applications in lightly SS contaminated wastewater in order to reduce cost. However, the risk of pump wear is high and pump life can be quite limited under real operating conditions, i.e. with the occasional use of clarified water of degraded quality for pressurisation.

Even without being pushed to their maximum performance, these pumps often lose undissolved air bubbles at the outlet. This implies the installation of an additional contact volume ensuring a water residence time of about 15 or 20 s (and up to 60 s for some manufacturers), or a deaerator whose purpose is to recover these undissolved air bubbles and eliminate them from the circuit, so that they do not arrive in the DAF clarifier. The volume recommended by some manufacturers of this deaerator can reach 20 and even 30 s of pressurised water flow, which is significant. Moreover, it is more or less equivalent to the volume of a compact saturator whose construction cost could be comparable to that of the deaerator.

2.3 Pressure Relief Devices

The conditions under which the pressurised water is brought back to atmospheric pressure (the pressure relief) are of great importance to the process of microbubble's formation, size, behaviour and stability over time. It is therefore important to draw attention to the most influential factors in order to better understand the design, advantages and disadvantages of the different pressure relief devices described in this chapter.

From a practical point of view, it can be considered that the formation of air bubbles during pressure relief from a pressure of more than 3–4 bar of pressurised water saturated with air to more than, say, 30–40% (i.e. in virtually all cases encountered in the practice), starts almost immediately at the outlet of the relief orifice. The size of the microbubbles formed following a pressure drop of more than 4 bar is more or less homogeneous and decreases little with the increase in pressure beyond this value. From this point onwards, the phenomenon that is probably the most harmful for flotation purposes is the coalescence of a certain portion of these microbubbles. This is because, under certain conditions, some of them may tend to coalesce to form larger bubbles which are less 'useful' for flotation.

The main factors influencing this coalescence phenomenon are:

1. It is easy to see that coalescence depends on the composition of the pressurised water and in particular on the presence organic maters some of which act as surfactants that can form a film around each microbubble. These films of electrostatic charges around the microbubbles tend to keep them whole and stable by creating a certain repulsion effect between them, at least up to a certain collision energy level with other bubbles. The richer the water is in surfactants substances, the finer and more stable the microbubbles remain. And vice versa—the purer the water and the lower the available electrostatic charges, the stronger the coalescence. For example, if one observes the pressure relief (made with a tap) of clarified and pressurised water from a cardboard factory (COD > 1000–2000 mg/l) in a test tube, it can be seen that it hardly produces any large bubbles, or only a few, hardly visible to the eye. In the same experiment with clean water (TOC < 1–2 mg/l), large bubbles can be clearly seen coming out of the pipe right after the relief valve.
2. The increase in bubble concentration promotes coalescence. The higher the concentration of the bubbles, the more likely they are to collide and coalesce. In other words, keeping a large amount of air in a small space promotes coalescence. This is the case, for example, with pressure relief in a pipe—after only a few tenths of a second after pressure relief, very large bubbles can already be seen forming air cushions at the high points of the circuit.
3. The increase of turbulence. The more turbulent the hydraulic conditions immediately after pressure relief, the more the resulting collisions between the bubbles favour this coalescence.

In reality, these three phenomena occur simultaneously. Observations show that after pressure relief, coalescence is rapid and intense until a sort of equilibrium is established between the concentration of the bubbles, their kinetic energy and the strength of their electrostatic charges which keeps them at a certain distance from each other by repulsion, after which the phenomenon slows down.

For a better understanding of this phenomenon, it is possible to observe the formation of bubbles in clean water during the pressure relief of pressurised water alone (without the addition of raw water) in a transparent tube at least 800–1000 mm high. It is sufficient to inject the pressurised water at a low flow rate at the bottom of the tube, filling it within 15–20 s and leaving it to overflow for the same amount of time to stabilise the pressure relief conditions before stopping the feed to observe the behaviour of the bubbles formed. If one considers a saturation rate of 60% of the pressurised water at 5 bar and 20 °C, this would correspond to a volume of air released at the time of expansion of about 5.6% of the volume of the water. Observations show that this concentration is conducive to coalescence and some of the air forms large bubbles in only a few seconds. These large bubbles quickly rise to the surface. As the amount of air in the water decreases, coalescence slows down until a sort of relative equilibrium is established, leaving the remaining microbubbles relatively stable. Not that coalescence stops completely, but it slows down significantly when the volume of air present in the water drops to probably around 2–3%, but this value is only a rough estimation. This is because it is very difficult to quantify the volume of air lost in the large (and very large) bubbles formed as a result of this rapid coalescence, which essentially lasts only a few seconds. The loss of large (400–500 μm) and very large (more than one millimetre) bubbles could be estimated at about 20 or 30% of the air and probably even more in some cases.

If this interpretation of the pressure relief and air bubble formation process is realistic, then it would be legitimate to think that, in order to reduce the risk of coalescence, it would be beneficial to dilute the white water with raw water immediately after the pressure relief in order to reduce the concentration of bubbles in the water. But, at the same time, it is also conceivable that it would be beneficial to first let all the excess air "come out" of the pressurised water for a short time before mixing this water rich in dissolved air with raw water that may be poor in dissolved air. This is because the dissolved air in the pressurised water would more easily pass into the raw water until it is saturated with air before starting to form bubbles, whereas bubbles that have already formed would be slower and less likely to re-dissolve in the water.

On the other hand, if one expands water containing little dissolved air, one can observe that the formation of microbubbles is not immediate. It takes some time—up to a few seconds—before the maximum number of microbubbles is produced. It can be deduced from this that the formation of all the microbubbles is not immediate after the pressure relief, although it is obvious that the phenomenon accelerates rapidly with the increase in the quantity of dissolved air and the amplitude of the pressure drop. In any case, one can imagine that, whatever the concentration of dissolved air available for expansion, the last microbubbles may take some time to form. It would seem that these last bubbles would be among the finest and most stable as they seem the least likely to coalesce, once most of the other bubbles have risen to the surface.

Another factor greatly influences the process of microbubbles formation and their stability over time. This is the orifice through which the pressure relief takes place. Experience has shown that the smaller the orifice, the better the quality of the bubbles produced. They are finer, more uniform in size and less prone to coalescence. The phenomenon can be so widespread in drinking water pressure relief that the use of a single large pressure relief orifice can be totally inappropriate and give very disappointing results in terms of white water quality. For this reason, the use of multiple small pressure relief devices in drinking water applications has become the preferred option over single devices relieving a large flow of water through a large orifice. On the other hand, the use of a 20 or 30 mm diameter pressure relief orifice can give quite satisfactory results in wastewater. Why is this? Well, it would seem that there is no proposed method of modelling the process of bubble formation in relation to the pressure relief conditions and the composition of the water. Thus, once again, one can only propose an explanation based on the interpretation of "collateral" results of tests directed at slightly different subjects and on intuition. Of course, once again, these opinions are the sole responsibility of the author.

Firstly, it seems logical to assume that, at the moment of pressure relief (which, remember, at a pressure of 4–5 bar, starts to produce microbubbles almost instantaneously, i.e. in a few thousandths of a second) the volume of air contained in the stream of expanded water towards the centre of a large diameter relief orifice is too large to form fine bubbles without dilution with ambient water. At the same time, the availability of surfactants in this volume of water may be insufficient to satisfy the conditions necessary to maintain millions of small diameter microbubbles with a huge developed surface area which, as a consequence, requires a lot of electrostatic charges to surround each of these microbubbles. Let's not forget that at 5 bar, the "excess" available air can represent up to 8% of the volume of the white water. This is a lot... Let's imagine a 50 mm diameter orifice in which the water flows at more than 23 m/sec. After the pressure relief orifice the jet will remain relatively compact for several metres, before it starts to really mix with the surrounding water. So what happens? Towards the centre of the pressure relief orifice the air immediately forms large bubbles as the jet remains compact and the air concentration remains very high. On the other hand, the portions of water near the periphery of the orifice would mix more quickly with the water surrounding the orifice, which would decrease the concentration of air and create more favourable conditions for the formation of micro-bubbles. Now let's imagine the same thing for a 2 mm diameter orifice. The expansion velocity will be of the same range, but the jet after the expansion orifice will only remain compact for ten or twenty centimetres at most (i.e. for a time of the range of a few tens of thousandths of a second), before mixing completely with the ambient water. This will ensure faster and more abundant dilution, i.e. conditions more favourable to the formation of microbubbles and to their sustainability over time.

The interpretation of some publications seems to give a slightly different explanation. According to them, the pressure losses caused by the friction of the water on the walls of the orifice would favour the formation of gaseous microcavities which would be at the origin of the formation of microbubbles. This pattern of microbubble formation, which is more or less unanimous among researchers, confirms, at least indirectly, the hypothesis that a large frictional surface at the moment of pressure relief favours the multiplicity of bubble-forming nuclei. Whereas inside a "jet" of large cross-section, the friction between the layers of water is much weaker and less favourable to the formation of these gaseous microcavities.

To illustrate, let's take a 20 mm diameter pressure relief orifice—it has a surface area of 314 mm^2 and a circumference of 62.8 mm. Its surface area is equivalent to that of 100 orifices of 2 mm diameter. On the other hand, the cumulative circumference of these 100 orifices of 2 mm diameter is 628 mm, which is 10 times that of the 20 mm diameter orifice. And it is easy to see that this difference becomes more and more important as the cross-section of the single orifice increases and the cross-section of the multiple small orifices decreases. In other words, a multitude of small orifices with a small cross-sectional area offers, for the same flow rate, a much larger contact surface with the orifice wall than a single orifice with a large cross-sectional area.

Another phenomenon could also be at play. The velocity of water passing through a 2 mm diameter hole in a 4 mm thick plate is of the range of 23–24 m/sec. At the exit of the hole, this high velocity logically creates a depression surrounding the flow in this area. This depression creates backflow and vortices around the exiting "jet" which promote dilution, but it also creates a vacuum around the orifice which increases the pressure difference between the inside and the outside of the "jet" and, in a way, "sucks" the dissolved air contained in the "jet" with additional force. If this assumption is correct, then a small diameter 'jet' would be much more sensitive to the phenomenon than a large diameter 'jet'.

This analysis is based on a personal and somewhat roundabout interpretation of research reports on the process of bubble formation carried out with little regard to the size of the pressure relief orifice. While these interpretations may be questionable in view of the advances in fundamental research, the veracity of the observed phenomena is real.

Which of these hypotheses gives the most plausible explanation and which of these phenomena plays the most important role in microbubble formation? Or is it a bit of everything and is it a result of the complex interaction of all these factors and perhaps other factors that we do not yet understand? In any case, one can say in conclusion that the ideal conditions for an optimal pressure relief, giving the maximum of fine and stable microbubbles and the minimum of coalescence, are the following:

- The pressure relief should be done through the smallest possible orifice, the limiting factor being the risk of clogging.
- The white water must remain isolated, for a few tenths of a second after pressure relief, in a confinement volume and slow down to an exit velocity from the said confinement volume not exceeding, if possible, a few tens of cm/sec before being mixed with the raw water. It should be noted that a confinement time significantly exceeding this time no longer has any advantage and may even have the opposite effect (coalescence). In any case, with time, the microbubbles can only coalesce more or less quickly depending on the hydraulic conditions and the composition of the substances present in the water. The slowing down of the white water, before it is mixed with the raw water, is important, especially when the raw water has been flocculated, because the velocity of the water at the outlet of the pressure relief orifice could destroy or damage the flocs, at least near the jet.
- At the outlet of the confinement volume, the white water should be mixed with the raw water as efficiently and quickly as possible to avoid too much air concentration in a small volume, again in order to minimise coalescence.
- After a delay of a few seconds at most, the mixture (white water + raw water) must pass into a volume that is sufficiently "spacious" and not very turbulent to

favour the formation of bubble/particle agglomerates rather than their destruction by turbulence.

Having listed the ideal conditions for optimal pressure relief, it would be logical to look at the other side of the subject, that is, what are the pressure relief conditions that can deteriorate the quality of white water. Well, they are sort of the opposite of the optimal conditions.

First of all, it's a pressure relief through a large orifice of small circumference, in other words a large round orifice. It's important here to make the difference between cross-section and perimeter. A pressure relief orifice in the form of a long, narrow slot will perform much better than a circular orifice of the same cross-section. For example, if we compare a 20 mm diameter orifice and a slot of, say, 2 mm width, we will find that for the same cross-sectional area (314 mm^2), the perimeter of the circular orifice is 63 mm, while that of the slot—318 mm, i.e. 5 times longer.

Secondly, it is to keep the white water in a confined space such as a pipe. The high concentration of expanded air (usually 5–7% in volume) would lead to an almost instantaneous coalescence of some of the bubbles until an equilibrium is established. Thus, in many cases, white water with an air cushion in the pipe is obtained in a few seconds. It is therefore advantageous to do the pressure relief at the very last moment, just before the white water is mixed with the raw water, in a spacious volume. And vice versa—keeping white water in a pipe for a long time is very disadvantageous and causes a lot of air to be lost.

Thirdly, mixing raw water with white water in a long pipe upstream of the flotation tank produces the same phenomenon of continuous coalescence, even if the white water is diluted by the raw water. The high turbulence in the pipe amplifies the phenomenon and forms air pockets towards the pipe vault where the air tends to concentrate. From the author's personal experience, an air concentration (by volume) in the raw water + white water mixture of more than 1–1.2% for relatively clean water and 2–2.5% for water even quite rich in organic matter, held in a pipe for even a few seconds, almost inevitably leads to coalescence. In practice, this configuration is of course manageable, but the air losses might be quite significant.

Nevertheless, at the risk of creating confusion, one could notice that, at the same time, if the mixing of white water with raw water is done in a more spacious volume, in a contact zone of a sufficient volume, providing favourable hydraulic conditions of low turbulence (water displacement velocity lower than 10–15 cm/sec), then a slowed and moderate coalescence of the "free" bubbles not associated with flocs could be beneficial. Indeed, when mixing the white water with the raw water, it is important that the bubbles are as fine as possible because this improves the quality of their adherence with the flocs. The smaller they are and the greater their developed surface area, the more electrostatic charges accumulated on their surface are available for "clinging" to the flocs. Once the floc-bubble agglomerates have formed, they begin their ascent towards the water surface in a cloud of free bubbles whose ascension velocity depends on their size. This cloud of free bubbles also plays an important role because it drags the already formed floc-bubble agglomerates into its mass. Consequently, if the free bubbles continue to undergo moderate coalescence, they will progressively form new bubbles of larger size, which will rise faster and faster, dragging the floc-bubble agglomerates faster and faster towards the surface. Thus, the moderate "post-coalescence" of free bubbles can be beneficial as it increases the flotation velocity of the air mass and allows the hydraulic load of the DAF clarifier to be increased considerably. This is most likely one of the phenomena that allows hydraulic loads of up to more than 40 m/h on some installations. If one considers that the size of the bubbles remains constant in the flotation tank, how can one explain the fact that the free bubbles of 40–70 μ which are introduced into the contact zone and whose ascension velocity is in the range of 3–4 to 10–12 m/h (in ideal conditions, i.e. free of any turbulence which in reality is not really the case), all end up at the surface of the tank? At a hydraulic load of more than 30 m/h they should be filling the entire volume of the DAF clarifier and some should even remain in the clarified water outlet! This phenomenon is particularly well illustrated in drinking water flotation installations, as the amount of flocs is very small compared to the amount of free air bubbles present around them.

What is the conclusion that can be drawn in view of these three penalising conditions? It is to avoid piping as much as possible to convey the white water and to mix it with the raw water. Unfortunately, the use of piping has practical advantages that are difficult to do without in many cases for reasons that will be discussed in the chapters describing the different types of DAF clarifiers.

All these "favourable" and "unfavourable" conditions are the basis for the analyses of the various pressure relief devices described in this chapter. One last important detail must be observed if the pressurised water, after pressure relief, is conveyed in a pipeline. Whatever the pressure relief device, it is important that:

– this device is not located at a high point in the pressurisation circuit
– the device is located below the water level in the flotation tank.

This will prevent the formation of an air cushion filling the entire cross-section of at least a part of the pipe after expansion. Otherwise, on contact with this air cushion, the bubbles would burst and be lost almost entirely.

2.3.1 Calibrated Holes

The calibrated hole is the simplest pressure relief device. Most often it is a simple drilled disc fixed between two flanges. The white water obtained from this device is not of the best quality, especially at high flow rates. On the other hand, a circular hole has the advantage of being relatively resistant to clogging, which makes this device very useful for the pressure relief of small flows of wastewater with a "high risk of clogging", such as effluents from the food industry or municipal wastewater. It is difficult to recommend a precise limit for the maximum "still acceptable" orifice diameter, but one can say that in practice, especially in the wastewater sector, the vast majority of calibrated diaphragms are used for small flows and have a diameter of 6–10 mm. At a pressure of 5 bar this corresponds to a flow rate of approx. 2–5.6 m^3/

h. For higher flow rates, it would be more appropriate to use several small orifices of, say, 8 mm diameter (3.6 m^3/h at 5 bar) rather than a single large diameter orifice. This would also allow pressurised water to be injected into the raw water at several points, if the design of the flotation device permits.

For calculating the flow rate from a single hole in a disc the following formula can be used:

$$Q = \mu S \sqrt{2gh}, \quad \mathrm{m}^3/\mathrm{sec}$$

S area of the orifice, m^2
h the pressure, m
g Earth's acceleration—g = 9.81 m/sec^2
μ coefficient of contraction.

For a circular hole a few millimetres in diameter, the usual μ value would be 0.61–0.65. But the μ value also depends on the ratio between the diameter of the hole and the thickness of the disc in which it is drilled. So if the diameter of the hole is similar to the thickness of the disc, the value of μ is closer to 0.64–0.65. If the thickness of the disc exceeds 2 times the diameter of the hole, the value of μ could exceed 0.7. The theoretical calculation may also deviate slightly from reality depending on how the holes are drilled. For example, drilling with a drill bit with a chamfer or with a laser does not give exactly the same results. If it's a large installation, it's best to test one device before making all the others. The presence of micro-bubbles after the orifice will also influence the value of the contraction coefficient, taking its value to 0.7 and up to 0.75 in some cases. Thus, it would seem that for pressure relief orifices 2 to 6–8 mm in diameter, the most appropriate value of μ would be 0.69–0.70.

2.3.2 Manual Valves

Manual pressure relief valves (see Fig. 2.15) are widely used in wastewater. They have two important advantages:

- They allow the flow rate of white water to be precisely regulated and easily varied at any time.
- They are very easy to unclog, if necessary: simply open them by one half or three quarters of a turn of the handwheel and close them again to the set point.

Several types of manual valves are used for pressure relief:

- Globe valves
- Needle valves
- Diaphragm valves
- The Haymore valve, which is more or less an adaptation of the globe valve
- The friction valve

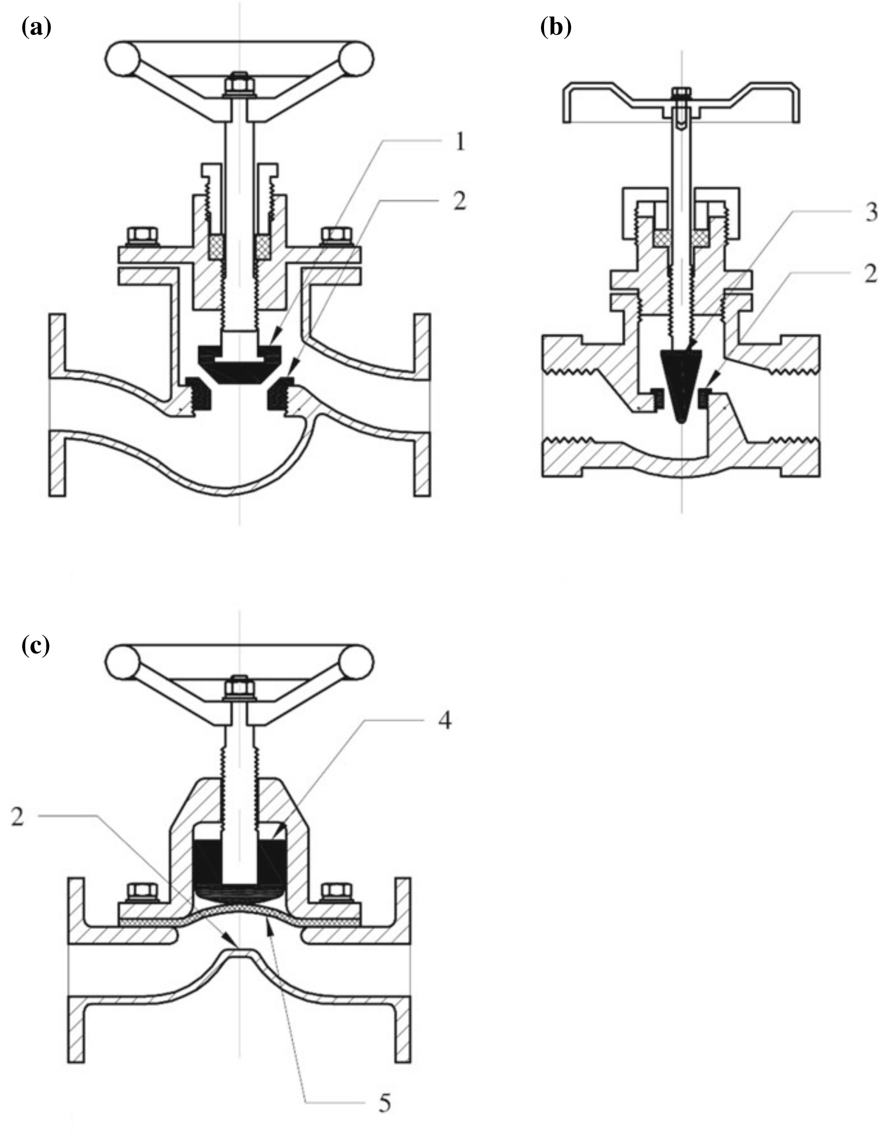


Fig. 2.15 Pressure relief valves. 1—valve, 2—sit, 3—needle, 4—piston, 5—membrane

What they have in common is that they allow the opening of a long, narrow slot which gives a better quality of white water than an orifice of a shape closer to the round, such as the orifices created by gate valves or knife gate valves. On the other hand, with the possible exception of the Haymore valve, the use of these valves has the disadvantage of confining the white water to a very small space and under conditions of very high turbulence within the valve itself and in the pipework downstream of the valve. This promotes coalescence and causes some loss of air with the formation of large bubbles.

2.3.2.1 Globe Valves

As an indication, the selection of the diameter of globe valves is most often made for a flow velocity in the range of 3–5 m/sec in a pipe of equivalent diameter. For effluents with a risk of clogging, valves with a diameter of DN32 to DN50 correspond to a velocity of 4–5 m/sec, while for diameters above DN50 the size chosen corresponds to a velocity closer to 3–4 m/sec. The most commonly used globe valves (see Fig. 2.15a) are sized between DN32 and DN80, i.e. for flows of 10 to 80 m^3/h. But for flow rates above 50–60 m^3/h it is recommended to use two valves in parallel, which also allows the pressurised water to be injected through two separate pipes, thus in a slightly less violent way. In this case the raw water is injected into the pipe at an angle of 45–60°.

Some manufacturers use multiple small globe valves (or needle valves) submerged directly in the contact zone of the rectangular clarifier. In this case, the standard valves are modified to accept an extension of the control shaft so that the control wheel can remain above the water surface.

2.3.2.2 Needle Valves

They are dedicated to small flows—normally up to 3–4 m^3/h, since their diameter rarely exceeds 3/4″–1″ and the pass-through diameter (of seat 2)—8 to 9 mm. Their main advantage is that they offer a fairly fine-tuning, which is appreciable in this flow range (see Fig. 2.15b).

2.3.2.3 Membrane Valves

These valves (see Fig. 2.15c) are equipped with a neoprene diaphragm (5) which is compressed by the piston (4) against the seat (2). Once again, it is mainly the small diameters that are used for small flow rates, as on large diameters the diaphragm sometimes tends to vibrate, which leads to problems with the stability of the control and reduces its lifetime.

2.3.2.4 The Haymore Valve

This valve was developed by Ralph Haymore specifically for the pressure relief of pressurised water (see Fig. 2.16a). It has been adapted for use in large diameter circular DAF clarifiers, where it has its main application today. It offers a novel solution to some of the problems of pressure relief valves mentioned in Sect. 2.30.

Although this solution is not perfect, it provides a more honourable performance than a simple globe valve mounted on a pipe.

Let's look at the context in which this valve is being used.

As described later in Sect. 4.1, in large diameter circular DAF clarifiers (say over 4–5 m), the contact zone in the centre is quite far from the periphery to which access is usually possible, except for having an access corridor underneath the unit, which is quite costly and often impractical. In addition, access to the contact zone

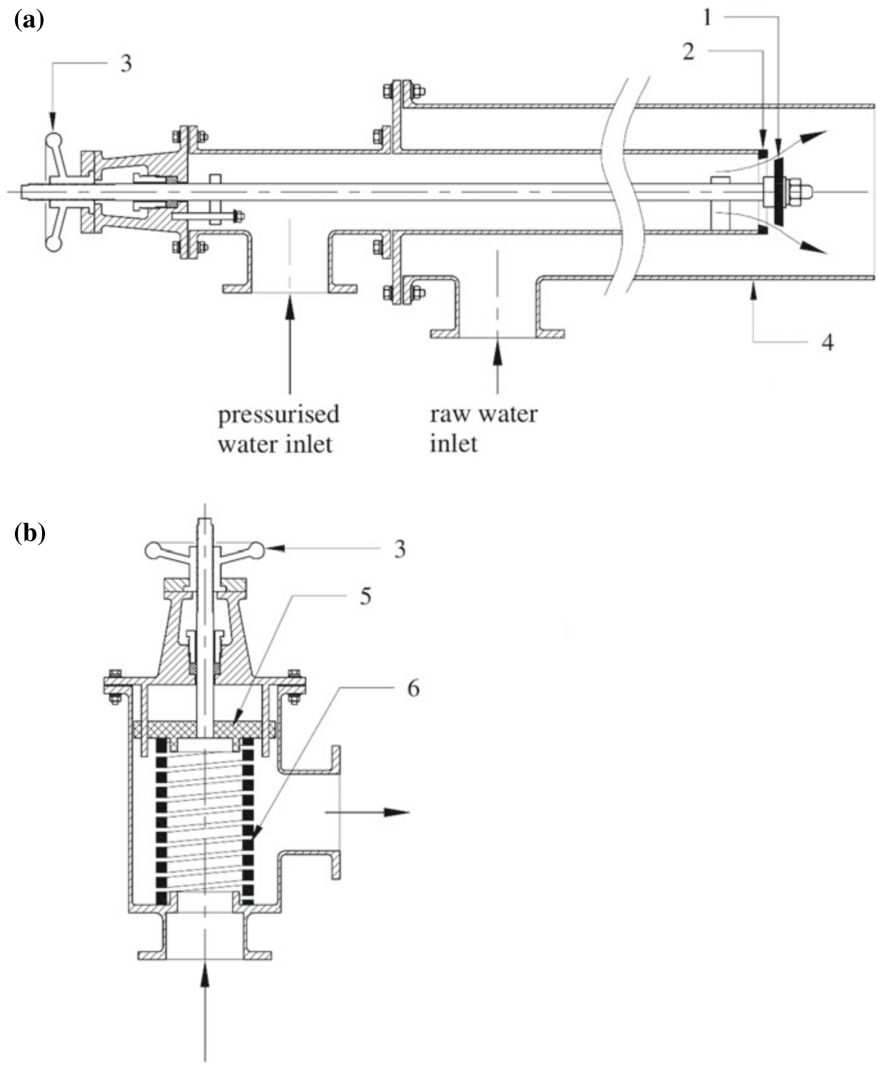


Fig. 2.16 Haymore valve and friction valve. 1—valve, 2—sit, 3—handwheel, 4—feeding pipe, 5—piston, 6—pressure relief spring

from above is compromised by the presence of rotating devices (rotating bridge or scraper). So, how can one avoid doing the pressure relief on the outside of the flotation tank (i.e. towards the periphery) and inject the white water directly into the centre without going through a pipe which risks promoting coalescence? In addition, how to ensure a homogeneous mixture with the raw water? And finally, how to design an easy-to-clean release relief device without using a sophisticated automatic cleaning apparatus that is immersed in the centre of the DAF clarifier and, therefore, exposed to the water's aggressions and difficult to operate?

As can be seen from the diagram, this is an adaptation of the globe valve concept. The inlet pipe (4) can have a long length allowing the handwheel (3) to adjust the position of the valve (1) in relation to the seat (2) which are several meters away from the handwheel (3). The special feature here is that the valve (1) is offset far into the raw water feed pipe (4) so that it can release the pressure at the very last moment right at the outlet of the feed pipe. This minimises coalescence while ensuring good mixing between the pressurised water and the raw water.

Some manufacturers fit this valve with a geared motor that uses a flowmeter in the pressurisation circuit to precisely regulate the flow of white water and automatically flush the valve if necessary.

When there is no other way than to go through pipes, the Haymore valve is, generally speaking, well adapted to the pressure relief of pressurised water in municipal wastewater treatment or industrial effluents. The main disadvantage is the relatively high manufacturing cost (custom built) compared to the cost of a standard commercially available globe valve.

2.3.2.5 The Friction Valve

The friction valve was developed in the early 1980s by Krofta especially for the pressure relief of pressurised water (see Fig. 2.16b). The originality of this valve lies in the use of a pressure relief spring (6) built in a square or trapezoidal profile. The pressurised water enters inside the spring (6). The handwheel (3) pushes the piston (5) which compresses the spring (6) to a greater or lesser extent, forming a very long slot between the turns. This slot can be of the size of a millimetre, which results in excellent white water quality at the moment of release. Unfortunately, the small volume of the valve body downstream of the expansion and the use of piping are factors that can cause coalescence. However, the main disadvantage of the friction valve is the small size of the expansion slot, which is very sensitive to clogging. In addition, a considerable opening of the spiral is required for cleaning. These weaknesses make the friction valve a somewhat capricious and difficult device to implement, which explains its low popularity. On the one hand, its sensitivity to clogging limits its application in wastewater. On the other hand, its use in drinking water is not advantageous compared to pressure relief nozzles which are better suited to the concept of high rate rectangular DAF clarifiers used in the majority of installations in this domain.

However, it is still possible to use a configuration with a larger slot width and thus reduce its sensitivity to clogging, but this reduces the quality of the white water produced at the expansion and, ultimately, the interest of its concept. Another solution would be to install a flow meter in the pressurisation circuit, motorise the valve and purge as often as necessary to maintain the required pressurisation rate.

2.3.3 Automatic Valves

As mentioned in the previous paragraph, it is possible to motorise the Haymore valve and the friction valve with a gear motor. There are even motorised globe valves (for other industrial uses). However, these are special constructions that are quite expensive because they are manufactured individually or, in the best case, in very small series. In addition, the electric actuator requires the installation of a control loop and an electromagnetic flow meter.

In practice, such assemblies with flowmeter and control loop are relatively rare because, in addition to their high cost, their reliability relies on the reliability of each component. They are better suited to large installations where the investment is easily justifiable, both from an economic and operation simplicity point of view (large works far from each other, installed outdoors, etc.). For small installations, this function can be fulfilled by automatic valves with pneumatic actuators. They have the advantage of being cheaper, simpler to install and (almost) more reliable to operate in everyday life.

The automatic valves used for pressurised water pressure relief are mostly of the globe type. They are standard products that can be adapted to the function practically as they are or with minor modifications. The one shown schematically in Fig. 2.17 has an angled seat and actuator, but a very similar design exists with a straight seat and actuator. The connections can be flanged (as shown) or screwed.

There are several manufacturers of this type of valve using different actuators with slightly different designs depending on operating pressures and valve sizes. The diameters available are generally between DN10 and DN100, which is more than enough to cover the entire flow range.

The operating principle of these valves is as follows:

The actuator (6) is equipped with a two-way piston controlled by a solenoid valve that sends compressed air to one side of the piston to close the valve or to the other side of the piston to open it. As closing requires more power to compensate for the water pressure at the valve inlet, the piston can be assisted by a spring on the closing side. In order to be able to use compressed air at a standard pressure of about 5–6 bar, the piston area is much larger than the cross-section of the seat (2). This is because the force of the piston is equal to the pressure of the pilot air multiplied by its surface area, so that a large piston can provide sufficient force to a small globe (1), even if the pressure of the air pushing the piston is lower than the pressure of the water on the globe. For example, let's assume that the cross-sectional area of the seat (2) is 5 cm^2 (2.52 cm diameter). The force of the water on the globe (1) at a maximum

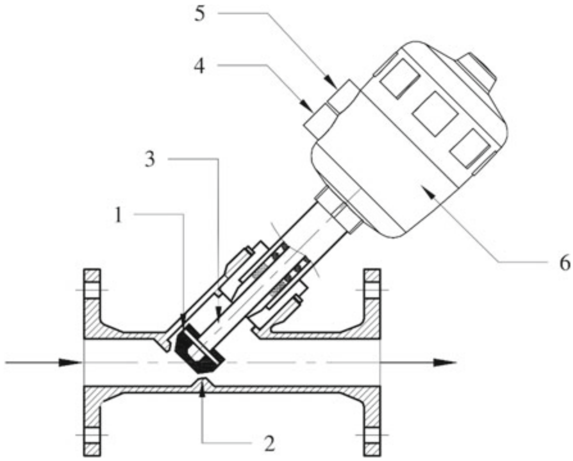


Fig. 2.17 Automatic globe sit valve. 1—valve, 2—sit, 3—rod, 4—air to open, 5—air to close, 6—actuator

pressure of 15 bar is $5 \times 15 = 75$ kg. To balance this force, an actuator with an 8 cm diameter piston (50 cm^2 cross-section) only needs 1.5 bar of control air pressure. Thus, it is possible to close a valve fed with water at 15 bar (peak pressure) with an air pressure (pilot pressure) just slightly above 1.5 bar.

A simple device inside the actuator allows the stroke of the spindle (3) (and therefore of the valve (1)) to be adjusted in the "closed" and "open" positions of the valve. This allows the flow rate through the actuator in the "closed" position and the valve opening during the flushing process corresponding to the "open" position of the actuator to be adjusted. This configuration allows the expansion of the pressurised water in normal operation (actuator closed) and a "preventive" flush of the valve from time to time, e.g. 2 or 3 s of flushing every 15, 20 or 30 min. This concept prevents clogging with a degree of reliability that is considered sufficient in many installations. Of course, it is possible to control the purge process not on a time basis, but based on information about the decrease in the pressurised water flow. This drop in the pressurisation flow rate can be detected by an electromagnetic flow meter or by a differential pressure sensor installed on the saturator, if the latter is equipped with a water dispersion device creating a significant pressure drop. But this configuration is more rare—preventive flushing on a time basis is sufficient in the vast majority of cases.

For the pressure relief function, a valve of this type must fulfil a few conditions:

– It is preferable that the valve is PN16 rather than PN10, i.e. designed for a maximum pressure of 16 bar.
– The minimum pilot pressure should not exceed 5–6 bar (sufficient to ensure that the valve closes at a water pressure of 16 bar). In other words, to ensure reliable closing at 5–6 bar water pressure, a pilot pressure of 4 bar will be more than sufficient. Thus, the pilot air pressure will never fail, if the same compressed air circuit supplies the pressurisation system which normally requires at least 5.5 or 6 bar of minimum pressure.

– It must have a device for regulating the stroke of the rod (3) equipped with a blocking system by a locknut, both on opening and on closing. These two locks prevent the valve from being progressively out of tune as it is flushed.
– The materials of construction of the wetted parts must be compatible with the composition of the water.
– The actuator specifications in terms of pilot air quality (lubricated or non-lubricated air) must match the quality of the instrumentation air to be used.

Lastly, some DAF manufacturers have developed their own pneumatically operated pressure relief valves which generally have two advantages over commercially available automatic valves adapted to the function:

– They are completely sealed (including the pneumatic actuator) and can be immersed directly in the contact zone of the flotation tank. This allows several small automatic valves to be used on large DAF clarifiers, thus achieving better white water quality and mixing conditions with the raw water.
– The shape of the seat and valve allows for greater flexibility of adjustment and also better resistance to clogging.

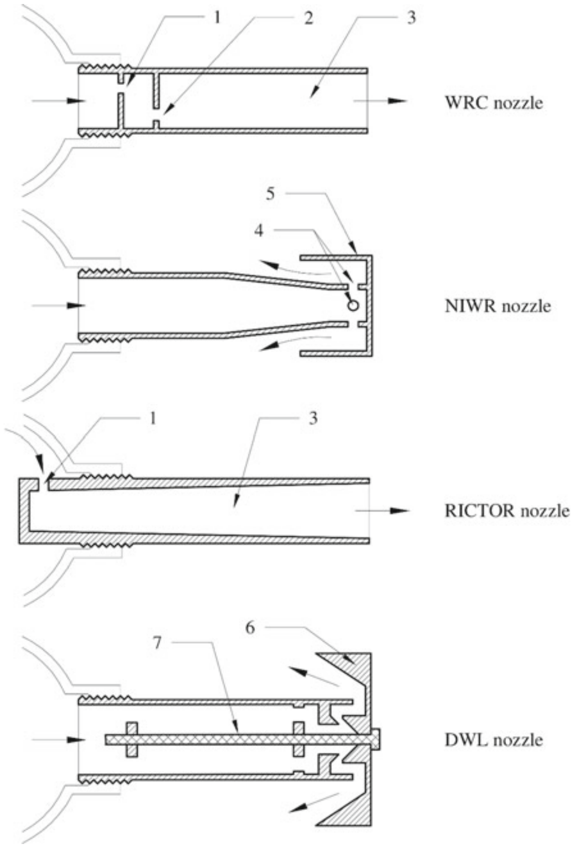
However, for obvious reasons of accessibility, it is preferable to calibrate and test these valves on a test stand before installing them in the plant. Once installed, it is very difficult, if not impossible, to modify their setting without draining the plant. And it is difficult to readjust them in an empty tank without operating the pressurisation system.

2.3.4 Pressure Relief Nozzles

The first pressure relief nozzles were developed in the 1960s–1970s for drinking water treatment applications. Of all the pressure relief devices, they are among those that best meet the four pressure relief conditions for obtaining the best white water quality. Figure 2.18 shows four schematic diagrams of different nozzles, but several manufacturers have developed, and often patented, their own pressure relief nozzles. In general, all these nozzles are made of plastic and are intended to be screwed onto a pipe through connecting sleeves (shown schematically on the left side of the diagrams). These pipelines with nozzles often form white water distribution manifolds.

Pressure relief nozzles can be divided into two categories: fixed orifice and adjustable orifice. Fixed orifice are circular (the least sensitive to clogging) and their diameter is usually between 2 and 3.5 mm, but there are also nozzles with orifices of 1.4 mm and up to 6 mm in diameter respectively. Fixed orifice nozzles can have a single orifice or multiple orifices. In both cases their flow rate is practically fixed, because above 5–6 bar the pressure increase has relatively little influence on the flow rate through a small orifice. For example, a 3.5 mm orifice gives an approximate flow rate of 0.75 m^3/h at 5 bar and 0.81 m^3/h at 6 bar. The difference in flow rate is only

Fig. 2.18 Pressure relief nozzles. 1, 2—orifice, 3—slowdown and containment zone, 4—multiple orifices, 5—cover, 6—adjustable plug, 7—threaded rod



7.4% for a 20% increase in pressure. The WRC, NIWR and RICTOR nozzles are fixed orifice (see Fig. 2.18).

In the WRC nozzle the pressure relief is done on a first orifice (1). The expanded water jet is projected onto a surface in front of the orifice before passing through a second orifice (2) to the slowing and confinement zone (3). The NIWR nozzle has a multitude (normally four) of pressure relief orifices (4) that spray water onto the inner wall of the cover (5). The deceleration and confinement zone is located under the cover (5). The RICTOR nozzle has a pressure relief orifice (1) that directs water onto the inner wall of the conical tube forming the slow-down and confinement zone (3).

Adjustable orifice nozzles provide the possibility to vary (within limits) the flow rate. The DWL nozzle allows pressure relief through a chicane that changes the direction of the water five times. This allows the water flow cross-section to be increased for the same head loss. The adjustment is made through the threaded rod (7) of the plug (6), which allows the same nozzles to be used for different flow rates, or to change the flow rate of an existing installation equipped with these nozzles.

What do these four nozzles have in common? They all implement, albeit in slightly different ways, the same pressure relief steps, i.e.:

- Pressure relief through one or more small diameter orifices.
- Projection of the jet onto a dispersion surface located in front of the pressure relief orifice at a distance equal, in most cases, to 2 to 5–6 times the orifice diameter.
- Confinement of the white water in a space allowing its velocity to be reduced before mixing it with the raw water.

The majority of drinking water installations are equipped with fixed orifice nozzles. The orifice plates of some of the more sophisticated designs are removable and allow the nozzle flow rate to be changed by simply replacing the orifice plate without affecting the rest of the nozzle or having to recalibrate the nozzles if they are adjustable flow rate type such as the DWL nozzle. This removable orifice plate design also allows for easier maintenance in the event of clogging as it avoids the necessity to remove the nozzle from the manifold.

It is difficult to comment on the performance of each of these nozzles as there is limited information available. Indeed, the cases where several types of pressure relief nozzles have been tested on the same installation, under the same conditions and with the same water are rare.

There are two important points in the implementation of pressure relief nozzles. The first is the choice of the diameter of the pressure relief orifice. The smaller the diameter, the better the result. On the other hand, there will be more nozzles and connecting sleeves to be welded to the manifolds (for the same pressurisation rate), which increases the cost of the whole system. The second is the risk of clogging. This risk always exists, even in drinking water where pressurisation is done with clarified water normally free of large particles, at least in theory… The smaller the orifice, the greater the risk of clogging, and the more the reliability of the installation could be compromised with, in addition, the shutdowns and maintenance costs that go with it. There are three solutions:

1. Avoid small diameter orifices (1.6–2 mm) and use larger orifices (e.g. 2.5–3 mm diameter). This will probably slightly reduce the quality of the white water and, in addition, will not solve the problem definitely. However, the pressure relief orifice of most pressure relief nozzles is closer to 3 or 3.5 mm than to 2 mm.
2. Install one or more filters in the pressurisation circuit. Usually these are pressure filters installed after the pressurisation pump upstream of the saturator. The filter threshold should not exceed 1/3 of the pressure relief orifice diameter. Depending on the quality of the water, the size of the installation and the required degree of automation, it is possible to use filters with manual or automatic cleaning.

Manual cleaning filters are usually basket filters. This is the simplest and most economical solution for small and medium-sized installations, but it requires regular intervention by the operator. In order to ensure continuous filtration, at least two filters or a double basket filter, called duplex basket, are required. Thus, one of the baskets is in use while the other is being cleaned. The changeover is done by a set of manual valves. Figure 2.19a shows schematically a simple basket filter. The basket

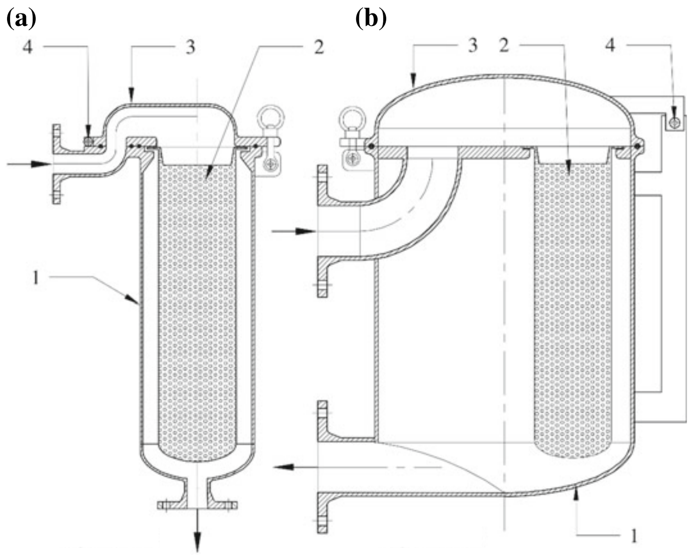


Fig. 2.19 Basket filters. 1—filter body, 2—basket, 3—cover, 4—cover opening axis

(2) is housed in the filter housing (1). The basket is cleaned by opening the cover (3), which rotates on the shaft (4). For larger flow rates, several filters of this type can be mounted in a battery. Alternatively, a larger filter like the one shown in Fig. 2.19b can be installed. This filter housing contains several baskets (typically 4–8). It allows a larger flow rate to be passed, limits the size of the installation and the number of isolation valves, and simplifies the pipework.

Self-cleaning filters use a fine filter mesh, sometimes preceded by a larger mesh pre-filter, of the range of 3–5 mm. The cleaning can be done by brushes mounted on a shaft which is rotated by an electric motor. In this case, the waste is recovered by reversing the flow of filtered water. It can also be done by a suction scanner mounted on a rotating axis which moves along the screen. The automatic unclogging is activated by a differential pressure sensor between the pressures upstream and downstream of the screen. The pressure inside the screen forces the waste to be discharged through the suction nozzles from inside the suction scanner. The opening of an automatic purge valve connects the suction nozzles and the interior of the rotary scanner to a pipe that opens to atmospheric pressure. This creates a vacuum, which allows the waste material to be removed as the suction nozzles sweep the filter surface of the screen.

The filtration system is designed and adjusted in such a way that the clogging of the screen on the one hand, and the automatic unclogging on the other, do not influence the flow rate and pressure of the pressurisation circuit too much. As an indication, the unclogging is activated at a differential pressure (pressure drop due to clogging) of 2–4 m (excluding pressure drop through the clean basket). The purge flow rate is about 8–10% of the maximum filter capacity for a cleaning time of a few tens of seconds. Figure 2.20 shows a schematic of a self-cleaning filter with scanner and suction nozzles, as well as a pre-filter. This is in some ways the most "complete" device used for this function. It works as follows:

The water to be filtered is introduced into the pre-filtration chamber in which the protective pre-filter (2) is installed. Then it passes through the fine filter screen (3).

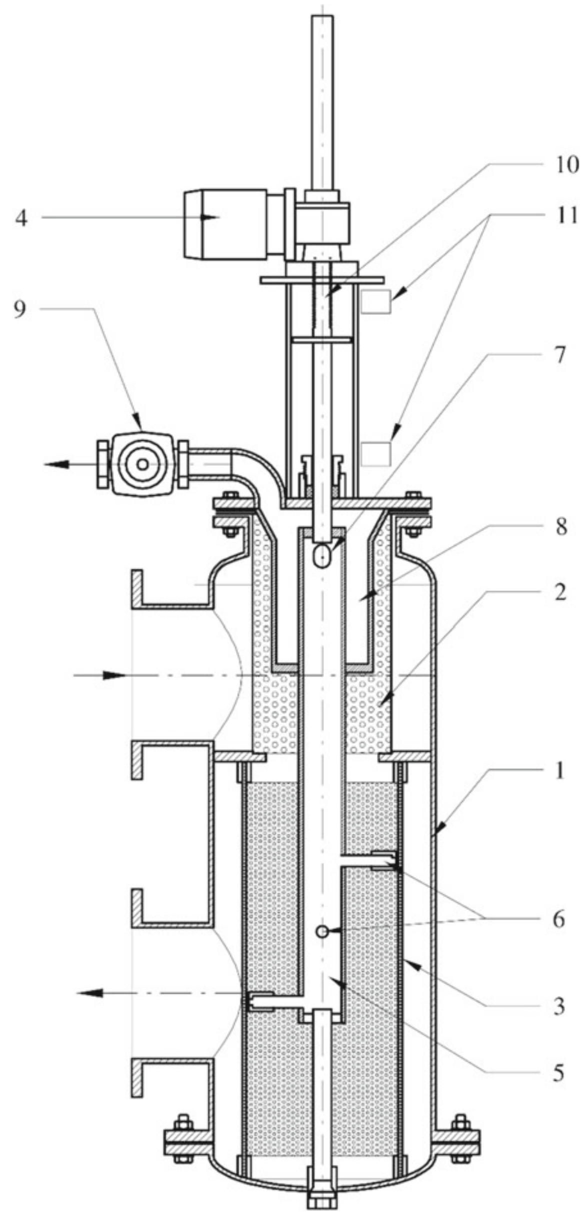


Fig. 2.20 Automatic self-cleaning filter. 1—filter body, 2—pre-filter, 3—screen, 4—gear motor, 5—reciprocating scanner, 6—suction nozzles, 7—outlet orifice, 8—outlet compartment, 9—back flushing valve, 10—threaded shaft, 11—proximity switch

This screen is usually made up of two and sometimes even three layers of different filter cloths, the coarsest (support cloth) being on the inside and the finest ("filtration cloth") on the outside of the screen. The filter cloth is cleaned by starting the gear motor (4) and opening the drain valve (9) which opens to atmospheric pressure. The suction scanner (5) with its suction nozzles (6) is rotated through the threaded shaft (10) and moved up and down along the screen (3) so that the suction nozzles (6) can finally sweep the entire inner surface of the screen (3). The purge water flowing at high velocity through the suction nozzles (6) carries away the deposits accumulated on the surface of the screen (3) and transfers them through the outlet orifices (7) into the purge chamber (8). From there, the purge water is discharged through the purge valve (9). Two proximity switches (11) delimit the path of the suction scanner (5).

3. If the installation includes sand filters downstream of the flotation clarification, it is possible to use the filtered water for pressurisation. This provides good water quality and avoids the installation of police filters in the pressurisation circuit. However, the sand filters have to take an additional hydraulic load corresponding to the pressurisation flow, i.e. about 10–12% of the raw flow.

2.3.5 Perforated Pressure Relief Pipes

Perforated pressure relief pipes are nothing else but a simplified variant of the pressurised water distribution pipes. The latter are equipped with pressure relief nozzles, whereas perforated pressure relief pipes do not have any. The nozzles are replaced by simple calibrated holes in the pressurised water distribution pipework itself—see Fig. 2.21. Calibrated holes (1) are drilled in the pressurised water distribution pipework (2) at regular intervals depending on the diameter of the hole (1), the length of the pipework and the pressurisation rate. A cover (3) arranged in front of the ports (1) at a distance of 3 to 5 times the diameter of the holes (1) serves as a deflector. A deceleration and confinement space (4) is arranged under the cover (3).

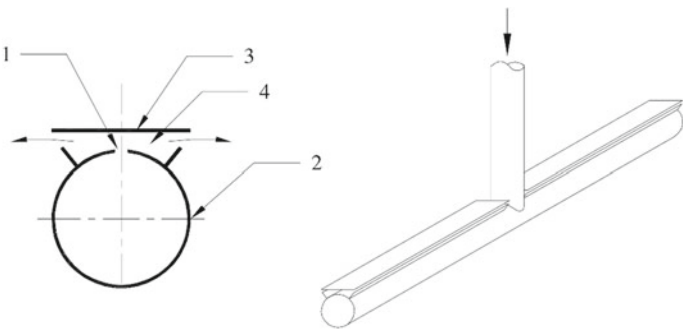


Fig. 2.21 Pressure relief ramp. 1—calibrated hole, 2—pressurised water distribution pipe, 3—cover, 4—slowdown and containment zone

This configuration offers a similar concept to that of the pressure relief nozzles by creating the same functions as those performed in said nozzles. At least in theory… Because it is obvious that this is a compromise that could be criticised for not having the ideal dimensions and perfect configuration of a specially designed pressure relief nozzle. In practice, however, this concept works well and it would often be difficult to find a significant difference with white water manifolds equipped with nozzles and installed in the same conditions, i.e. at the same depth. Because the depth at which the pressure release is carried out is important, especially for pressure relief nozzles, perforated pressure relief pipes and compact diffusers (described in the next paragraph) installed in DAF clarifiers with a contact zone in which there is a very high concentration of air bubbles.

Indeed, the deeper the pressure relief takes place in the contact zone, the greater the risk of rapid coalescence, as bubbles coming from too great a depth increase significantly in volume as they rise and become more prone to coalescence. This is probably because, as they stretch, the layers of electrostatic charges that surround them become more fragile. However, it is not advisable to diffuse the white water too close to the surface, as this reduces the contact time with the raw water and deteriorates the hydraulic conditions of the mixture. For drinking water DAF clarifiers, which are the main users of this type of pressure relief device, it would seem that the optimum depth of pressure relief is between 2 and 3 m. Expansion beyond 4 m may result in a reduction in the amount of fine bubbles passing through the flotation zone and therefore a reduction in the thickness of the fine bubble layer covering the said zone. This layer of fine bubbles covering the flotation zone plays a decisive role in the efficiency of the clarification and therefore in the quality of the clarified water. Conversely, a pressure relief at less than 1–1.2 m from the water surface would reduce the contact time and mixing quality between the white water and the raw water.

Although perforate pressure-relief pipes are cheaper than pressurised water distribution pipes with nozzles, they have two disadvantages:

- Once they are built, it is almost impossible to modify them. However, it is possible to install two or even three pipes sized for different flow rates and then combine them as required. Provided, of course, that the design of the saturator allows such flexibility.
- In case of clogging of the holes they are difficult to clean. It is strongly recommended to install drains in the extremities of the manifold so that solid waste that falls into the pipe can be effectively washed out when cleaning the orifices.

2.3.6 Compact Diffusers

As mentioned in the previous paragraphs, the calibrated holes of the perforated pipes and the pressure relief nozzles tend to clog over time, unless the pressurisation system is equipped with police filters. If clogging occurs, cleaning is difficult because the manifolds are submerged and difficult to access. Some manufacturers separate the manifolds into several pieces that can be removed separately from the water, but the operation still requires the shutdown of the clarifier. For the rest of the designs, the main disadvantage of the cleaning operation is the need to empty the DAF clarifier, which means either a halt in production or reduced production, if the installation has several DAF clarifiers. Unless one has a spare DAF clarifier. For large installations with several units, the N + 1 configuration is often the preferred solution. On the other hand, having a spare DAF clarifier on small and medium-sized installations is quite penalizing in terms of investment. For example, two 500 m^3/h DAF clarifiers can be 1.6–1.8 times more expensive than a single 1000 m^3/h unit.

Compact diffusers offer an alternative solution, which on the one hand provides quality pressure relief through small diameter calibrated holes, and on the other hand allows each diffuser to be removed from the tank for quick cleaning, without significantly affecting the operation of the clarifier. In this way, it is possible to isolate a diffuser, take it out of the water, clean it quickly and put it back into service before moving on to the next diffuser without stopping the operation of the installation.

The main part of the compact diffusers is a plate with several small diameter calibrated holes—2 or 2.5 mm—fixed in a device allowing a quick disassembly. Depending on the installation conditions the diffuser can be placed directly in the contact zone or inside a "T" piece of pipework serving as a confinement and deceleration chamber.

An example of this concept used in a rectangular DAF clarifier with a contact zone is shown in Fig. 2.22. In both cases the diffusers are arranged along the pressurised water feeder. The distance between the diffusers can vary from 0.8 to 1.5 m depending on the size of the clarifier. The aim is to have at least 5 diffusers so that the shutdown of one of them does not influence too much the flow of white water injected into the contact zone.

Figure 2.22a shows schematically a diffuser (1) mounted at the extremity of a rigid pipe (2) supported by the support (9). Pressurised water is supplied through the feeding pipe (3). The isolating valve (4) isolates the diffuser. By removing the dismountable coupling (8) the rigid pipe (2) with the diffuser (1) can be easily removed for cleaning.

Figure 2.22b shows schematically a side view and a front view of a variant of the same concept. In this case, the diffuser (1) is mounted at the extremity of a flexible hose (5) sliding in a guide tube (6) which ends in a "T" piece (7).

The flow rate of a diffuser of this type can easily reach 40 m^3/h. Thus, with six or seven diffusers, it is possible to supply even the largest drinking water DAF clarifiers with pressurised water. They should be used for direct injection into the contact zone. When installed in a pipe, these devices lose their value because of the coalescence that occurs inevitably in the pipe.

In the most efficient version of this type of device, the expansion is made through fine stainless steel mesh. The quality of the white water obtained is simply amazing due to the fineness of the bubbles and their durability. The reason for this is probably the very large friction surface between the water and the multiple wires of the cloths at the moment of expansion as well as the very small size of the multiple expansion holes formed by the mesh of the cloths. However, this concept is reserved almost exclusively for drinking water. And it would be preferable to supply it with water

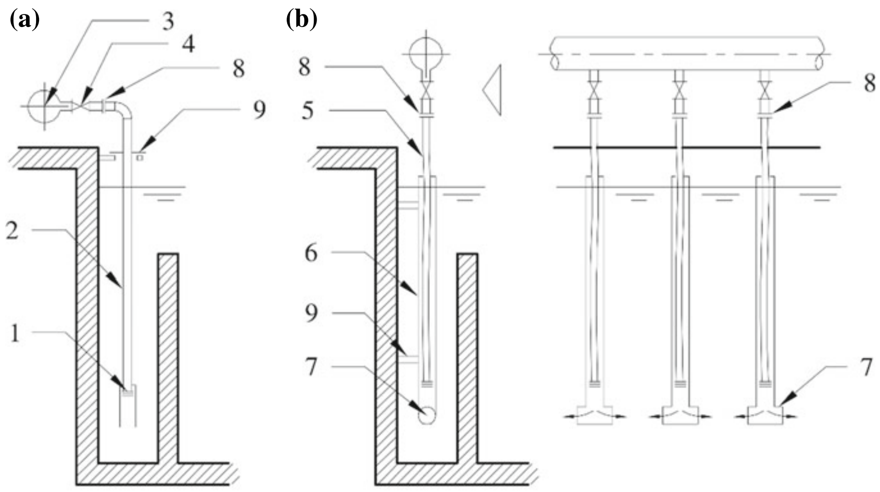


Fig. 2.22 Compact diffusers. 1—diffuser, 2—rigide pipe, 3—feeding pipe, 4—isolation valve, 5—flexible hose, 6—guide tube, 7—T piece for confinement and diffusion, 8—dismountable coupling, 9—support

filtered by sand filters or to foresee the installation of a rather fine police filter, otherwise the stainless steel cloths would clog up quite quickly (especially with surface water) and the cleaning sessions could become too frequent to be acceptable for the operator.

2.3.7 Energy Recovery Turbines

It is obvious that the pressure relief of pressurised water is, in a way, a pure waste of energy. Water and air are pressurised to several bars and then released to atmospheric pressure a few tens of seconds later. The idea of trying to recover this wasted energy is quite logical and comes quite naturally.

The most suitable way (and practically the only possible way…) is to use an energy recovery turbine as a pressure relief device. Several major centrifugal pump manufacturers have developed such turbines for different applications. Some have even made them their speciality. The most advanced pump/impeller units are able to recover more than 70% of the energy spent on pressure rise. And some devices even exceed 80%. The stakes are therefore high and the gain can easily justify the investment. Unfortunately, dissolved air flotation has not really taken advantage of this concept for several reasons.

Firstly, it is not always easy to install the pressurisation pumps in the right place so that the pressure relief takes place as close as possible to the point of injection of the pressurised water. Secondly, the formation of air bubbles in the turbines reduces their efficiency and can cause cavitation. But the main disadvantage of this concept is the final result, which is disappointing in the (vast) majority of cases. It is obvious that, in view of what has already been said about pressure relief and bubble formation, a turbine in which there is neither great turbulence, nor multiple thin slots, nor much friction between the water and the turbine is not a good pressure relief device. The results in clear water are disappointing (hardly any microbubbles) or very modest with a small greyish cloud in an exuberance of large bubbles. The more organic matter and especially surface-tension products the water contains, the better the result. But, generally speaking, it remains modest. There are a few installations with energy recovery in the oil industry where the quality of the pressurised water obtained is just acceptable to operate the DAF clarifiers, but the loss of a lot of coalescing air and large bubbles is obvious. In fact, the pressurisation systems are often so oversized that it is questionable whether the energy actually recovered really compensates for the energy wasted unnecessarily. It might sometimes be more sensible to reduce the pressurisation rate, but to install more efficient pressure relief devices. In any case, the question is worth asking, but a detailed study should be carried out before embarking on the realisation of an energy recovery installation with a pressurisation pump plus turbine assembly.

Chapter 3
Circular DAF Clarifiers

Circular DAF clarifiers have the advantage that they are usually cheaper to build than rectangular DAF clarifiers. Of course, this comparison is valid for the same surface area and comparable hydraulic concepts. This is because a circular tank is more resistant to water pressure than a rectangular tank with flat walls that require multiple reinforcements. This is also true, in a way, for floated sludge recovery devices. A device that rotates around a central bearing is often (for the same capacity) simpler and cheaper to build than a surface scraper that moves in a more complex, translational fashion.

For this reason, circular DAF clarifiers are often preferred to rectangular ones, especially for large installations. On the other hand, like all equipment, they also have their disadvantages. Firstly, if there are several clarifiers in the installation, they will take up more space than rectangular clarifiers which fit together better and may have common walls. Secondly, circular DAF clarifiers with central distribution (which is the majority of cases) offer little space for a flocculation tank integrated in the centre of the unit. Even if such a central tank is one third the diameter of the flotation tank, its surface area will only be 11% of the total flotation surface or 12.5% of the remaining flotation surface. Even with a depth of 3.5 m, at a 'conventional' flotation surface hydraulic load of 8 m/hr, this would represent a residence time of less than 3 min. This may be sufficient for many applications, but probably not for typical drinking water clarification cases. And if one seeks to use an external flocculation tank, one would have to face other problems, the most important of which, apart from space, is the transfer velocity of the flocculated water from the flocculation tank to the centre of the DAF clarifier. Because if one wants to preserve properly the integrity of the formed flocs, it would be necessary to have a transfer piping sized for a velocity not exceeding 30–40 cm/sec, which gives quite significant piping diameters and elbows. Alternatively, several smaller diameter pipes could be placed in parallel. In any case, concentrating a large flow of flocculated water in the centre of the DAF clarifier, which offers a fairly small space, would create turbulence that would be more or less difficult to manage. This is probably the main reason why circular DAF clarifiers are

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rarely used in drinking water clarification. It is not so much the clarification capacity of circular DAF clarifiers that is the problem, but the management of flocculation, water inlet and distribution.

Circular DAF clarifier with central distribution has some hydraulic specificities that deserve to be mentioned. It should be pointed out that the consequences of these features are not necessarily a disadvantage, even on the contrary from a certain point of view. These clarifiers have a different hydraulic behaviour compared to rectangular ones. This is due to the circular shape of the tank and the fact that the water moves from the centre to the periphery. In this movement of water from the inlet to the outlet, the logical aim is to create the most favourable hydraulic conditions for good liquid/solid separation, i.e. the least turbulent possible. If one simplifies things slightly, one could say that this means having a water velocity that is low enough to allow proper separation of the particles, without turbulence disturbing this separation to any significant extent, or worse, putting them back into suspension in the water. If one were to simplify things a little more, one could say that the velocity of the water from the inlet to the outlet is the main parameter for the sizing of a clarifier. In practice, two parameters are usually used; the velocity of water flow from the inlet to the outlet (in m/h or mm/sec) and the hydraulic load of the flotation tank, which is the flow rate divided by the flotation surface (in $m^3/m^2 \cdot h$ or simply in m/h).

If one looks generally at the hydraulic concept of a rectangular flotation tank with an inlet and an outlet at both ends of the tank, one can say that the water moves between these two points at a more or less constant velocity depending on the specifics of the inlet and outlet devices.

Well, the situation is very different in a circular clarifier with inlet at the centre and outlet at the periphery. It is obvious that the water velocity is very high in the centre, near the inlet area, and gradually decreases as it approaches the periphery of the tank.

Figure 3.1 shows schematically a vertical cross-section of a circular DAF clarifier with a diameter of 8 m (area 50 m^2) and a rectangular DAF clarifier with the same area and depth respectively. It is assumed that the introduction and collection of water is carried out evenly over the entire depth.

Figure 3.1a shows, as a principled example:

- The evolution of the water velocity as a function of the distance from the centre travelled by the water of a circular flotation tank operating at a hydraulic load of 8 m/h (left curve above the tank).
- The trajectory of a floating particle at a constant flotation velocity (right curve inside the tank).

Figure 3.1b shows the trajectory of the same floating particle in a rectangular flotation tank whose length/width proportions are in the "classical" range for an "average" size of the tank. As an indication, one can assume a length of 10 m for a width of 5 m or a length of 7.5 m for a width of 6.6 m. These proportions are, of course, debatable and can be modified slightly, but this will not significantly change the velocity of the water obtained. At the same hydraulic load (8 m/h) the water velocity remains constant.

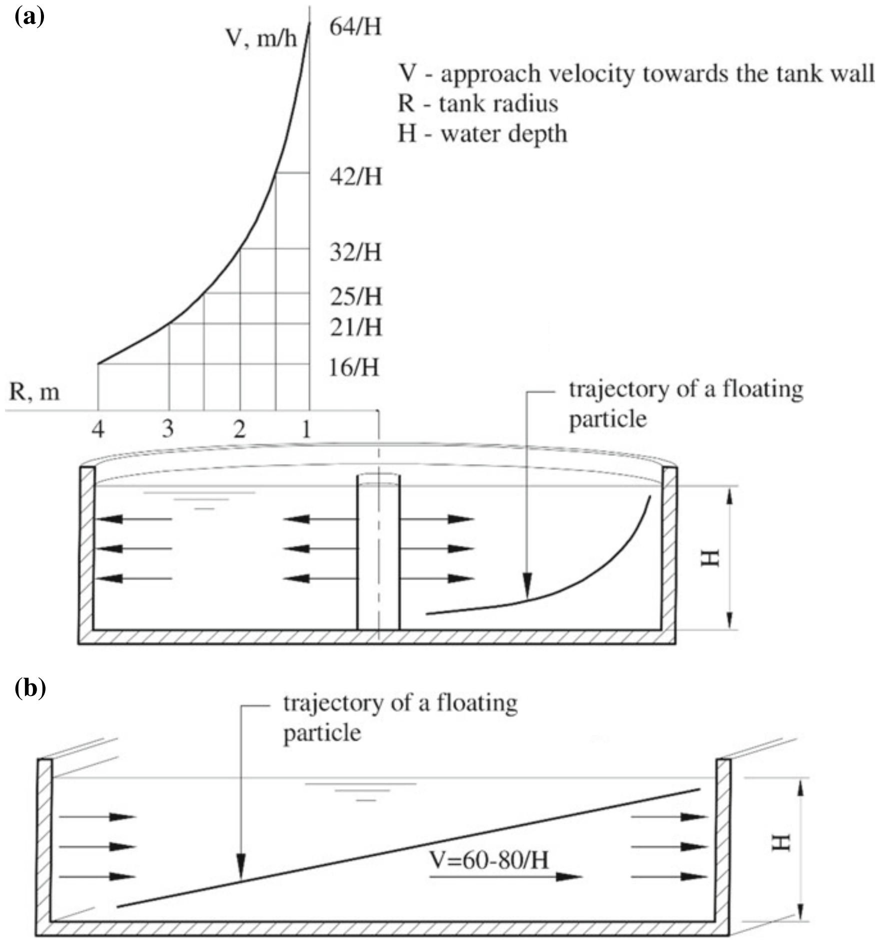

Fig. 3.1 Water velocity in circular and rectangular DAF clarifiers

If one compares these two flotation tanks with identical surface areas, it will be easy to see that, at the same hydraulic loads, the conditions of water movement are not the same. In the circular flotation tank the approach velocity of the water towards the outer wall of the tank, i.e. the approach velocity towards the outlet, is variable with the radius and varies between 64/H (m/h) near the centre and 16/H (m/h) at the periphery (the division by H takes into account the depth H, which is considered to be the same for both shapes of the flotation tanks compared). In the rectangular flotation tank of equivalent surface and hydraulic load, this velocity is constant, in the range of 60/H or 80/H (m/h) depending on the section of the tank selected. The trajectories of the same floating particle are not the same in a circular flotation tank and a rectangular flotation tank. In the rectangular flotation tank the trajectory of the particle is (ideally…) a straight line because the approach velocity of the water towards the outlet is constant.

In the circular flotation tank the trajectory of the particle is (still ideally…) a parabolic curve, because the approach velocity of the water towards the outlet is variable. Comparing the velocities in the two cases, it can also be seen that in the circular flotation tank the approach velocity of the water towards the outlet is, in general, much lower than in the rectangular flotation tank. The difference just before the exit is about 4–5 times. This low approach velocity of the water towards the outlet allows circular DAF clarifiers to create, especially towards the end of the water path, conditions of very low turbulence, which are very beneficial for the separation of "difficult" particles with a particularly low flotation velocity.

In practice the velocity and direction of water displacement in each point of the tank differs somewhat from this "idealized" model. There are several reasons for that:

Firstly, the distribution of water at the inlet is never even over the entire height of the central tank. Usually it is above half or even two thirds of the water depth, as the area below is typically reserved for bottom sludge collection.

Secondly, although distributing the water more at the top of the water layer has the advantage of shortening the path of floating particles to the surface, it is obvious that distributing all the water too close to the surface would cause too strong a horizontal surface current causing turbulence that could propagate quite far from the centre and thus compromise clarification in a large part of the tank. Also, distributing the white water too close to the surface will inevitably cause vortices that expose the air bubbles to the air too quickly and too often, causing many of them to explode on contact with the air, to no avail.

Thirdly, the clarified water is not collected from the full height of the shell as shown in Fig. 3.1a. It is collected at depth, usually 20–40% of the water depth (from the bottom), as this is where the clarified water is of best quality. The closer to the surface one collects, the greater the risk of recovering flocs that are still struggling to rise, because they are heavier, because they have retained fewer air bubbles or because they have lost some of them along the way.

Fourthly, the air bubbles and flocs that rise in the flotation zone create currents in the water. As they rise to the surface, some of the water above them must sink to take their place. The two currents (upward and downward) pass through each other and slow each other down, which inevitably creates micro-turbulence in addition to the currents.

All of this results in a water trajectory that differs more or less from the "ideal" trajectory shown in Fig. 3.1a, depending on the design of the water distribution and collection facilities.

Figure 3.2 shows schematically three types of circular flotation tanks with different feeding and, respectively, collecting devices for the clarified water. The three designs create slightly different 'hydraulic images'. The "hydraulic images" are shown for illustrative purposes and may vary for the same unit depending on the size of the unit and the feed flowrate. These images do not take into account the influence of

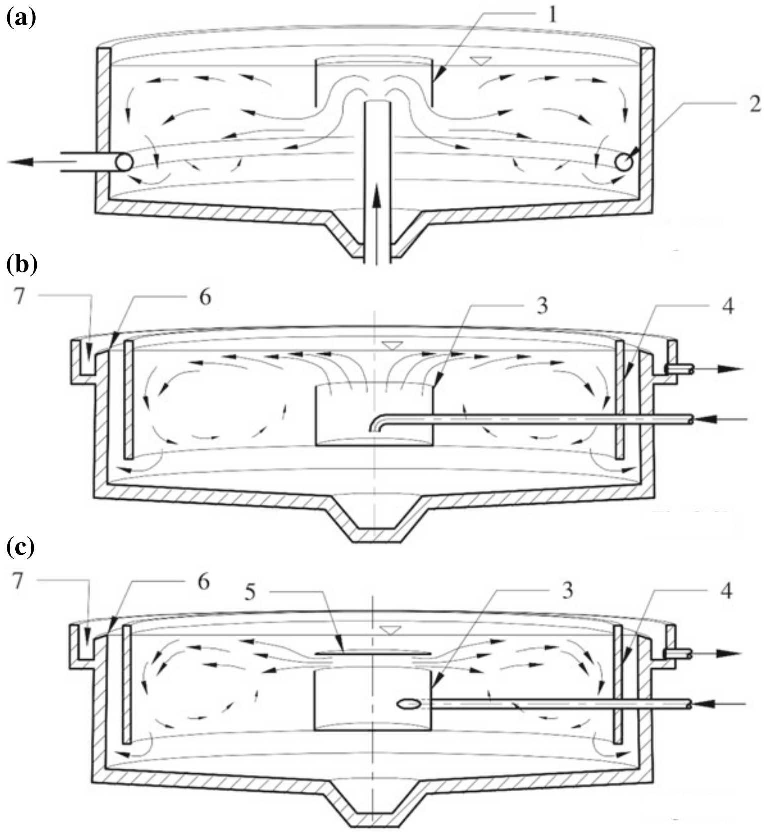

Fig. 3.2 Schematic presentation of the water currents depending on the inlet and outlet devices. 1—inlet wall, 2—clarified water collector, 3—central tank, 4—peripheral submerged baffle, 5—central tank cover, 6—weir, 7—clarified water channel

the amount of air supplied by the pressurised water, which can also influence the currents significantly.

Figure 3.2a shows a central distribution with a submerged central baffle (1) and a clarified water collection ring (2) near the bottom. The water is distributed at about half depth with an initial orientation towards the bottom. This gives a relatively even progression of the water towards the shell and a moderate radial surface current. The distribution of the floated sludge is relatively even over the entire flotation surface.

Figure 3.2b shows a central distribution tank (3) open at the top, giving an orientation of water flow towards the surface. Depending on the depth at which the upper edge of the central tank (3) is located, this design creates a stronger or weaker radial current that pushes the floated sludge towards the tank shell. This results in an accumulation of floated sludge towards the periphery and has the advantage of imposing a shorter travel distance for the flocs that are introduced near the surface. The clarified water is collected under a peripheral submerged baffle (4) and overflows into the clarified water channel (7).

Figure 3.2c shows a central distribution tank open at the top. A cover (5) creates an opening in the upper part of the tank (3) that directs the water flow horizontally. The dimensions of the opening between the cover (5) and the edge of the tank (3), as well as their level in relation to the water surface, can vary depending on the size of the clarifier and the flow rate. The entry of the raw water or raw water + white water mixture is often done tangentially (as shown) to create a rotation of the water inside the tank (3) to ensure a good mixing, a homogeneous distribution on the whole periphery of the tank (3) and, possibly, some seconds or tens of seconds of flocculation time.

In all cases, the inlet and outlet devices must be adapted to the function of the DAF clarifier (clarification of a large flow or thickening of a small flow of concentrated sludge), to the characteristics of the effluent (floc flotation rate), to the mode of injection of the white water, to the possible need for a flocculation tank in the centre of the unit, etc.

Another important element in the design of a circular DAF clarifier is the method of injection of the white water. There are three possibilities.

The first, and probably the most common, is to inject the white water into the raw water feed pipe—see Fig. 3.3a. An pressure relief valve (3) is used, usually of the globe type. The injection is made towards the periphery of the tank because of the easy access. This mode has the advantage of ensuring a very intimate mixing of white and raw water, and is flexible and easy to operate. It allows precise setting of the pressurised water flow rate and easy unclogging of the pressure relief valve if necessary. The cleaning can also be automatic if the construction of the valve allows it (automatic valve). The main disadvantage of this mode is that it causes air bubbles to coalesce in the piping between the pressure relif valve and the pipe outlet in the central tank, which results in the loss of some air. As already described, the purer the water, the greater the coalescence. Also, it increases with the time spent in the pipes. It is therefore recommended not to have too low a water velocity in the feeding pipe. For example, a DAF clarifier designed for 1000 m^3/h of raw water with 200 m^3/h of pressurisation is likely to perform very poorly if fed with 100 or 200 m^3/h of raw water, as the raw water + pressurised water mixture spends too much time in the pipework and in the central tank before reaching the flotation zone. However, if the wastewater flow rate is not very variable and if one is prepared to sacrifice some of the air (i.e. to increase the pressurisation flow rate and therefore the power consumption) for the sake of simplicity of operation, this method of injecting the white water will still give a good result. In clarification or thickening of biological sludge it works quite well with an injection of polymer at the same time as the white water (in-line flocculation). This injection method can also be used after coagulation in an external tank if the in-line flocculation works well, i.e. if the flocculation time provided by the feeding pipe and the central tank is sufficient.

The second possibility is shown in Fig. 3.3b. It is based on the use of the Haymore valve, which has the advantage of introducing the white water almost directly into the central tank, thus minimising coalescence in the feed pipe of the said central tank.

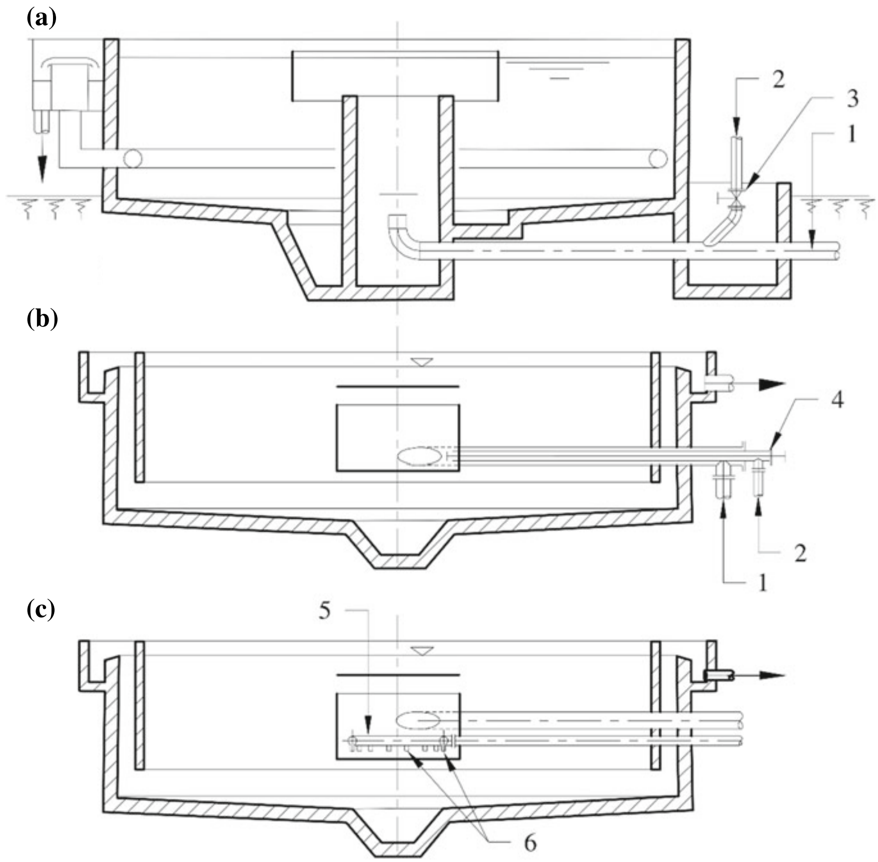

Fig. 3.3 Presurised water injection modes. 1—raw water inlet, 2—pressurised water inlet, 3—pressure releif valve, 4—Haymore valve, 5—pressurized water distribution ring, 6—pressure relief devices

This solution is mainly reserved for wastewater, possibly with in-line flocculation, as the mixing of the white water with the raw water is a bit violent and would not be well supported by fragile flocs.

The third possibility is to perform the pressure relief directly in the central tank—Fig. 3.3c. In this case, a white water distribution ring installed in the central tank and equipped with nozzles or other pressure relief devices (e.g. several pressure relief valves) could be used. It may be advantageous to direct the white water towards the bottom of the tank rather than upwards in order to provide a confinement and deceleration space for the white water and to avoid a too violent mixing with the raw water. But the choice depends mainly on the pressure relief device, as nozzles or multiple pressure relief valves would require different implementations. Technically, this method of injecting white water is certainly the most efficient, but it is also the most difficult to operate because, in the event of clogging, access to the pressure relief devices is very limited and may even require emptying the tank.

3.1 Circular DAF Clarifiers with Surface Scraper

The surface scraper was the first mode of floated sludge recovery used on open circular DAF clarifiers*. It is still used by many manufacturers who have adapted this concept to different applications, feed modes and white water injection modes.

**Note: The word "open" is not there by chance, because in the 1950s Adka, Krofta and probably some other manufacturers built circular DAF clarifiers closed by a conical cover under which the floated sludge was accumulated in the upper part of the cone and overflowed through a weir. This technology has since been abandoned as it has too many disadvantages—too high a device because of the angle of the cone (of the range of 40–45°), fouling of the inner wall, difficulties of access and cleaning etc.—for only one advantage; no moving part or just a simple little wall scraper around the weir.*

The operation of a surface scraper is simple: the layer of floated sludge formed on the surface is pushed towards the periphery by the flow, but also by the scrapers provided for this purpose. Once it has accumulated towards the periphery of the flotation zone, it is picked up by rotating hinged scrapers that carry it back to one or more radial chutes where it overflows.

It is difficult to describe all the versions of circular surface scraper flotation systems available on the market. As always, each manufacturer has developed his own design of the scraper, the central tank, the white water injection system etc.… Nevertheless, one could define two groups of surface scraper DAF clarifiers according to the scraper drive mode: central drive and peripheral drive.

3.1.1 Central Drive Scrapers

Figures 3.4, 3.5 and 3.6 show conceptual drawings of three versions of DAF clarifiers with central drive surface scrapers. The DAF clarifier shown in Fig. 3.4 is equipped with a fixed through-bridge on which the drive reducer (3) is installed. The raw water and possibly white water is fed into the central column (1) which is fixed to the bottom. The raw water + white water mixture is diffused through the windows (2). The drive reducer (3) drives the central shaft on which a central frame (4) surrounding the central column (1) is hanging. This frame (4) supports the bottom scraper (5) equipped with scraping plates (6). This scraper is always symmetrical for mechanical reasons (balance), even if the small quantity of bottom sludge does not require such a scraping and removal capacity. The set of flights supports (8) with hinged flights (9) is also hanging from the central axis and rotates with the central frame (4) and the bottom scraper (5). The flights (9) push the floated sludge layer towards the floated

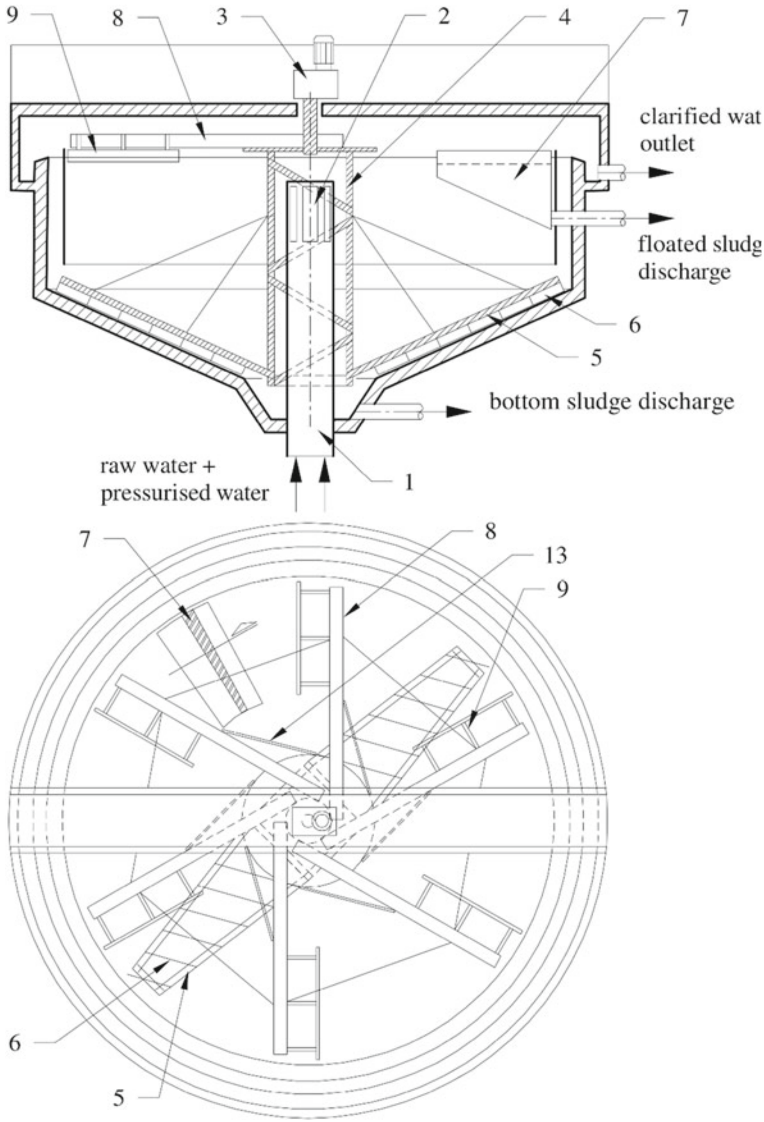

Fig. 3.4 Circular DAF clarifier with scraper and fixed central column. 1—central column, 2—distribution windows, 3—drive reducer, 4—central frame, 5—bottom scraper, 6—scraping plates, 7—floated sludge collecting channel, 8—flights support, 9—hinged flight, 13—fixed flight

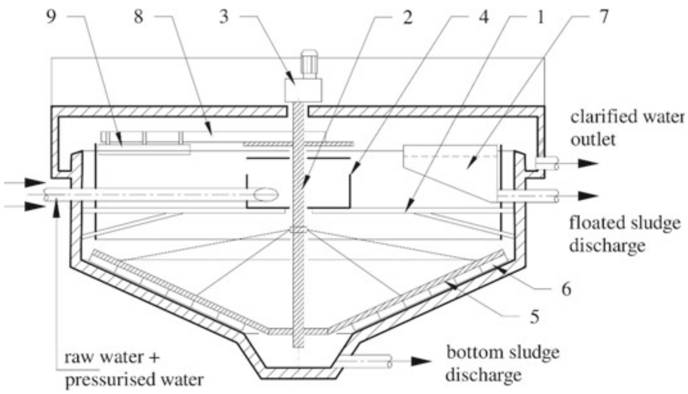

Fig. 3.5 Circular DAF clarifier with scraper and without central column. 1—central tank support, 2—drive shaft, 3—drive reducer, 4—central tank, 5—bottom scraper, 6—scraping plates, 7—floated sludge collection channel, 8—hubged flights support, 9—hinged flight

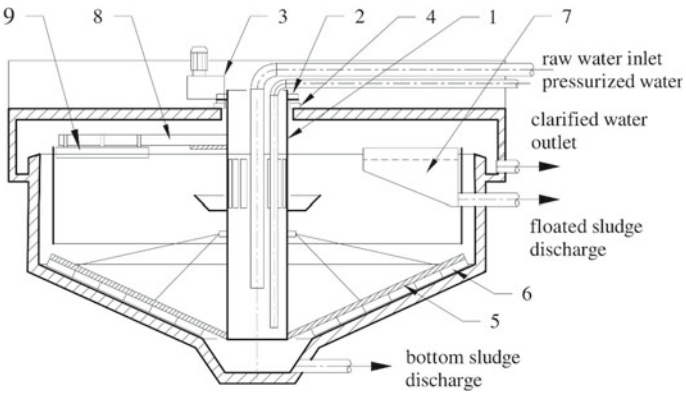

Fig. 3.6 Circular DAF clarifier with scraper and rotating central column. 1—rotating central tank, 2—central tank's rack, 3—drive reducer, 4—bearing, 5—bottom scraper, 6—scraping plates, 7—floated sludge collection channel, 8—hinged flights support, 9—hinged flight

sludge-collecting channel (7) which is fixed to the tank shell. The clarified water is collected under the peripheral submerged baffle and leaves the unit through the peripheral weir and the clarified water collection channel. The bottom sludge scraped by the bottom scraper is periodically flushed or pumped by a pump connected directly to the bottom sludge outlet pipe.

Figure 3.5 shows a vertical cross-section of a second version of the central drive scraper. Here the central tank (4) is not connected to the bottom, but is supported by supports (1). The raw water/white water mixture is fed through a pipe that leads directly into the central tank (4). There can also be two separate pipes—one for raw water and one for white water. In this case, the drive shaft runs through the bottom of the central tank (4) and down to the bottom to drive the bottom scraper. Compared to the version shown in Fig. 3.4, this solution allows for a larger diameter central tank and avoids the central frame. However, the central tank needs supports (1).

For both versions the weight of the moving part can be supported by the bearings of the drive reducer or by a separate bearing, external to the reducer. The first solution is more suitable for small DAF clarifiers of a few metres in diameter—usually less than 6 to 8 m in diameter. For larger diameter units it is more convenient to have an external bearing. A vertical section of a third version is shown in Fig. 3.6. In this case the central tank (1) rises above the fixed bridge and remains open. There is no central drive shaft—this role is fulfilled by the central tank itself. It rests on a large diameter bearing (4) which carries the entire weight of the moving part. The central tank is driven by a rack and pinion system consisting of a drive reducer (3) and a rack fixed to the periphery of the central tank.

This concept has two advantages over the two previous concepts:

– It allows the central tank to be kept open, and therefore the raw and pressurised water supply pipes can be brought down from the fixed bridge as shown.
– The implementation of this very robust support and drive system allows large diameter DAF clarifiers with heavy moving parts to be fitted.

Irrespective of how their scrapers are driven, DAF clarifiers larger than a few metres in diameter are often equipped with fixed flights (13) that push the floated sludge layer towards the periphery so that it can be picked up by the hinged flights (9) (see Fig. 3.4).

3.1.2 Peripheral Drive Scrapers

The conceptual diagram of a flotation unit with a peripherally driven scraper is shown in Fig. 3.7. In this case the fixed diametral bridge is replaced by a rotating bridge (10). This bridge (10) rests on a central bearing (11) located at the very top centre of the central column (1). The central frame (4) carrying the bottom scraper (5) is supported by the rotating bridge (10), as are all the flights supports (8). The entire moving part is thus hanging from the rotating bridge (10) which is driven by a drive reducer (3) located at the periphery of the bridge and by a drive wheel (12) running on a rolling surface (14).

As for the flight supports (8), there are two possibilities. For small diameter flotation tanks they are supported only by the central platform as shown in Figs. 3.4, 3.5 and 3.6. For large diameter flotation tanks, the external part of the flights supports (8) is supported by a single wheel running on the rolling surface (14). This solution makes their construction lighter and improves their rigidity.

Compared to the centrally driven scraper, this solution has its advantages, but also its disadvantages. The main advantage of this concept, especially with the flights supports supported on the periphery by individual wheels, is that it reduces the mechanical forces in the mobile construction considerably and makes it easier to drive large moving parts without the need for heavy and costly gearboxes (which is the case with the central drive). The torque supported by the bridge and the drive mechanism is much lower. The same applies to the peripheral drive motor gearbox—a central gearbox must be able to withstand considerable mechanical forces and have several reduction stages to provide a sufficiently slow rotation speed of the moving part. In other words, the central gearbox is very substantial in terms of size, weight and robustness. Compared to it the toy-like peripheral drive gearbox is much smaller, is sized for much lower forces and has, at worst, only two reduction stages. The cost is, obviously, much lower.

However, this concept requires some additional equipment such as:

– The installation of a rolling surface (14) for the drive wheel (12) and, possibly, also for the peripheral wheels of the flights supports.

– A rotating electrical slipring (not shown in the diagram) to power the drive reducer (3).
– A central bearing (11) on which the rotating bridge (10) rests.
– In addition, the central column (1) must rest on the bottom of the tank in order to support the central part of the rotating bridge.

Figure 3.8 shows in more detail the operation principle of a hinged flight (as shown in the cross-section through the floated sludge channel in Fig. 3.7 for a more complete view). The purpose of the scraper is to push the layer of floated sludge into the floated sludge collection channel (7). This channel is equipped with:

– An upstream beach plate (18) on which the hinged flight (9) slides while pushing a certain amount of sludge.
– Flights supporting bars (17) which prevents the flights from falling into the channel (7).
– A downstream beach plate (19) on which the flight (9) descends into the water.
– A side wall (20) at each end of the channel, the purpose of which is to prevent the sludge pushed by the flight onto the upstream beach plate (18) from flowing out on either side of the flight.

The flight (9) with its two, three or four hinged arms (depending on the length of the flight) is equipped with a neoprene lip (16) that provides a certain seal with the upstream beach plate (18) of the sludge channel (7) and also with the two side plates (20). It is supported by the flight support (8) through a hinge pin (14) allowing the flight to move up and down following the slope of the beach plates (18) and (19). A simple level adjustment device (15) allows the horizontality and level of each flight to be adjusted so that the end of the lip (16) is maintained slightly above the edge of the upstream beach plate (18) to prevent it from hooking the lower edge of the said beach plate as it moves horizontally through the water.

The assembly functions as follows:

As each flight moves through the water it pushes a certain volume of floated sludge as shown in Fig. 3.8a. On reaching the upstream beach plate (18) the neoprene

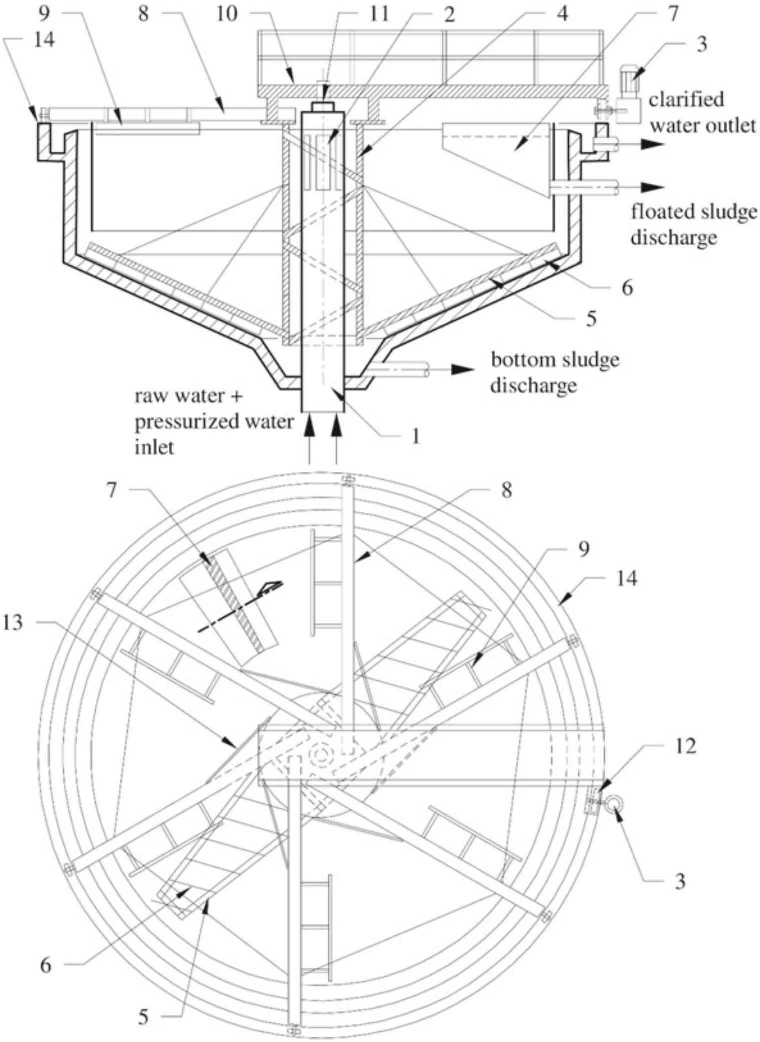

Fig. 3.7 Circular DAF clarifier with peripheral drive. 1—central column, 2—distribution windows, 3—drive reducer, 4—central frame, 5—bottom scraper, 6—scraping plates, 7—floated sludge collecting channel, 8—flights support, 9—hinged flight, 10—rotating bridge, 11—central bearing, 12—drive wheel, 13—fixed flight, 14—rolling surface

lip begins to slide along the beach plate 'enclosing' the volume of sludge trapped between the flight (9), the beach plate (18) and the two side plates (20) (Fig. 3.8b). This volume is pushed up the beach plate so that it can overflow into the channel (Fig. 3.8c). Then the flight slides on the flight supporting bars (17) over the channel, back down to the downstream beach plate (19) and returns to its horizontal position in the water.

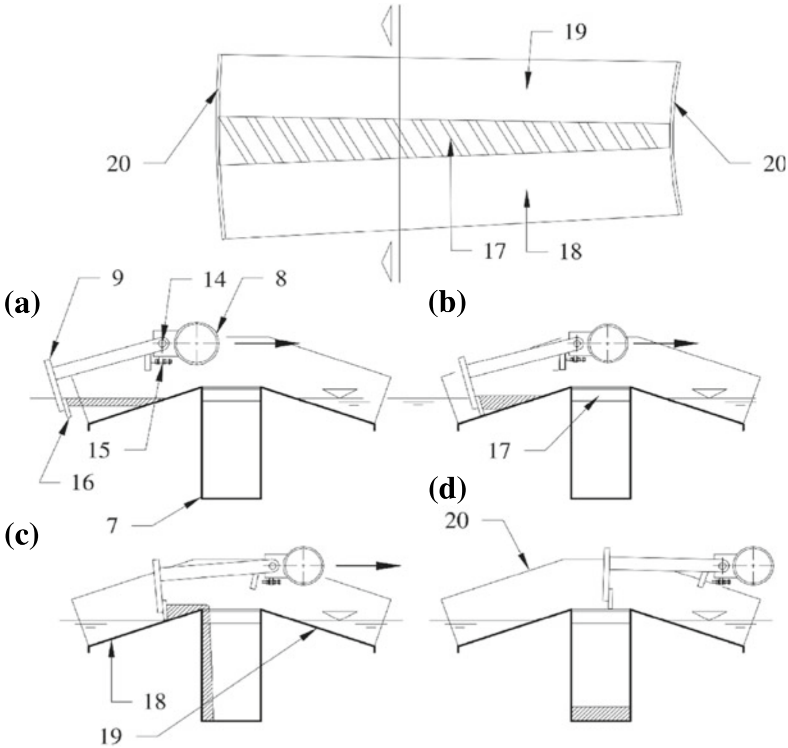

Fig. 3.8 Operation principal of a hinged flight. 7—floated sludge collection channel, 8—flights support, 9—hinged flight, 14—hinge pin, 15—level adjustment device, 16—neoprene lip, 17—flights supporting bars, 18—upstream beach plate

The size range of the surface scraper DAF clarifiers available on the market is very wide. The diameter varies from 2 to over 20 m. Units up to 6–8 m in diameter are usually equipped with a centrally driven scraper. Beyond that, both versions exist and each manufacturer has developed its own concept. The cylindrical depth of the tanks depends, of course, on the diameter and the application, but it usually varies between 1.5 and 2.5 m. It is lower for units operating in clarification on low-concentration water. However, for DAF clarifiers used for biological sludge thickening, the cylindrical depth can even exceed 2.5 m in order to be able to accumulate a 60 to 80 cm thick floated sludge blanket, without this layer disturbing the clarification and the good distribution of the sludge over the whole surface.

The slope of the bottom depends on the diameter and can vary from a few degrees to 20–25 degrees for small units.

What are the specifics of the design and operation of surface scraper flotation systems, apart from the scraper drive modes described above?

Firstly, by the very design of the surface scraper, the scrapers push the sludge layer, which increases in thickness as the scraper progresses, to the extraction point which is the sludge collection channel. Thus, if the DAF clarifier has only one sludge extraction channel, each volume of sludge, "hooked" by a scraper just after it passes through the sludge collection channel, will have to travel all the way around the flotation tank before it is extracted. It is important that this long journey is made in conditions of low turbulence to avoid deaerating the sludge by friction of the layers and losing flocs. But it also has its positive side: if the floated sludge blanket is very thick (more than 20–30 cm), as in the case of sludge thickening, the scraper pushes only sludge and the friction between the layers can contribute to a densification of the sludge as the harrow allows to better concentrate the sludge in a static settling thickener. It is often the case that, under all other equal conditions, this friction caused by the scrapers can slightly increase the concentration of the extracted floated sludge.

Secondly, the hinged flights of the scraper rarely cover more than the outer half of the radius of the tank. The reason for this is purely mechanical and lies in the design of the hinged flights and the beach of the floated sludge collection channel. The linear paths of the two ends (inner and outer) of the scraper are not the same. This poses a problem with the dimensions and angle of inclination of the beach, which, in theory, should change with the radius to keep the flight horizontal. These mechanical constraints are more or less manageable by small tricks in the support of the flight allowing a slight flexibility of the levelling as it ascends the beach, but the effect remains limited. This imposes the use of fixed flights (13) to push the sludge layer towards the outer area swept by the hinged flights (9).

Another important element is the sludge removal capacity of the hinged flights. If the angular velocity of the scraper remains the same at any radius during rotation, the peripheral linear velocity will increase as the radius increases. It is obvious that the scraping speed should not exceed certain limits, as too fast a speed of the scraper would create excessive turbulence in the sludge layer and could cause partial destruction of this more or less fragile layer. In addition, a too fast speed of ascent of the floated sludge on the upstream beach plate would deprive the scraper of one of its main advantages, especially in the clarification of low concentrated waters, which is to leave the possibility of "draining" the water from the sludge during the ascent of the latter on the slope of the beach plate. Indeed, if the flight encloses an always identical volume against the upstream beach plate, it often happens that this volume is composed of an upper layer of sludge and a lower layer of water. If the scraper rises slowly, the water will have time to flow under the neoprene lip (which is only relatively watertight…), while the sludge, which has a certain mechanical structure and a much higher viscosity than water, remains trapped between the scraper and the beach. This allows the water to be "drained" so that only the sludge is discharged, resulting in a higher concentration of the extracted sludge. It is therefore important that the flights moves slowly up the slope of the upstream bank with a maximum speed of no more than a few centimetres per second. The maximum "acceptable" speed depends, of course, on the properties of the sludge and the strength of the sludge blanket, but, as a guide, rarely exceeds 5–6 cm/sec at the edge of the scraper. In practical terms this means that a flight on a DAF clarifier of, say, 5 m diameter, could make one complete revolution in about 300 s. For a 15 m diameter clarifier, using the same peripheral speed of the flight (5 cm/sec), the complete revolution will take about 900 s, or three times longer.

This constraint leads to a limitation in sludge removal capacity. Under all other equal conditions, the extraction capacity of each scraper remains more or less the same per linear metre of flight, whereas the capacity of the DAF clarifier, and thus the amount of sludge to be extracted, increases with the square of the radius. One can therefore conclude that:

- The angular speed of the scraper rotation should logically decrease with increasing the tank diameter, so as to limit the peripheral speed of the flights. In order to maintain the sludge removal capacity of the flotation system, the number of flights must be increased.
- As the concentration of TSS at the inlet increases (and therefore the amount of floated sludge to be removed increases), the number of flights must be increased to ensure that all the produced sludge is removed.

Therefore, the combination of the two factors (large diameter flotation tank producing a lot of floated sludge) can result in more than 20 flights on a large diameter tank. This problem can be partially solved by increasing the number of floated sludge collection channels. For example, it is not uncommon to find circular DAF clarifiers with a surface scraper equipped with two, three or even four sludge collection channels. This allows the number of flights to be reduced and the already heavy mobile part to be lightened. On the other hand, this solution leads to a multiplication of sludge collection points around the clarifier, which is more restrictive to manage. If the sludge is thick and the distances are significant, it will be risky to hope for reliable gravity collection at a single point. It would be safer to have several sludge pumping stations or pipes with a steep slope and therefore deep enough to reach a single collection point.

Surface scraper circular DAF clarifiers can be used for both clarification and sludge thickening, provided that the constraints of the scraper extraction capacity are respected, which may be a limiting factor in some cases. The example of a theoretical calculation below gives an order of magnitude of the maximum extraction capacity of such a unit:

Assuming a slope of the upstream bank of about 15° and a 15 cm immersion of the scraper (which still makes upstream banks of more than 1 m), one can expect to scrape (theoretically, without taking into account the inevitable leaks) a maximum of 40 l of sludge per linear meter of flight. For a 20 m diameter flotation tank and 5 m long flights this would be approximately 200 L per flight and per scrape. Therefore, for a DAF clarifier with a single floated sludge collection channel and 20 flights (which is a lot!), travelling at a peripheral speed of 6 cm/sec or about 17 min for a complete revolution, which represents about 70 scrapes per hour, a maximum of 14 m^3 of sludge per hour can be discharged. On this basis the maximum SS loading of this type of DAF clarifier in clarification and sludge thickening can be roughly estimated. In clarification, with a hydraulic load of 6 m/h net, such a 20 m diameter DAF clarifier can handle a flow rate of about 1800 m^3/h. If we estimate the concentration of floated sludge at 4% (which is a pretty good value), the 14 m^3 of sludge scraped per hour will correspond to a quantity of sludge of 14 × 40 kg/m3 = 560 kg/h, i.e. a concentration of 560:1800 = 0.311 kg/m^3 (i.e. 311 mg/l) of TSS in the raw water only. In sludge thickening this corresponds to a SS load of 560 kg/h:300 m^2 surface area = 1.87 kg/m^2 h. If the same approximate calculation is made for a 12 m diameter clarifier, under the same conditions (with the same number of flights, the same limitation of the peripheral speed of the flights of 6 cm/sec and a depth of the flight of 15 cm), one will obtain an extraction capacity of the range of 11 m^3 of sludge per hour, i.e. a maximum of 440 kg/h of sludge at 4% or 660 mg/l of TSS at the inlet and, respectively, 3.89 kg/m^2 h in thickening.

What conclusions can one draw from this example? There are two:

- This rough calculation may be disputable in view of the specificities of the different design modes and types of scrapers available on the market, but it gives an order of magnitude and demonstrates that the limitation of the peripheral speed of the scraper strongly affects the scraper extraction capacity of large DAF clarifiers compared to small ones. Theoretically, for sludge thickening, it would be advantageous to use several small DAF clarifiers rather than one large unit. The same applies to clarification—large DAF clarifiers are only suitable for water with low TSS content.
- It is obvious that the values calculated above can be doubled or tripled simply by adding several floated sludge extraction points, i.e. one or two additional sludge collection channels. However, this makes the DAF clarifier even more cumbersome to build and raises the already mentioned problem of collecting the floated sludge when there are several extraction points.

Finally, it should also be remembered that surface scrapers require regular maintenance, especially the neoprene lips of the scrapers. If they are deformed or worn, they will quickly lose their water tightness and the extraction capacity of the scrapers will decrease rapidly.

3.2 Circular DAF Clarifiers with Spiral Scoop and Central Inlet

3.2.1 The Spiral Scoop

First of all, let's briefly recall what a spiral scoop is.

The collection of floated sludge by a spiral scoop was popularised in the 1960s by Krofta. This device was a great success and quickly became a reference in the field. It greatly simplified the construction of circular DAF clarifiers and greatly improved the simplicity and reliability of the floated sludge collection.

The design philosophy of the spiral scoop is, in some ways, the opposite of the surface scraper system. Scrapers push the sludge layer to a fixed extraction point, whereas the spiral scoop is itself a mobile extraction point. It scoops portions of the sludge layer over the entire surface of the clarifier like a spoon, without pushing or stirring the sludge which remains stationary. The scooped sludge is discharged into a central funnel for disposal.

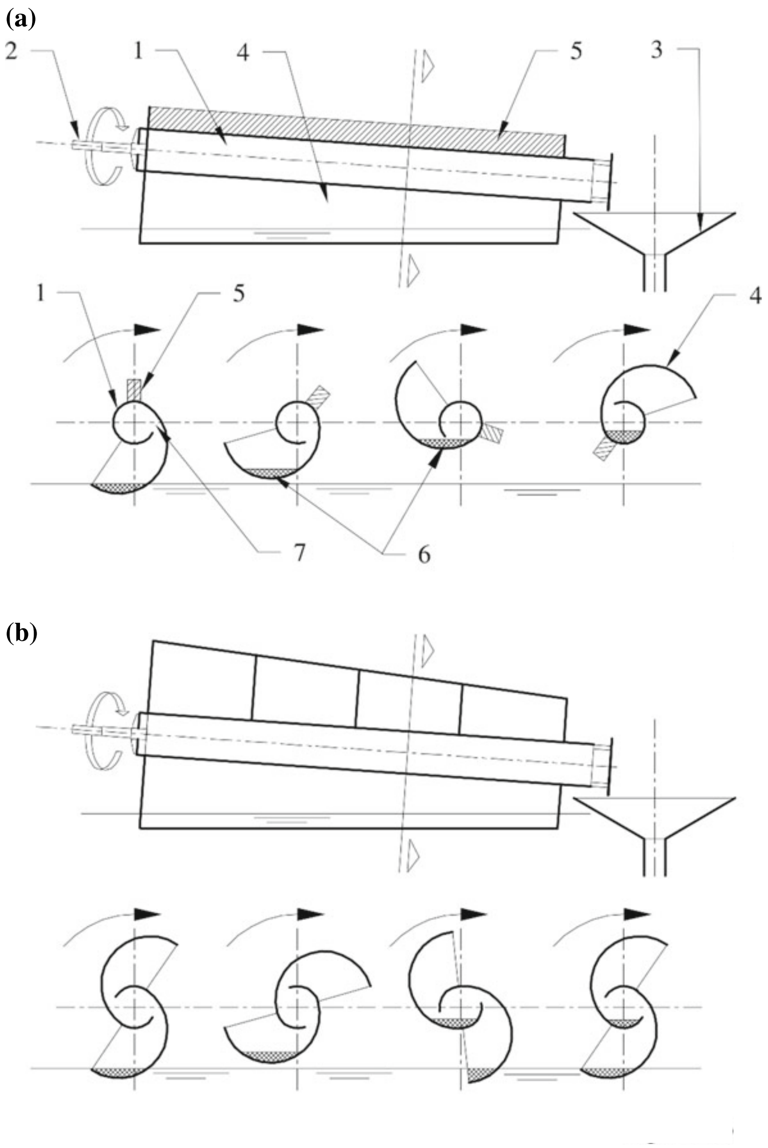

Fig. 3.9 Spiral scoop. 1—central tube, 2—drive shaft, 3—sludge funnel, 4—spiral scoop, 5—counter-weight, 6—scooped sludge volume, 7—discharge slot

Early scoops had a single spiral scoop (4) like the one shown in Fig. 3.9a. A counterweight (5) balanced the whole assembly with respect to the axis so that the rotation of the scoop was balanced at all times. Very soon the double scoop appeared, offset by 180°, as shown in Fig. 3.9b. Its advantages over the first version are obvious: firstly, the scoop is naturally balanced and secondly, it doubles the extraction capacity. On the same principle, triple scoops are also built, offset at 120°. This version is mainly reserved for large clarifiers—usually over 12 m in diameter.

The scoop is positioned radially above the water surface and operates as shown in the successive diagrams (according to the cross-section), located below the overview. It is rotated by the drive shaft (2) and rotates around the axis of the central tube (1).

At each pass the end of the spiral scoop (4) penetrates the sludge layer and scoops a certain volume of sludge (6). This volume depends of course on the level of the sludge blanket—the closer it is to the central tube (1), the greater the volume scooped by the scoop. As the spiral scoop (4) rotates, the volume of sludge (6) gradually rises towards the central tube (1). A discharge slot (7) along the central tube (1) allows this volume of sludge (6) to pass into the tube. As this central tube is inclined towards the sludge funnel (3), the sludge flows by gravity into the said funnel. The device is designed in such a way that the speed of rotation of the spiral scoop, taking into account the angle of inclination and the length of the central tube (1), allows sufficient time for the volume of sludge (6) to flow into the funnel (3), before the discharge slot (7) is again at the bottom of the central tube.

The extraction capacity of a spiral scoop depends on several factors:

– The diameter of the scoop, i.e. the diameter of the central tube and the diameter of the spiral spoons.
– The angle of inclination of the centre tube—the greater the angle, the faster the sludge in the central tube is removed.
– The number of spoons (2 or 3 spoons).
– The depth of the immersion of the spoons in the floated sludge layer. In other words, the level of the sludge layer in relation to the spiral scoop—the "higher" the layer, the greater the volume scooped by the spoons.
– The speed of rotation of the scoop—the faster it rotates the more sludge it scoops over time.

By combining all these variables it is possible to achieve a very high extraction capacity which is sufficient to cover practically all cases and applications of dissolved air flotation with a single spiral scoop.

For example, the standard spiral scoop of a 4 m diameter DAF clarifier can extract 14m^3 of sludge per hour in normal operation without being pushed to the limit. The triple scoop of a 20 m diameter clarifier can easily extract up to 250–300 m^3 of floated sludge per hour. It is obvious that this extraction capacity has nothing to do with the 14 m^3/h per extraction channel of a surface scraper of the same diameter (see calculation in the previous section).

This high extraction capacity of the spiral scoop offers many advantages. Firstly, only one scoop is needed to cover all situations. Secondly, the spiral scoop removes the sludge without pushing it and without creating turbulence, so there is no risk of destruction of the sludge layer, deaeration and floc loss. Thirdly, it offers the possibility, by a simple adjustment, to vary the depth of immersion along the radius—more on the outside or more on the inside of the tank. This can be of interest for sludge thickening applications where the thickness of the floated sludge layer is not quite even across the radius of the flotation tank. In fact, adjusting the depth of immersion of the scoop along the radius is always advantageous if maximum concentration of the floated sludge is to be maintained.

However, it should be pointed out that, apart from all its advantages, the spiral scoop has one disadvantage compared to the surface scraper system—it does not drain the water from the sludge layer. As it rotates it dives to a fixed depth and scoops a fixed volume without distinguishing between water and floated sludge. If the layer of floated sludge is, say, 5 cm thick and the scoop dives to 10 cm, it will ultimately scoop out about 55% sludge and 45% water, which will reduce the concentration of the extracted floated sludge by the same amount. Therefore, when thickening sludge on a spiral scoop DAF clarifier, it is necessary to ensure that the scoop does not scoop water, while scooping the volume of sludge produced. In theory, such a precise adjustment is impossible to achieve in steady state conditions as it would mean extracting, through the scoop, exactly the same volume as the volume of sludge actually produced by the DAF clarifier, which, by definition, inevitably varies with variations in raw sludge concentration, flow rate, sludge characteristics etc.… So, if the scoop scoops a little more than the volume of sludge produced, it will eventually exhaust the sludge layer and start to scoop a little water. And conversely: if the spiral scoop scoops less than the volume of sludge actually produced, then the flotation tank will end up being filled with sludge and the balance will be made by losing sludge with the clarified water, the quality of which will inevitably be degraded. So if one is looking to thicken sludge, one has to choose—either one or the other. Either accept a small risk of dilution of the floated sludge, or accept a slightly degraded quality of the clarified water from time to time.

In reality the situation is somewhat less dramatic than the theoretical situation described above. The main reason for this is that as it accumulates in a thicker and thicker blanket the concentration of the upper part of the sludge blanket increases slightly due to the air trapped in the lower layers continuing to push upwards, which over time allows for a slight drainage of water and some compaction of the upper sludge blanket. Therefore, the thicker the sludge blanket, the higher the concentration of scooped sludge. The phenomenon can occur in different proportions depending on the characteristics of the sludge, but in the majority of cases it acts as a regulator, within certain more or less narrow limits, of the quantity of scooped sludge. When one speaks of the scooped quantity, one means of course the weight in terms of dry matter, more or less concentrated in the same volume, depending on the thickness of the sludge layer.

The other, more elegant solution is to install a measurement of the thickness of the floated sludge blanket and to control the extraction by this measurement. Probably the most reliable measurement is provided by ultrasonic probes with transmitter and receiver located at a certain distance (15–20 cm) from each other, which are specifically designed for the detection of density change of the liquid medium. The automation consists in accelerating the rotation speed of the scoop when the probe, which is immersed at a given depth in the sludge layer, passes from water into the sludge. Conversely, the speed of rotation of the scoop is reduced when the probe moves from the sludge into the water. Good results can also be obtained with optical sensors, but the latter seem to be more sensitive to changes in the sludge colour and to soiling and require more regular maintenance.

3.2.2 *The Clarifiers*

Figure 3.10 shows a typical spiral scoop DAF clarifier. The device shown has a concrete outer tank (bottom and shell) and a metallic central tank (1). Other designs are also possible: concrete bottom with metallic shell and centre tank, or concrete bottom, shell and centre tank. Finally, the unit can be entirely metallic, including the bottom, but this option is mainly reserved for small units not exceeding a few metres in diameter. The raw water + white water mixture arrives in the central tank (1), which can have a larger or smaller diameter depending on the volume required to ensure a possible flocculation time. The floated sludge is scooped out by the spiral scoop (2) driven by the drive reducer (3), which is almost always powered by a frequency inverter for more flexibility of the extraction setting. The spiral scoop is mounted radially on a rotating bridge (4) driven by a drive reducer (9) which rotates the drive wheel (12) of the bridge (4).

The clarified water is collected at the periphery, rather towards the bottom of the tank, by a clarified water collector (6). The collector shown in the diagram is made of standard tubes forming an octagonal ring. This is the most economical solution and is suitable for small DAF clarifiers up to about 6-8 m in diameter, depending on the flow rate being treated. Larger DAF clarifiers are fitted with triangular or trapezoidal collectors. These collectors are rounded and are fitted against the shell. The cross-section of the clarified water collector (6) is always variable—it increases on the side of the adjustable weir (5). The aim is to maintain a certain water velocity in the collector to avoid settling and fouling inside the collector. This clarified water collection assembly (collector (6) and adjustable weir (5)) is better suited to spiral scoop DAF clarifiers than the simple peripheral weir such as those of the scraper DAF clarifiers, because the weir (5) is adjustable and, unlike the peripheral weir which is always fixed, allows the level of the sludge layer to be varied easily, compared to the spiral scoop, whose level remains invariable, since it is placed on the rotating bridge (4). It is important that the clarified water collection orifices located at the bottom along the clarified water collector (6), as well as the cross-section of the said collector, are properly sized according to the DAF clarifier's feed flow rate and, above all, the possible variations in this flow rate. This is because these clarified water collection orifices, as well as the collector itself, create head losses which inevitably vary the level of the floated sludge layer and therefore influence the volume scooped at each rotation of the scoop. To reduce these head losses it would be advantageous to increase all the cross-sections, but this would enlarge the collector and increase the

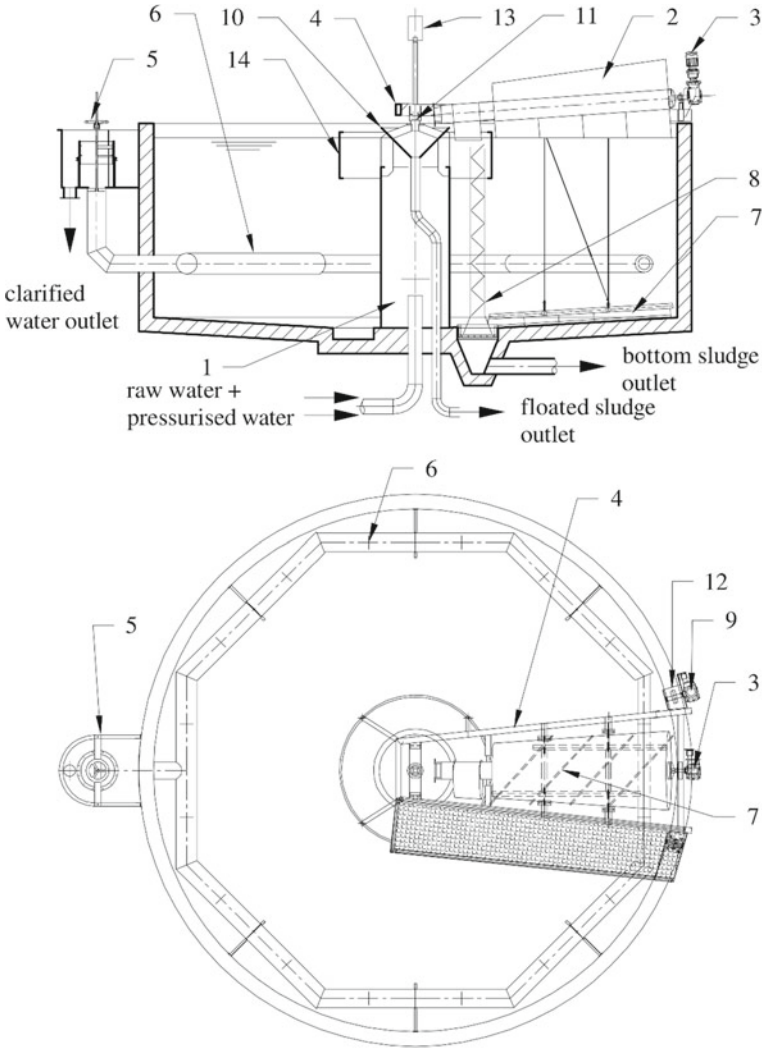

Fig. 3.10 Circular DAF clarifier with spiral scoop. 1—central tank, 2—spiral scoop, 3—scoop drive reducer, 4—rotating bridge, 5—adjustable weir, 6—clarified water collector, 7,8—bottom scraper, 9—bridge drive reducer, 10—floated sludge cone, 11—central bearing, 12—drive wheel, 13—rotary contact, 14—inlet well

risk of settling and fouling inside it, especially when the DAF clarifier is underfed. Conversely, a small section collector would maintain a good self-cleaning velocity of the water, but would force the operator to intervene to vary the scoop rotation speed, the water level (through the adjustable weir), or both, at each significant variation of the feed rate. At the same time, if the water composition is relatively constant in terms of TSS concentration, if the flow variations are relatively moderate and if the weir-collector assembly is well designed, then the level variations, caused by the flow variations, will be able to compensate for the scooping depth of the spiral scoop. It will scoop more sludge when the flow increases and less when it decreases, so as to obtain a sort of self-regulation of the floated sludge extraction.

The bottom scraper (7) and the internal scraper (8) are simply hanging from the rotating bridge (4). The depth of the tank of this type of DAF clarifiers is in the range of 2 to 3.3 m depending on the diameter. The bottom is slightly inclined so as not to complicate the civil works.

This type of spiral scoop DAF clarifiers works very well in clarification of all kinds of wastewater, but is particularly well suited to the biological sludge thickening. The depth of the floated sludge layer can be up to 1.2 m thick, without any risk of degradation of the clarified water quality. It is ideally suited to automated floated sludge removal with ultrasonic probes.

Another “simplified” version of the same concept is shown in Fig. 3.11. This is mainly reserved for small diameter metallic units—less than 6 m in diameter. The depth varies from 1 to 1.5 m depending on the application and diameter. Smaller units less than 4 m in diameter have only one reducer driving the spiral scoop. The bridge drive wheel is mounted on the scoop shaft and moves the bridge with the rotation of the scoop. These shallow depth devices are well suited to industrial effluents—paper mills, food processing, oil. However, they also work well in biological sludge clarification with polymer. For operation without polymer it is preferable to opt for the first version (see Fig. 3.10) with a deeper tank and water distribution behind an inlet well (14).

Finally, circular DAF clarifiers are almost always fitted with bottom scrapers as they are well designed for this purpose. This is far from being the case with all rectangular DAF clarifiers, which, on the contrary, are rarely equipped with bottom scrapers. Inverted pyramids and screw conveyors are used much more often, sometimes with limited success… Because bottom sludge always accumulates over time, and a scraper remains the benchmark for efficiency. There are even cases where the recovery of bottom sludge is almost as important as the proper functioning of the flotation. For example, a pulp preparation plant in a paper mill using recycled paper can generate an impressive amount of bottom sludge containing sand, soil, small pieces of plastic etc., which is not welcome either in the flotation recovered fibres or in the clarified water that is recycled, at least partially, in the manufacturing process.

Generally speaking, circular DAF clarifiers have their advantages especially in wastewater treatment and sludge thickening applications. Their design is not very advantageous for the clarification of drinking water. The problem is mainly with the coagulation and flocculation stages—they require a long residence time which their central tank cannot provide. And an external coagulation/flocculation tank poses the problem of transferring the flocculated water to the centre of the DAF clarifier, as the floc is often very fragile and, as already mentioned, requires transfer velocities of less than 25–30 cm/sec, and therefore large cross-sections. Injection of pressurised water directly into the central tank is not always easy for accessibility reasons. The Haymore pressure relief valve offers a partial solution to this problem, but it is still limited in length. Above all, the injection of the pressurised water is still quite

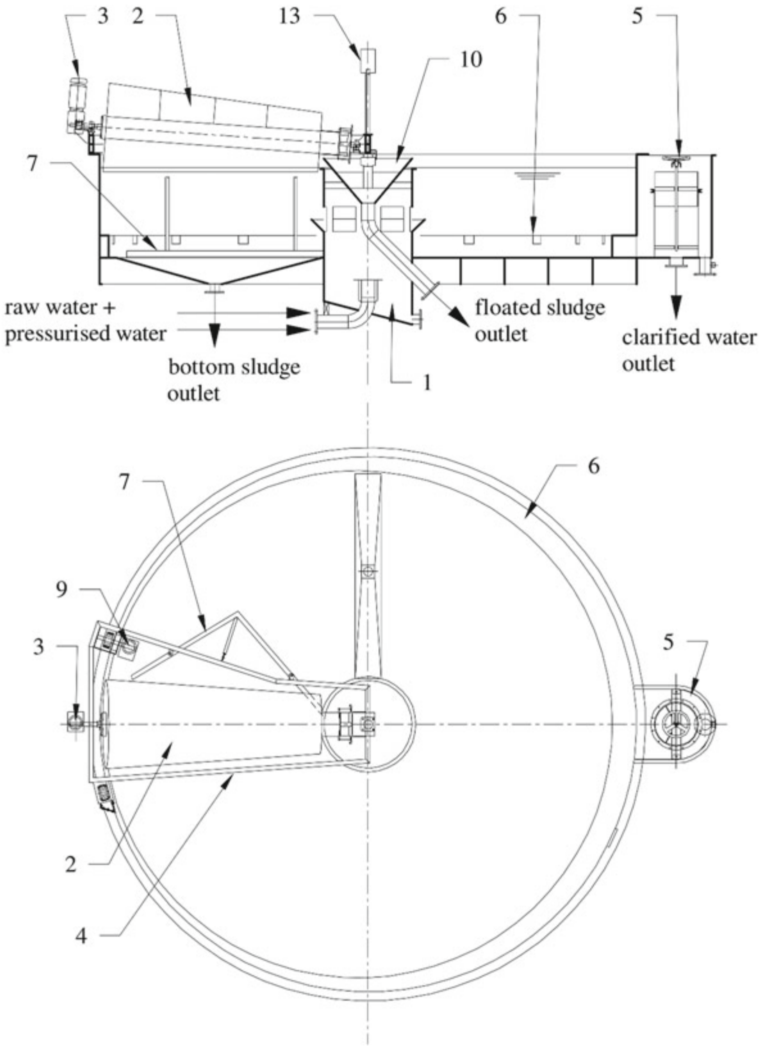

Fig. 3.11 Circular DAF clarifier with spiral scoop and shallow tank. 1—central tank, 2—spiral scoop, 3—scoop drive reducer, 4—rotating bridge, 5—adjustable weir, 6—clarified water collector, 7—bottom scraper, 9—bridge drive reducer, 10—floated sludge funnel, 13—rotary contact

violent and the quality of the white water obtained on expansion may be a little low for drinking water applications. On the other hand, circular units are well suited for in-line flocculation, which is often used in wastewater. The short flocculation time of a few tens of seconds, provided by the central tank, is sufficient in most cases. In addition, the flocs form in presence of the air bubbles that are easily trapped inside the flocs when they form, which is a boon for flotation. The injection of pressurised water into the inlet pipe is also better tolerated by wastewater, which contains more organic matter, thus better preserving the integrity of the air bubbles and reducing coalescence in the pipes.

3.3 Circular DAF Clarifiers with Spiral Scoop and Radial Inlet

These radial DAF clarifiers were developed by Krofta in the mid 1970's mainly for the paper industry for fibre recovery from white water and also for effluent treatment. Over the years these clarifiers have been so successful (several thousand units installed in 40 years) that they have been used, sometimes inappropriately, in almost all applications of dissolved air flotation. What is the reason for this success? There are multiple reasons. The highly innovative technological concept of these machines allows the depth of water in the flotation tank to be reduced to just 40 cm. This shallow depth offers many advantages and impresses not only users, but also water treatment specialists, who are not used to such shallow depths for any type of clarifier. Also, compared to the well-known "classic" flotation clarifiers, whether rectangular or circular, the operating principle of these clarifiers, known as the zero velocity principle, gives them an "avant-garde" technical side that is somewhat flattering and is a marketing advantage in of itself, apart from the other, more real advantages of this technology.

What is the zero velocity principle? Let's imagine any "classic" clarifier that will necessarily have a fixed water inlet and a fixed outlet for the clarified water. In this case the clarification, i.e. the separation of the solids from the water, takes place during the flow of the water between the inlet and the outlet. It is obvious that this flow of water between the inlet and the outlet must be as unturbulent as possible so that the separation of the two phases can take place without too much turbulence disturbing the water at any point along the way. And there are not many solutions to this problem, except to reduce the flow velocity of the water to a minimum (economically acceptable) by increasing the cross-sections. In "conventional" unassisted DAF clarifiers this concept usually leads to fairly large flow cross-sections with depths in the range of 1.2 to 2.5 m or more, and water flow velocities of a few millimetres per second.

Let's now imagine the problem in reverse: if, instead of moving the water between a fixed inlet and outlet, one moved the inlet and outlet so that the water did not have to move. What if one could have a circular channel in which a combined 'inlet/outlet' device was arranged to rotate in this channel. The raw water is introduced into the channel from one side of the device, through the inlet, and the clarified water is collected just behind this inlet. If this "inlet/outlet" device were stationary, the water introduced through the inlet would have to go around the channel to reach the outlet. However, if the inlet/outlet device rotates in the opposite direction to the direction in which the water is introduced and at the same velocity as that at which the water leaves the inlet device, then each volume of water, introduced somewhere

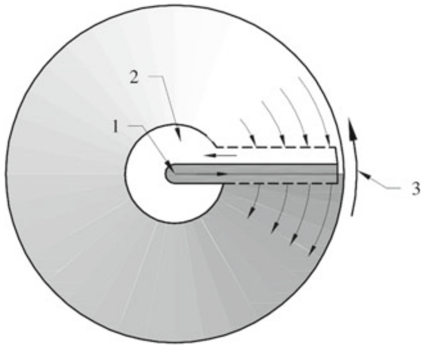

Fig. 3.12 Zero velocity principle schematic presentation. 1—inlet device, 2—outlet device, 3—bridge rotation sense

in the circular channel, will no longer be forced to move towards the outlet, since it is the outlet that will approach it. This is the so-called of zero velocity principle resulting in the addition of the velocity at which the water enters the channel and the velocity at which the inlet (and therefore also the outlet) moves backwards in the opposite direction. It is illustrated in Fig. 3.12 showing how dark raw water clarifies over time in the circular channel before leaving it.

The inlet device (1), fed from the centre of the unit through a rotary joint, is integrated with the clarified water outlet device (2). The water is introduced in a clockwise direction and the inlet/outlet device rotates in the opposite bridge rotation direction (3). If the speed at which the water is introduced is equal to the speed at which the said device moves backwards, then the two speeds cancel each other out. As a result, the water does not have to move along the channel. It will remain where it was introduced by the inlet device (1) until the outlet device (2) comes to collect it. There is no longer any flow of water in the channel since the problem is solved by the zero velocity principle. Consequently, the need for a large cross section, with a corresponding depth, is no longer relevant. A minimum water depth of 40–45 cm is sufficient to place the clarified water collectors and the spiral scoop, while still ensuring a distance of about 35 cm (in terms of depth) between the collection levels of the two phases, which is sufficient.

What is special about these clarifiers ?

Firstly, they require setting the speed of the carriage carrying the "inlet/outlet" assembly. This setting is based on the flow rate into the unit (raw flow rate + pressurisation flow rate). The philosophy of the setting is very simple—the volume of water in the tank should be exchanged for the time of one full revolution of the carriage. For example, the floatation zone of a 10 m diameter, 40 cm deep clarifier contains a volume of approximately 28 m^3, (excluding the central clarified water part). If the inflow is 500 m^3/h and the pressurisation flow is 100 m^3/h (i.e. 600 m^3/h in total), then the carriage will have to make $600: 28 = 21.4$ revolutions per hour, i.e. one revolution in $60: 21.4 = 2.8$ min (168 s). Moreover, this very short residence time of the water (which can go down to 150 s at maximum hydraulic load) is certainly exceptional, but it corresponds well with the shallow depth of the water in the tank. Indeed, the rising velocity of the bubble cloud in a pressurised water sample is rarely less than

20 cm/min, which is sufficient to overcome a water depth of 40 cm in 2 min. This setting can be done manually, as a 10, or sometimes even 15% error, hardly influences the proper operation of the unit in the vast majority of cases. However, it is preferable to have an electromagnetic flowmeter on the raw water and to have the rotation speed of the carriage controlled by a frequency inverter. The pressurisation flow rate is fixed and must be integrated into the calculation of the total flow rate measured by the flow meter.

Secondly, this concept, in its various historical and current forms of implementation, requires that all the floated sludge produced at the end of the rotation cycle is scooped out under all circumstances. Otherwise the sludge blanket would increase in thickness and fill up the thin water layer very quickly, before exiting through the clarified water collectors. There is no room to accumulate a sludge layer in 40–45 cm of water depth. The direct consequence of this constraint is the need (dictated by common sense…) to adjust the unit so as to always scoop all the sludge plus a little water, even at maximum mass and hydraulic load, to be sure not to accumulate sludge under the scoop. This makes it above all a clarification apparatus and not a sludge thickening apparatus.

Figure 3.13 shows a schematic diagram of the most common version of this clarifier. Figure 3.13c and d show just the feed part for clarity. The raw water + white water mixture enters the central water inlet column (17). The rotary joint (12) feeds the radial distribution header (10) equipped with distribution control flaps (20). The water then passes into the stilling compartment (16) which is equipped with orientation channels leading into the flotation zone. The clarified water is collected by the collectors (14) which return it to the central part formed by the rotating wall (4). The water level is regulated by the adjustable weir (21) provided in most units. The layer of floated sludge, formed progressively along the cycle, is scooped by the spiral scoop (8). The bottom and tank wall (1) are continuously cleaned by neoprene lips (not shown). Units larger than 12–13 m in diameter are usually equipped with a double rotary joint coaxial with the rotary joint (12). This second rotary joint allows pressurised water to be fed under pressure to the rotating carriage (5). The pressure relief is then achieved by multiple valves injecting the white water directly into the stilling compartment (16), which in this case also acts as a contact zone. This option reduces the coalescence of air bubbles in the long pipework and distribution header (10) and, indirectly, reduces the pressurisation rate and the energy cost, which becomes important for large size units. This is because this clarifier is available up to 21 m in diameter with a raw flow rate of more than 2000 m3/h. The sizing values in terms of raw water hydraulic load are in the range of 6 to 7.5 m/h for a SS load not exceeding 10–12 kg/m^2.h, up to 14–15 kg/m^2.h in clarification of cardboard and de-inking effluents.

This technology offers several advantages which, when properly implemented, make it a classic in industrial effluent clarification. The clarifiers are very light (maximum load 700 kg/m^2) and can be installed on a simple slab and even on some roofs. However, the most common installation is the metallic support of about 2–2.4 m height, which has the advantage of leaving the space under the unit completely

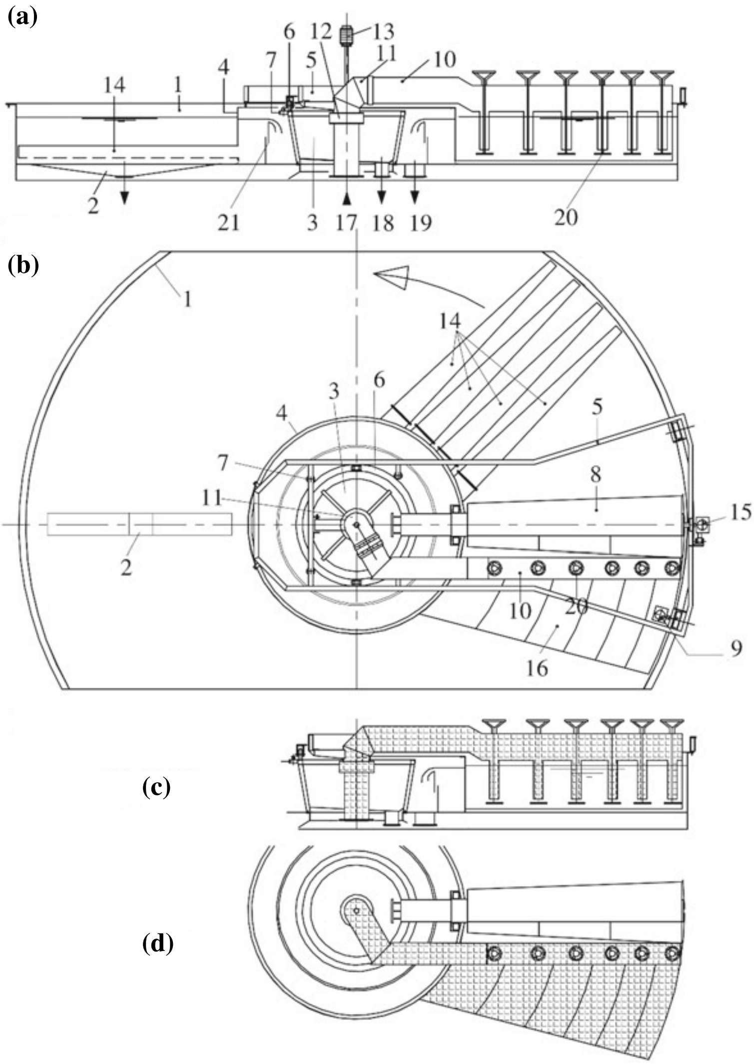

Fig. 3.13 Circular DAF clarifier with radial water inlet and outlet. 1—tank, 2—bottom sludge channel, 3—central floated sludge tank, 4—rotating wall, 5—rotating carriage, 6—central rolling surface, 7—centring wheels, 8—spiral scoop, 9—carriage drive reducer,10—distribution header, 11—rotating elbow, 12—rotary joint, 13—rotary contact, 14—clarified water collectors, 15—scoop drive reducer, 16—stilling compartment with flow orientation channels, 17—raw + pressurised water inlet, 18—floated sludge outlet, 19—clarified water outlet, 20—distribution control flaps, 21—adjustable weir

available for pressurisation equipment, floated sludge collection, chemical preparation and dosing, etc. The length of piping is also reduced to a strict minimum. These DAF clarifiers are also very easy to drain and clean due to the very low water volume and accessibility, which is very much appreciated by paper mill operators who often change their production and colour. With regard to colour changes in paper mills (when the DAF clarifier is used for fibre recovery in the white water), the "piston" mode operation allows, in certain cases, to change colour without stopping or draining the unit. On a well-tuned unit the change from one colour of floated sludge to another is almost perfect in just 60° of carriage travel.

There are, however, some details to bear in mind about these clarifiers. It should be remembered that this technology was developed by paper makers for applications mainly in the paper industry. Fibre recovery from white water, clarification of pulp preparation and deinking plant effluents, clarification of mixed mill effluents are the classic applications of these DAF clarifiers. They are mainly operating with in-line flocculation, whether for paper or food processing effluents or for biomass clarification in biological treatment. Sludge thickening is not their main function, it is clarification. They are also not best suited for drinking water clarification or, more generally, for clarifying "clean" water after a long coagulation/flocculation process resulting in fragile flocs, even though there are references of such clarifiers in clean water preparation for industrial use that work well. The reason for this is the distribution device at the inlet which creates strong turbulences destroying any fragile floc. Of course, it is always possible to partially reconstitute these flocs in the stilling compartment, but this requires a clear polymer overdosing which is not really acceptable in many cases. In any case, this is an application to be avoided as is biological sludge thickening.

Chapter 4
Rectangular DAF Clarifiers with Non-assisted Clarification

These are the simplest and most basic DAF clarifiers and probably constitute the largest number of installations. There are several reasons for their commercial success:

– With few exceptions, they are almost always small flow units—up to 60–80 m^3/h, 120 m^3/h at most for the largest of them. This range is far from covering all the potential applications of dissolved air flotation technology, but it does correspond to the small flow rates which are by far the majority of cases in the treatment of industrial effluents, such as the various food, pharmaceutical and cosmetic industries, where one of the treatment stages is very often clarification by flotation, whether in primary treatment, clarification after biological treatment on fixed cultures, or in tertiary treatment.
– Their metal tanks, shapes and dimensions are suitable for road transport, which means that the equipment can be delivered to the site fully assembled in the workshop and ready to use, or nearly so. In any case, the on-site work is very limited.
– Compared to circular DAF clarifiers, their shape requires less surface area and is better suited to industrial buildings, which are generally rectangular.
– The design allows for one or more successive pH correction, coagulation and flocculation tanks to be added to the DAF clarifier, which is more complicated with a circular DAF clarifier. This is a great advantage if there is a lack of space or if there is any reason to have an all-in-one unit.

Hydraulically, the operating principle of these clarifiers is simple: the water enters the flotation tank at the beginning through a flow distribution device, passes through the flotation zone in which clarification takes place, passes under a syphoid wall located at the opposite end of the tank marking the end of the flotation zone, and leaves the flotation tank through a device for maintaining and regulating the water level. The technological sizing of this type of DAF clarifier is usually quite conservative, as the design requires some compromise between hydraulic optimisation and transport

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
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constraints. The total hydraulic load (raw water flow + pressurised water flow) is usually between 6 and 8 m^3/m^2*cdot*h (6–8 m/h). The SS load depends of course on the sludge characteristics, but is usually around 9–12 kg/m^2*cdot*h. Of course, the best way to determine the sizing parameters is to test them (if possible), or to use a well-chosen and truly representative analogy.

As mentioned above, the dimensions of these units are, in the vast majority of cases, suitable for road or sea transport. The standard containers can receive loads of 2250 mm in width, 2250 mm in height (2600 mm for high cube containers) and 11,800 mm in length. For a standard truck these values are respectively a maximum width of 2500 mm, a height of 2500 mm and a length of about 11,000 mm. For a special transport, these dimensions are approximately 2900 mm wide, 11,000 mm long and 3400 mm high (truck with low platform). It is, of course, possible to divide the tank into two parts to be assembled on site and in this way to ship larger units by road, but this entails constraints that limit the implementation of this concept.

Rectangular metal tank DAF clarifiers can be classified into several groups according to different criteria. These criteria can be related to the materials of construction, their hydraulic concepts, their method of removal of the floated and the bottom sludge etc. For example, the tanks and, more generally, the wetted parts of the equipment can be built either in stainless steel, in mild steel painted with different types and qualities of paints, or in non-metallic materials. These non-metallic materials are most often GRP (Glass Reinforced Polyester) or PP (Polypropylene) for the tank and for some parts of the scrapers, but also many plastics used for bearings, chains etc. Stainless steel equipment is generally the most expensive to build, depending on the grade of stainless steel, but it is also the strongest and most durable, with the exception of some cases of particularly corrosive effluents such as produced water from oil fields or sea water. In these cases non-metallic materials are best, unless one invests in duplex or super duplex steel, which is quite exceptional. Mild steel units are cheaper to build, but require more or less expensive coatings depending on the chemical composition of the water to be treated. In addition, these coatings need to be "refreshed" or redone periodically. GRP or PP equipment does not have corrosion problems, but the low mechanical strength of these materials (compared to steel) requires the installation of metal reinforcements on the tanks and on certain elements supporting high static or dynamic loads. For this reason, these materials of construction are mainly reserved for small units.

Their hydraulic concept can be based on co-current floated sludge collection (when the floated sludge is collected on the clarified water outlet side) or counter-current (when the floated sludge is collected on the inlet side). The floated sludge can be removed with a surface scraper with chains, with paddle wheels, by a combination of both or by simple overflow. A few manufacturers have developed reciprocating scrapers that move back and forth. They are equipped with flights fixed on hinged supports, allowing the scraper to push the sludge on the way out and to lift the flight above the sludge layer on the way back.

All these details combined give a large number of construction possibilities and different flotation concepts. It would be difficult to describe all of them as the number is large and they are often specific units developed by a single manufacturer.

However, it is possible to describe in more detail the different main components of these clarifiers and their operation in order to better understand their advantages and disadvantages. Such a description is given in the following chapters.

The main elements of a rectangular metallic tank DAF clarifier are as follows:

– The tank.
– Raw water inlet and pressurised water pressure relief devices.
– Floated sludge collection.
– Bottom sludge collection.

It would be useful to describe these elements separately to better understand all the possible combinations between them.

4.1 The Tank

Most often it is rather elongated, i.e. it is longer than it is wide in relation to the direction of water flow. One might think that the reason for this is the transport constraint that favours elongated units and also the fact that a surface scraper seems to benefit more from an elongated geometry. This is partly true for units above a certain size, but it is curious to note that even small units of 2 or 3 m^2 flotation area are almost always rather long (in the direction of water flow) than wide. Indeed, as described in Chap. 3 (Fig. 3.1b), for equal flotation areas, a rather wide flow section is more advantageous in terms of water flow velocity than a long narrow section. This is easier to illustrate if we take the concept to its extreme. Imagine a very long and narrow flotation zone, similar to a channel. The water would flow through it for the same time as through a square flotation tank with the same flotation area, but at a higher velocity the smaller the flow crossection, causing so much turbulence that separation of the SS would become impossible. It can be concluded that a wide rather than a long tank, in relation to the direction of flow of the water, would be more advantageous for the quality of the clarification. Unfortunately, this rule is not always easy to respect for several reasons, apart from the transport constraints concerning equipment above a certain size:

- The width of the tank is limited by the width of the scraper, in particular by the length of the flights and the drive shaft. However, this constraint is somewhat relative for this type of DAF clarifier, as a scraper does not pose any particular mechanical problems below 4–5 m in width.
- The homogeneous distribution of raw and pressurised water over a large width may be more difficult compared to a small width with a more compact contact zone, where the concentration of pressurised water will be higher and its mixing with the raw water more intense.

All this makes it much easier to build and transport rather long than wide units, and so much the worse for the hydraulics and the quality of clarification. That being said, some manufacturers are making DAF clarifiers with a flotation area as little as

2 m wide and almost 10 m long with a water depth of only 1–1.2 m. Theoretically the flotation area is there, clarifiers up to 20 m^2 are still transportable in a container in one piece, but this is a bit of a departure from optimal proportions…

4.2 The Raw Water Inlet and Pressure Relief Devices

The second element is the set of devices for the pressure relief, the white water distribution and the raw water inlet. There are three concepts on the market:

The first concept consists of injecting the white water into the feeding pipe of the DAF clarifier. The pressure relief is made with one or two manual or automatic valves, installed as close as possible to the point of injection of the white water into the raw water to minimise coalescence. The injection point is also located as close as possible to the inlet of the raw water + white water mixture into the contact and distribution zone of the clarifier for the same reasons. The way in which the white water is injected into the inlet pipe also depends on the flocculation method used. If the flocculation is rapid and only about ten seconds of mixing is required for floc formation to be complete, it will be possible to inject the flocculant in-line and the white water as shown in Fig. 4.1a, keeping the injection velocity in the range of 1.2–1.5 m/s. The flocculant (8) can be injected into the raw water far upstream of the white water injection point (as shown in Fig. 4.1a) or into the white water downstream of the pressure release valve (as shown in Fig. 4.1b). This method of injecting the pressurised water ensures thorough and violent mixing of the raw water, white water and polymer. It promotes flocculation, but only to a certain extent and only if the turbulence in the contact and distribution zone (4) across the width is rapidly reduced. On the other hand, if flocculation is slow and the raw water has been previously flocculated in a dynamic flocculator or a pipe flocculator, the injection of white water should be done as quickly as possible after the pressure relief, but at the same time in the least violent way possible to avoid destroying the flocs that have been carefully formed in the flocculator. The approach is then different and consists in injecting the white water into the inlet pipe at a speed close to that of the raw water to minimise turbulence, i.e. around 0.5 m/s maximum. One solution is shown in Fig. 4.1b as an example.

The raw water supply to the DAF clarifier with a single entry point into the contact zone, shown in the two figures, is suitable for small units up to a maximum width of 1600–1800 mm, if the inlet depth is at least 1000–1200 mm under the water level. For wider units (up to 2200 mm) a flow distribution baffle should be provided. For units wider than 2200–2400 mm it would be better to opt for a different flow distribution concept across the width, as a single inlet point would create too strong currents. This can be a syphoidal wall or a distribution box.

The second concept is to make the pressure relief through several (at least four or five) small pressure relief valves (manual or automatic) or several calibrated diaphragms. After each pressure relief device the white water is injected directly into the contact and distribution zone, usually through a hose (see Fig. 4.2a). The injection

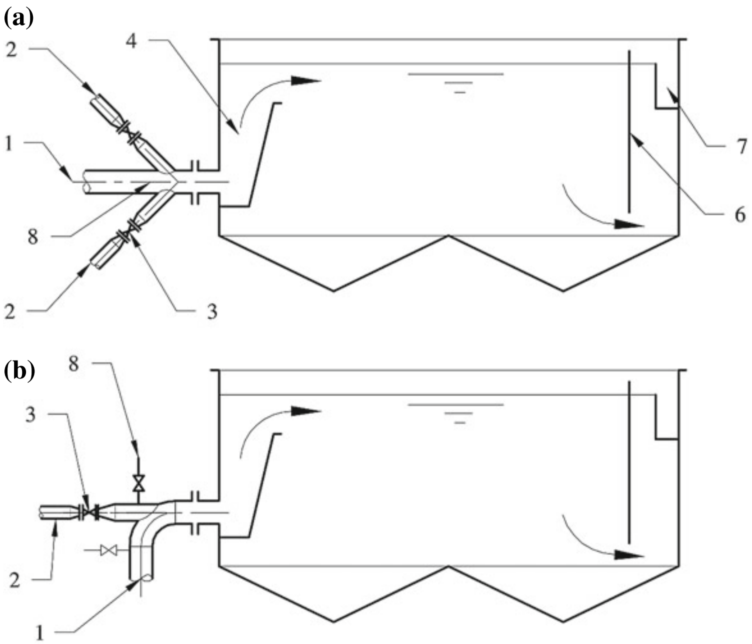

Fig. 4.1 Pressurised water injection in the raw water feeding pipe. 1—raw water feeding, 2—pressurised water feeding, 3—pressure relief valve, 4—contact zone, 5—flotation zone, 6—submerged partition, 7—outlet channel with weir, 8—polymer injection

points are located towards the bottom of the contact zone (4) and are distributed at equal distances across the width of the tank. This approach allows a good distribution of the white water over the width of the tank, but logically requires a homogeneous distribution of the raw water as well. This is achieved by using either a syphoidal wall or a raw water distribution box (10) as shown in Fig. 4.2a. From the box (10) the raw water is introduced into the contact zone through a slot or through distribution windows (11).

Some DAF clarifiers do not have a separate contact zone. The raw water is distributed through a simple water distribution box across the width of the tank (see Fig. 4.2b). If this is the case, white water is injected into this box at several points. This type of box takes up less space than a separate contact zone and offers acceptable hydraulic conditions for in-line flocculation, especially for a rather long tank. On the other hand, the mixing is a bit violent for previously flocculated water and the flocs risk being damaged. Unless the flocculant is overdosed so that the broken flocs can be reconstituted again at the outlet of the box… In addition, this type of box creates more currents than those at the outlet of a classic contact zone (4), which ensures a more homogeneous and slower water flow.

Some manufacturers use this concept by adding two, and sometimes even four, additional white water injection points on the wall along the flotation tank. This

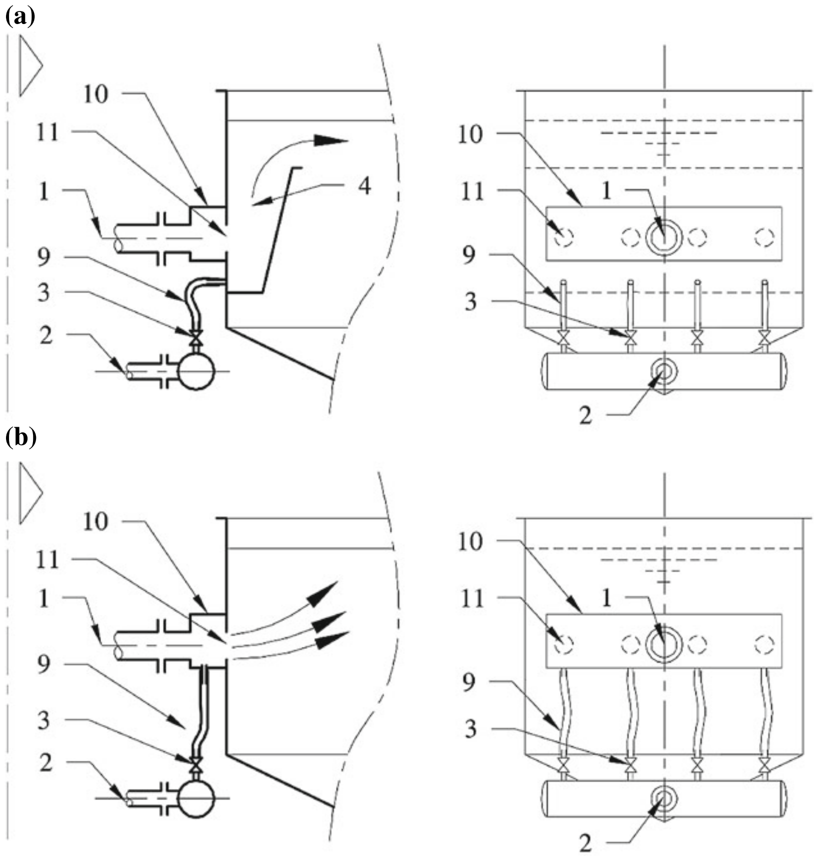

Fig. 4.2 White water injection—clarifier with distribution box. 1—raw water feefing, 2—white water, 3—pressure relief valve, 4—contact zone, 9—flexible hose, 10—distribution box, 11—distribution windows

trick creates considerable turbulence around the injection points, which disrupts clarification, but has the advantage of bringing 'fresh' white water to the middle, and even towards the end of a tank, which is probably too long, where the microbubbles injected at the inlet are already more or less gone.

The third concept uses a pressurised water distribution pipe at the bottom of the contact zone. The pressure relief is done by a single manual or automatic valve and the distribution of the white water is done through orifices placed along the pipe (Fig. 4.3). This solution reconciles all the constraints by ensuring optimal conditions for white water distribution. However, the inevitable coalescence in this distribution pipe causes some of the air to be lost, which must be discharged.

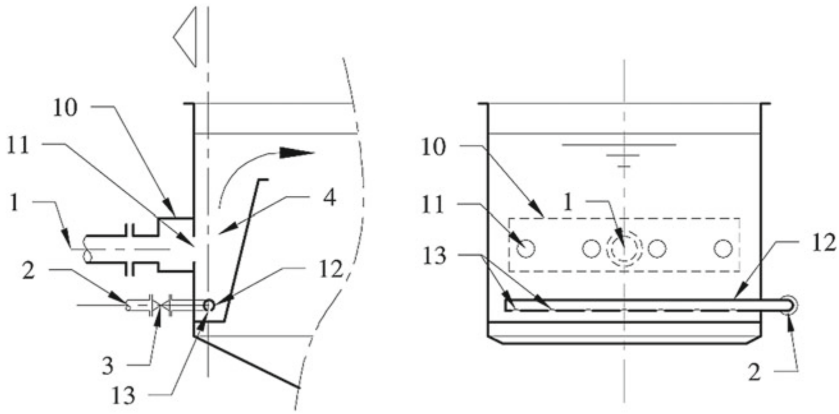

Fig. 4.3 Pressurised water distribution pipe. 1—raw water feeding, 2—pressurised water feeding, 3—pressure relief valve, 4—contact zone, 10—raw water distribution box, 11—water inlet window, 12—pressurised water distribution pipe, 13—holes for pressurised water even distribution

4.3 Floated Sludge Collection

The collection of the floated sludge accumulated on the surface can be done by two means. The first is the hydraulic method, which consists of periodically overflowing the layer of sludge accumulated on the surface into a chute. This method of removing the floated sludge is simple, reliable and inexpensive. Nevertheless, given the area of application of this type of DAF clarifiers, it is virtually never used, as it has two major drawbacks.

Firstly, it is only suitable for cases where the water contains low amounts of TSS and the thickness of the floated sludge layer increases slowly over time. The typical application is the drinking water clarification when the raw water contains only a few milligrams per litre of TSS. Too high a SS loading would quickly form a sludge layer that is too thick and difficult to overflow or would require too frequent overflow sequences or, if necessary, almost permanent overflow.

Secondly, the overflow of the sludge layer also carries a lot of water with it. This results in a high dilution of the overflowed sludge so that its concentration is reduced, at best, 6–10 times, often much more. If the quantity of floated sludge is small and its reprocessing does not pose any particular problems within the plant, this low concentration and the corresponding water loss may be acceptable. On the other hand, a large volume of sludge to be overflowed can quickly become unmanageable. Overflow facilities for floated sludge are described in more detail in Chap. 6.

The second means of collecting floated sludge is the mechanical one, which consists of pushing and extracting the sludge with different types of scrapers. While these are effective in obtaining the most concentrated floated sludge possible, they are more expensive and require a minimum of maintenance.

Another aspect of floated sludge collection is the choice of the extraction point. Apart from a few special designs, most rectangular non-assisted DAF clarifiers have their raw water inlet at one end of the tank and the clarified water collected at the opposite end. The floated sludge forms a blanket on the surface which is pushed by the inlet flow to the opposite side of the tank. If this sludge blanket is discharged by periodic overflow, then the overflow will always be on the opposite side of the inlet where the current naturally brings the sludge layer. The question of positioning the overflow chute does not arise. This is also the case with reciprocating scrapers and paddle wheels, as their ability to move a large volume of floated sludge is limited and it is easier to take advantage of the current than to go against it. On the other hand, if the layer is removed by a surface scraper, which has the capacity to push a large volume of sludge, then the choice of sludge extraction point will be less obvious. From this point of view there are two concepts of rectangular surface scraper flotation systems.

The first is the so-called co-current concept (Fig. 4.4a). The sludge is pushed in the direction of the water flow and is extracted above the clarified water collection point. The second is the so-called counter-current concept (Fig. 4.4b), where the floated sludge is pushed against the water flow and extracted above the raw water inlet. It is difficult to say with certainty which of these two concepts is clearly the better one, because, as always, each has its advantages and disadvantages, depending on the application in which it is used and the geometry of the flotation tank.

Scrapers, operating in co-current, have the advantage of creating less turbulence in the area of the interface between the sludge blanket and the water, as the scraper pushes in the direction of the water flow and the difference between the velocities of the two phases is relatively small. Therefore, floc detachment caused by this turbulence is rarer. On the other hand, the extraction of a thin layer of floated sludge (with a thickness less than the immersion of the flights) can cause turbulence resulting in floc detachment. This is annoying, because these detachments take place above the clarified water outlet, at the end of the tank, where there are not many free air bubbles left to recover the detached flocs. Unless the amount of white water is sufficient to form a thick blanket of bubbles, covering the entire flotation surface up to the end of the tank. But this may require oversizing of the white water flow, especially for rather long tanks.

For scrapers operating in counter-current, the situation is somewhat reversed. The direction of scraping causes greater turbulence at the interface between the sludge blanket and the water, as the speed of the water flow and the flights add up. This can cause floc to detach. But on the other hand, possible floc detachments at the extraction point, which is the most critical point, are not really troublesome, as they occur above the inlet where the concentration of air bubbles is the highest and more than sufficient for the flocs to be recovered quickly.

To solve this problem of turbulence at the interface between the floated sludge layer and the water, some manufacturers use a trick which consists of placing a series of fixed lamellae (4), parallel to the scraper's flights and located just below them - see Fig. 4.4c. These lamellae (4) are about 8–10 cm high and are arranged more or less vertically at a distance of a few tens of centimetres from each other. Each

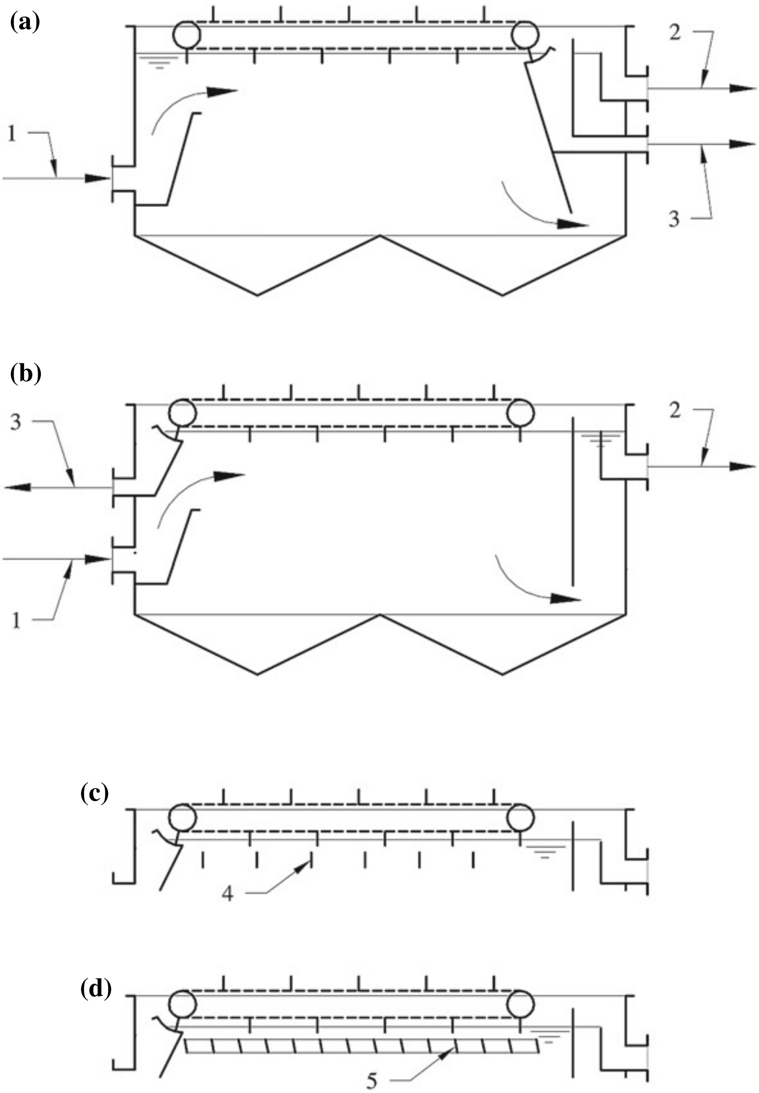

Fig. 4.4 Co-current and counter-current surface scrapers, **a** Co-current floated sludge collection, **b** Counter-current floated sludge collection. 1—raw water feeding, 2—clarified water outlet, 3—floated sludge discharge, 4—lamellas, 5—rack

pair of lamellae encloses a sort of buffer volume between the space swirled by the flights moving in one direction and the water moving in the opposite direction. Other manufacturers take the concept to the extreme by installing a grid (5) 8–10 cm high, just below the flights, with a mesh size of 12–15 cm—see Fig. 4.4d.

In both cases this buffer volume, enclosed between the lamellae or between the mesh of the grid, serves its purpose well and prevents the entire floated sludge blanket from being carried away by the scrapers, thus limiting floc detachment. On the other hand, the sludge often tends to stick to the lamellas and form large blocks of sludge. The racks are even more susceptible to clogging by sludge which can clog the cells and eventually block the rack. These devices therefore require more or less frequent mechanical cleaning depending on the properties of the sludge and the operating conditions.

In general, the purpose of the various types of surface scrapers is to push the floated sludge blanket towards the extraction point and, in most cases, to extract the sludge. In some flotation systems the transport and extraction of the sludge is carried out by separate devices.

There are several types of scrapers which can be classified as follows:

- Two-shafts chain scrapers.
- Three-shafts chain scrapers
- Paddle wheels.
- Combined scrapers.
- Reciprocating scrapers.

All these scrapers have one thing in common—they have flights that are partially immersed in the floated sludge blanket. These flights are mounted on a mobile device that allows them to push and eventually extract the floated sludge. Extraction is done by causing the scraper to trap the volume of sludge it pushes against a semi-submerged inclined surface called a slope or beach, to push it out of the water and into a collection chute.

It should be recalled that the main role of scrapers extracting floated sludge is to extract all the sludge produced with as little turbulence as possible, in order to avoid flocs detaching.

The important parameters to consider when designing a scraper are directly related to the two requirements mentioned above. These are:

- The depth of immersion of the flights.
- The volume of sludge trapped against the beach.
- The speed at which the scraper moves forward.
- The distance between the flights.

The depth of immersion of the flights is adjusted by changing the water level in the clarifier. Ideally, towards the end of the travel at the sludge extraction point, the lower edge of the flights should not be above the water/sludge interface. This means that the scraper removes the entire volume of sludge produced, as well as a small volume of water, which represents a sort of safety buffer volume (see Fig. 3.8a–d). There are, of course, many cases where it is advantageous to accumulate a layer of sludge much thicker than the depth of immersion of the flights, especially in cases where the main objective is to thicken the floated sludge. This configuration has the advantage of avoiding floc detachment, as the turbulence caused by the flights remains inside the sludge layer without disturbing the water/sludge interface. On the other hand, the extraction is no longer “self-regulating” and the level of the water/sludge interface must be monitored as it may drop too low when the clarifier fills up with floated sludge. The sludge may then pass quickly into the clarified water.

The volume of sludge trapped against the beach, combined with the speed and the number of flights, allows the calculation of the extraction capacity of the scraper, which must, of course, be more than sufficient to guarantee the extraction of the sludge produced in all circumstances, including some occasional overloads.

All these four parameters vary within certain limits in order to allow the optimal operation of the scraper. The immersion depth of the flights generally varies between 4–5 and 15 cm. Beyond this, the hydrostatic pressure of the volume of sludge coming up the beach can start causing leakage. The speed at which the flights move varies between 1 and 5 cm/s. Too fast a speed, beyond 5–6 cm/s, can start to destroy the fragile sludge blanket. All these interactions and interdependencies are described in more detail in the coming paragraphs.

4.3.1 Two Shafts Chain Scrapers

Such a scraper is shown schematically in Fig. 4.5. It performs both functions—transport and removal of floated sludge. The flights (1) are fixed to the two parallel chains (2) by means of brackets at the end of each flight. A drive reducer (6) drives the drive shaft (4) to which the sprockets (3) are fixed, which in turn drive the chains (2). Each flight pushes a certain volume of floated sludge (10) towards the beach (5). In this case this beach (5) has a cylindrical shape and its formation axis coincides closely with the drive axis (4) and that of the sprockets (3). At the moment of arrival of the flight (1) against the beach (5), the volume of sludge (11) located between the beach (5) and the flight is trapped in this space suddenly closed by the flight. The flight continues to move forward by rotating around the axis of rotation (4), pushing the volume (11) against the beach (5) until it overflows the upper edge of the said beach. The seal between the flight (1) and the beach (5) is provided by a brush or neoprene lip (8) which is mounted so as to rest lightly against the beach (5). The design and operation of this type of scrapers is relatively simple, but there are a few details that merit attention.

From a functional point of view, it would be interesting to take a closer look at the method of sizing the scrapers and in particular, the parameters mentioned in the previous paragraph. Figure 4.6 shows different moments in the scraping cycle. Figures 4.6a,b show a “normal” scraping cycle operating in self-regulation. As each flight moves towards the beach, it pushes the floated sludge layer (1) trapped between the said flight and the flight ahead of it. The thickness of this layer is relatively even and increases slightly over time as the scraper moves forward. This increase is due to the flotation of new sludge flocs. However, the situation changes at the last flight before the bank, as the front of the sludge blanket it pushes is blocked by the beach while the flight continues to move forward. Thus, the flight compresses the sludge blanket against the beach, resulting in the formation of a compressed

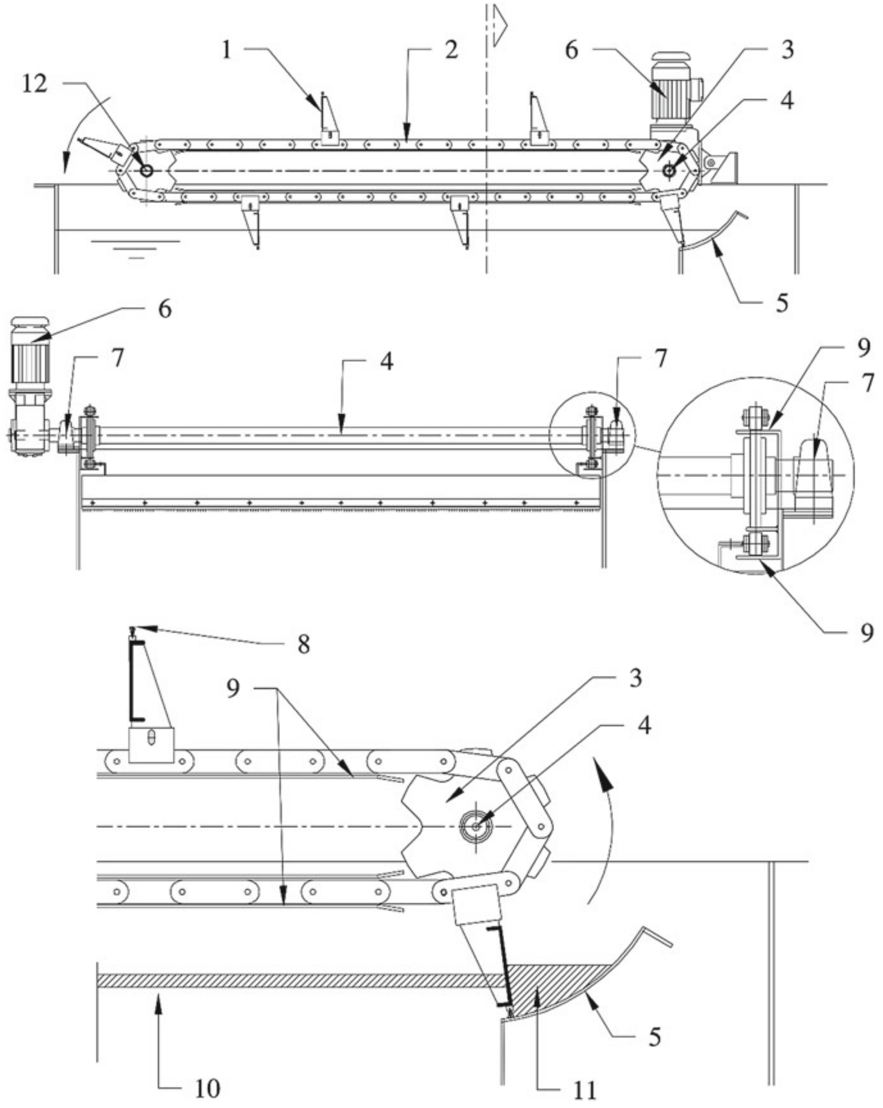

Fig. 4.5 Two-shafts surface scraper. 1—flight, 2—chain, 3—drive sprocket, 4—drive shaft, 5—beach plate, 6—drive-reducer, 7—bearing, 8—brush, 9—chain support, 10—floated sludge blanket, 11—volume of the sludge trapped between the flight and the beach plate, 12—return shaft

sludge blanket (2), the thickness of which increases steadily with the progress of the flight. At the moment of contact of the flight with the beach, the entire volume of compressed sludge is trapped between the flight and the beach. For stable self-regulating operation this trapped volume of sludge (3) must be slightly smaller than the total volume trapped between the flight and the beach as shown in Fig. 4.6b. In this case the flights will overflow all the sludge conveyed by the scraper.

The situation shown in Fig. 4.6c is different. The layer of sludge pushed by the scrapers is too thick and when it is compressed by the last flight against the beach, its volume exceeds the volume enclosed between the flight and the beach. In this case the flight cannot go up and push all the sludge out. Some of this compressed sludge volume will remain under the outer edge of the flight and form the unscrapped sludge cushion (4). The formation of such a cushion means that the volume of sludge removed by the scraper is less than the volume of sludge actually produced. This

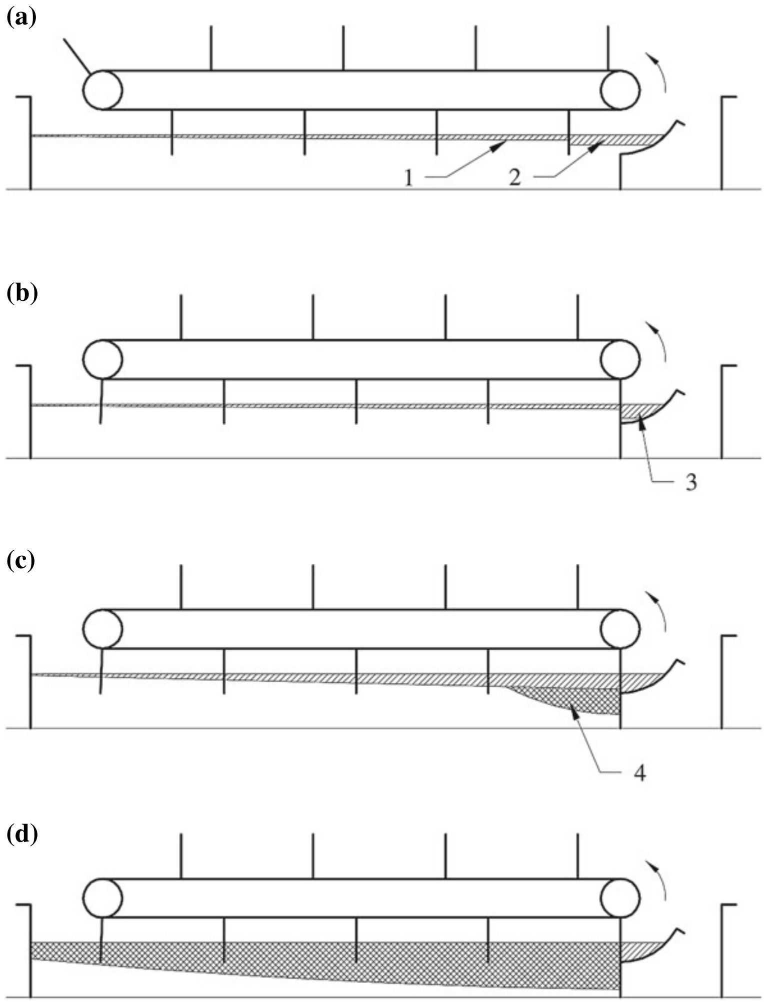

Fig. 4.6 Scraping adjustment modes. 1—floated sludge blanket, 2—compressed floated sludge blanket, 3—volume of trapped sludge, 4—unscrapped sludge cushion

can have two consequences. Firstly, the hydraulic conditions around the cushion (4) are quite turbulent and can cause floc to detach. Secondly, the thickness of the floated sludge layer can increase considerably as shown in Fig. 4.6d. The growth rate of sludge accumulation depends on the difference between the volume of sludge produced and the volume actually extracted. The greater the difference, the faster the sludge layer will fill the flotation tank. As described in Chap. 3, increasing the thickness of the sludge blanket often results in an increase in the concentration of the upper portion of the sludge blanket, which will therefore contain more solid matter. Thus, if the difference between the volume of sludge produced and the volume of sludge removed is small, it is possible that a new equilibrium is created at a certain level of thickness of the sludge blanket.

The thickness of the sludge blanket will stop increasing and will stabilize, as the scraper will be able to meet the need by increasing the concentration of the upper portion of the sludge blanket. This is a delicate but possible balance that is often sought in sludge thickening. It is possible to operate the scraper in this regime, provided that the feed flow to the DAF clarifier and the TSS concentration are stable.

To calculate the extraction capacity of a scraper, it is essential to know not only the depth of immersion of the flights, the volume trapped against the slope and the distance between the said flights, but also the concentration of the floated sludge, as this parameter enables the volume of the sludge to be calculated. The calculation will be easier with an example:

Let's assume a flotation tank with a flotation area of 4 m long and 2 m wide, i.e. 8 m^2 of surface. The raw flow rate is 40 m^3/h and the maximum TSS concentration is 1 g/l. It can be assumed (for simplicity and to keep a small safety margin) that all TSS will be retained in the sludge and that the clarified water will be perfectly pure. The expected concentration of the floated sludge is 3–3.5%, but as a precautionary measure a concentration of 2% should be used as this may occur occasionally, for example, in the event of a chemical treatment problem or a reduction in the pressurisation rate due to a small blockage in the pressure relief device. The immersion of the flights depends on the water level in the tank. For this example, it is estimated that the immersion is 8 cm. Given the geometry of the beach, it is easy to calculate (or measure on a sectional drawing) the cross-sectional area of the volume of sludge trapped between the flight and the beach at the moment of contact. Let's assume that this section is 120 cm^2. For a beach width of 2 m this represents a volume of $120 \times 200 = 24{,}000$ cm^3, or 24 L of sludge that will (ideally) be removed with each flight.

The weight of sludge produced will be 40 m^3/h $\times$ 1 kg/m^3 = 40 kg of sludge per hour. At a concentration of 2% this is 40/0.02 = 2000 litres per hour.

To remove this volume a minimum of 2000 l/h/24 l per scrape = 83.33 scrapes per hour. In other words, one would have to scrape every 3600/83.33 = 43.2 s.

If the speed of the scraper is 2 cm/s, then the distance between the flights should be 43.2 s $\times$ 2 cm/s = 86.4 cm maximum.

This is the theoretical calculation. In practice, a slightly shorter distance will be used, depending on the pitch of the chain. It would also be wise to allow for a capacity reserve of 15–20% because of possible sludge leaks on the sides of the flights and under the sealing brushes (or lips). This reserve can be in the distance between the flights or in the scraping speed, which could possibly be increased to 2.5 cm/s, if the strength of the sludge blanket allows it. Alternatively, it is possible to increase slightly the immersion of the flights, in leaving in any case the edge of the beach at least 4–5 cm above the water level.

Obviously, the accuracy of this calculation is somewhat relative as it is based on assumptions, but it gives an idea. And the calculation should be checked each time, as the choice of a "standard" scraper can be misleading in both directions.

From a mechanical point of view, there are several important details:

1. The choice of the chain, and more precisely the pitch of the chain.

Unfortunately, it is not uncommon to find chain scrapers on the market with a chain pitch of only 40–50 mm. Such a pitch is too short and does not provide sufficient stability for the flight, which "bends" too easily at the slightest effort. This "bending" effect is relatively weak for two-shafts scrapers because, at the moment of contact with the beach, the chain is held relatively well by the drive sprocket and the flight remains in position, even if the chains are quite slack. However, on the three-shafts scrapers that will be described later (see Fig. 4.9) it can be very problematic. This is because the chain of each scraper is relatively slack on the return side, to avoid excessive mechanical efforts. If the chain is pulled by an obstacle catching the lower edge of the flight (typically this is the lower edge of the beach or the simple friction of the flight on the beach plate), this will allow the chain link to rotate slightly around its axis until the pull caused by the shortening of the chain compensates for the force. Figure 4.7 shows this phenomenon.

In Fig. 4.7a the pivoting of the flight has caused the chain to shrink as a result of the shift of the two axes of the link equal to the sum of a + b. The same flight mounted on a small pitch chain (Fig. 4.7b) can rotate much more, before causing the same a + b shrinkage of the chain. It can be seen that a small chain pitch facilitates the "bending" of the flight much more than a large chain pitch. For this reason, it is

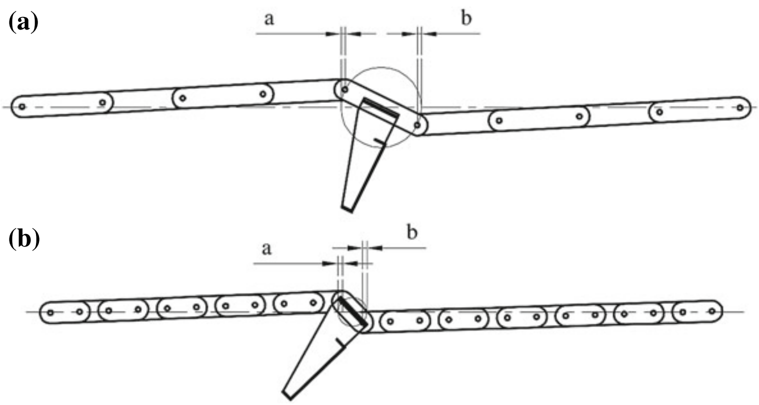

Fig. 4.7 Importance of the chain pitch for the flight stability at equal chain extension (a + b)

advisable to choose a pitch of at least 100 mm for small DAF clarifiers in metallic tanks. The chains of large scrapers have a pitch of about 150 mm.

2. The flights supporting mode.

The flights are always fixed on the two chains, but they can be supported in two different ways. The first is shown in Fig. 4.8a. In this case the flights are attached to the links of the chains equipped with wheels. By means of the wheels, the chains roll on the chain supports (8). If the scraper is equipped with two sprockets of the same diameter, like the one shown in Fig. 4.5, this mode would be suitable for small scrapers of short length (less than 3–4 m). Longer scrapers (more than 6–7 m), built on this principle, can sometimes cause some problems with the chains floating on the way back. This is because, if the chains are pulled by the drive sprocket, and therefore relatively taut on the way to the beach, they are less taut on the way back. As a result, chains that are too long can float on the upper chain supports, which can cause the flights to snag and even derail one of the chains. The solution to this problem is to use either a chain tensioner (rare as it is impractical) or a drive sprocket that is larger than the return sprocket and let the chains hang freely for some distance after the drive sprocket, as shown in Fig. 4.8b. The weight of the chains and the flights is usually sufficient to keep the chains relatively taut also on the return. In addition, the radius of the beach (5) increases as the size of the sprocket (3) increases, which is beneficial for sludge extraction as it is more gradual and allows more time for water drainage.

The second way of supporting the scrapers is shown in Fig. 4.8c. The pinions (3) are fixed not towards the periphery, but set back - on the inside of the shafts. The flights are indeed attached to the chains, but they are not supported by them. It is the opposite: the flights are supported by the flights supports (9) in both directions and it is the flights that carry the chains. This allows the chains to hang loose between the flights and, due to their weight, to provide a certain tension on the return side of the whole scraper, which is usually sufficient to keep everything in place and avoid snagging and derailing. This is the concept of the large size scrapers.

3. Sealing at the point of contact between the flights and the beach.

The seal between the flights and the beach, and also on the sides, is often the Achilles heel of this type of scrapers. Whether they are brushes or lips made of neoprene (or other soft, elastic material), these elements are in fact wearing parts, as they are subject to friction, repeated deformation and sometimes, if the construction materials are poorly chosen, chemical aggression from products contained in the water. Soft lips often lose their flexibility more or less quickly and become deformed over time. Their construction material sometimes also has the disadvantage of absorbing water or, as they say, "drinking" water, which causes the strip to stretch and eventually become wavy and lose its ability to properly hug the surface of the beach. Brushes, if well selected, are less sensitive to this type of deformation and generally last longer. However, for some reason that seems to escape logic, they are used more rarely…

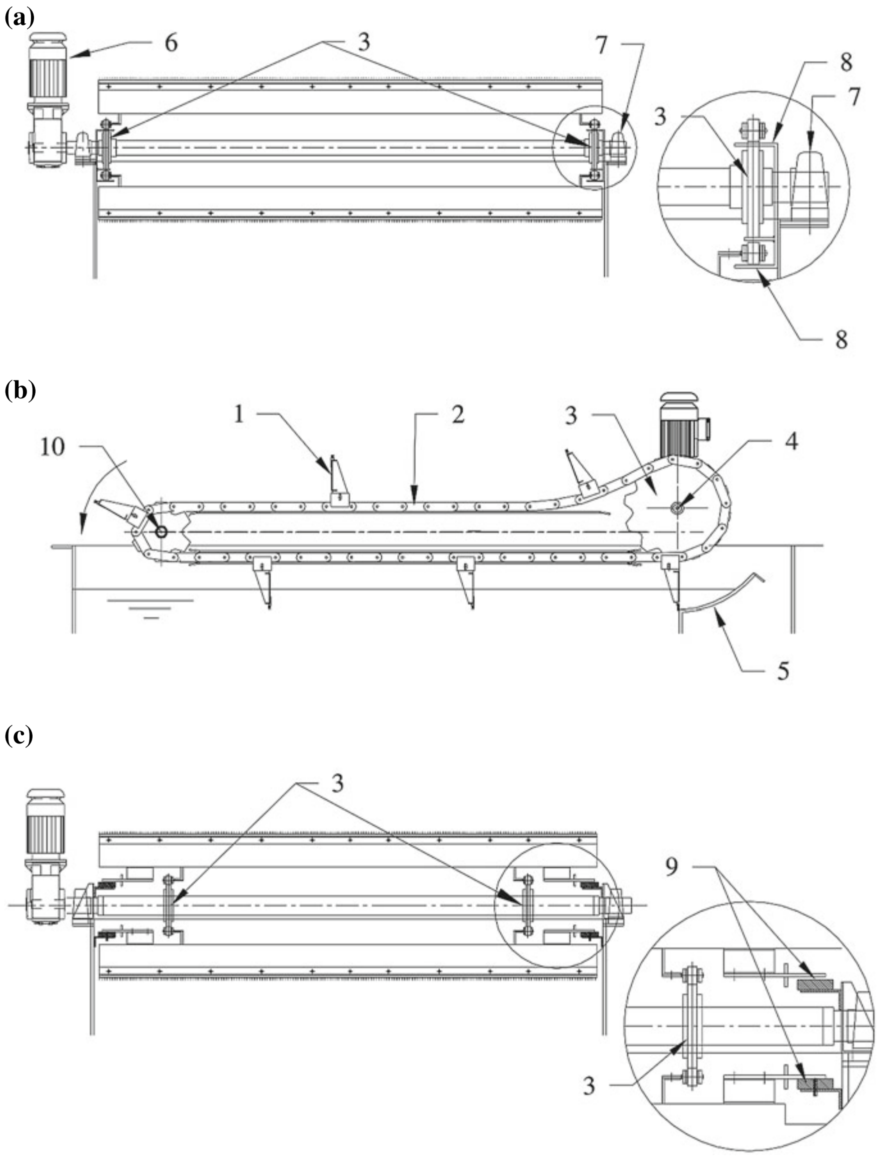

Fig. 4.8 Scraper's flights supporting. 1—flight, 2—chain, 3—sprocket, 4—drive shaft, 5—beach plate, 6—drive reducer, 7—bearing, 8—chain support, 9—flights support, 10—return shaft

4.3.2 Three Shafts Chain Scrapers

Figure 4.9 shows a schematic of a three shafts scraper. The differences with the two shafts scraper are in the shape of the beach and the way the scrapers are guided along this beach.

Two shafts scrapers necessarily have a cylindrical beach. The flights are guided into contact with the beach by the two drive sprockets in which the chains are firmly fitted over a run of at least 180°, which gives the flight a good stability to press the sealing brushes (or lips) properly against the beach. The scrapers rotate around a fixed shaft. It is practically impossible for the scraper to "bend" under the resistance caused by the sealing lip pressing against the beach, even if the chain pitch is not very long. Three shafts scrapers have a flat beach, inclined at about 15°–20°. In order to follow this beach, the scraper must make a translational movement. This movement is provided by a third pair of guide sprockets (7) attached to a third guide shaft (8). The guide shafts (8) and the drive shaft (4) form a surface which is parallel to the beach (8). Thus, between the two drive (3) and guide (7) sprockets, the chains (2) remain parallel to the beach (5) as the flights slide along it. In this configuration the stability of the flights in contact with the beach is somewhat relative, as it is not ensured by a firm support of the chains against the sprockets. In the space between the two sprockets the chains are not supported and remain relatively straight, only because they are tensioned by the weight of the portion of the chains hanging on the return between the drive sprocket and the upper chain (or flights) support. Therefore, if the sealing resistance is strong and the chain pitch is small, the flight can "bend" more easily. This is the main inconvenience of this concept. It requires a large chain pitch and a more careful adjustment of the position of the flights on the beach, so that the pressure of the seal on it is sufficient without being excessive.

On the other hand, this concept also has two significant advantages:

Firstly, if the angle of inclination of the beach is small, it will allow a large volume of floated sludge to be trapped between the flight and the beach, much larger than in the case of a two shafts scraper of the same dimensions. Consequently, the extraction

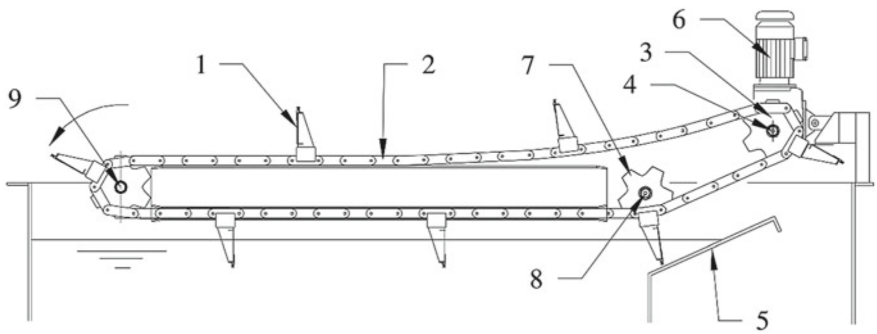

Fig. 4.9 Three shafts surface scraper. 1—flight, 2—chain, 3—drive sprocket, 4—drive shaft, 5—beach plate, 6—drive-reducer, 7—guide sprocket, 8—guide shaft, 9—return shaft

capacity of each flight becomes greater and it is therefore possible to increase the distance between the flights by decreasing their number for the same scraped area.

And secondly, a long, flat, gently sloping beach allows for a longer and more gradual drainage of water from the floated sludge during extraction. This can increase more or less their concentration depending on their dewatering properties.

4.3.3 Paddle Wheels

Paddle wheels consist of a rotating shaft with a few paddles —see Fig. 4.10. The number of paddles usually varies between three and eight. Typically, paddle wheels are used for floated sludge removal—Fig. 4.10a. It is a very simple and reliable device. In addition, as it is a perfectly centred rotation, it is possible to fit the paddles to the cylindrical beach well enough to dispense with a sealing element. Indeed, it is quite possible to adjust the clearance between the paddles and the beach to less than 2–3 mm, even for long paddle wheels up to 9 m in length. This makes the device wear-free as it has no wearing parts left. Another very valuable advantage of the paddle wheel in this function is its very high floated sludge removal capacity. By multiplying the number of paddles, the distance between them is reduced so that it is possible to scrape every few seconds and, if necessary, to achieve almost continuous sludge removal.

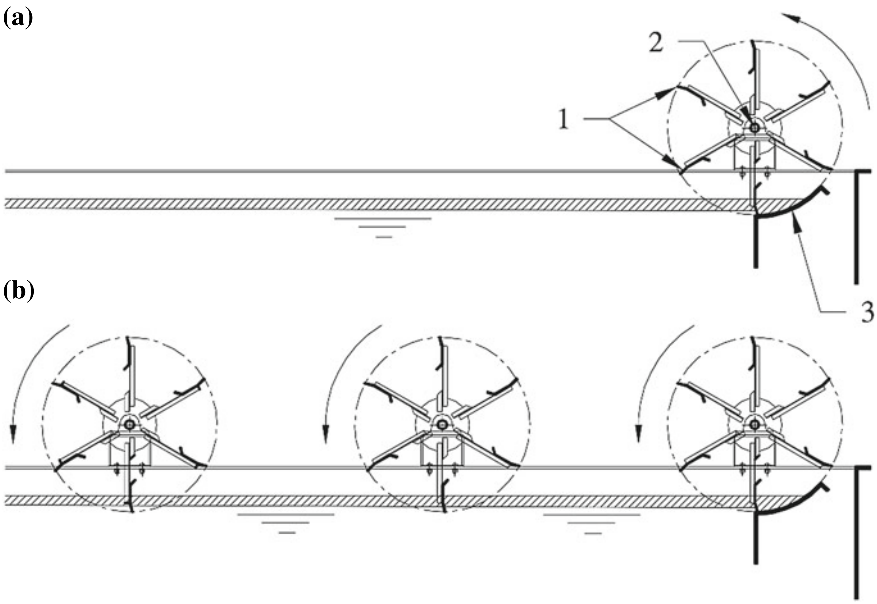

Fig. 4.10 Paddle wheel. 1—paddles, 2—shaft, 3—beach plate

The paddle wheel, on the other hand, has one major disadvantage. It is certainly perfect for pushing the sludge layer in front of it, but this is not enough to obtain a correct extraction, as the sludge blanket still has to be brought towards the wheel. In some cases of drinking water clarification, when the amount of floated sludge is very low, one can take advantage of the surface current in the flotation tank, which can eventually bring the sludge blanket to the wheel, but this is tricky. And if the sludge blanket becomes too thick, it may start to stick to the walls of the tank and remain stuck despite the strength of the surface current. It would then be optimistic to rely on the ability of the paddle wheel to 'pull' the sludge, as this can only work if the sludge blanket is very compact and solid and the wheel turns very slowly.

To overcome this problem, some manufacturers use several successive paddle wheels as shown in Fig. 4.10b. In this case, the last one removes the floated sludge and the previous paddle wheels only push the sludge blanket towards it. This is a compromise, as the efficiency of the whole system is highly dependent on the distance between the paddle wheels. If they are several metres apart, the result may be disappointing. The closer they are to each other, the better the performance, but without achieving the smoothness and uniformity of a chain scraper. In addition, driving many paddle wheels with a single geared motor and transmissions is a difficult thing to do in an elegant way… It involves a lot of chains that run all the way around the tank and need to be protected by casings. A better solution would be to have an independent geared motor for each wheel, but this would be more expensive in terms of equipment, wiring and frequency inverters.

4.3.4 Combined Scrapers

One such scraper is shown in Fig. 4.11. It consists of a chain scraper and a paddle wheel. The drive can be made by two independent geared motors (Fig. 4.11a) or by a single motor and chain drive (Fig. 4.11b). The aim of this concept is to combine the very high extraction capacity of the paddle wheel with the reliability, smoothness and flexibility of a chain scraper, whose role is limited to collecting the sludge from the entire flotation surface and pushing it to the paddle wheel for extraction.

Apart from its high extraction capacity, this concept has the advantage of not having any sealing elements on the chain scraper blades, as they do not extract the sludge and therefore do not need them. And the paddle wheel doesn't have any, because its paddles are perfectly adjustable to the beach. This greatly reduces maintenance and increases the reliability of the system. Finally, the number of flights on the chain scraper is reduced to a minimum, because they only push the sludge blanket. In practice it is sufficient to have at least two flights immersed in the sludge at any moment (for small scrapers) or a maximum distance of 2–2.5 m between flights (for scrapers longer than 4–5 m). This type of scraper is intended for flotation systems treating water with a high TSS content that produce a large volume of floated sludge or for flotation systems with a very high hydraulic loading, concentrating the floated sludge on a small area that consequently receives a very large sludge volume

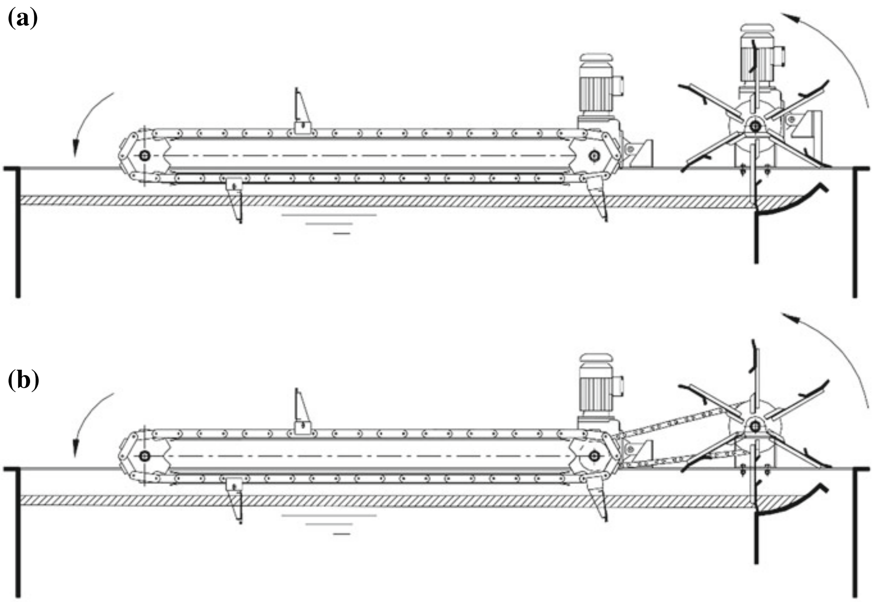

Fig. 4.11 Combined surface scraper

that needs to be removed quickly. In some cases they may be slightly more expensive than chain scrapers, but they are more practical, more reliable and easier to operate. Because, for the same extraction capacity, a simple chain scraper would have to have a distance between the flights of about 30–40 cm, or even less, which is approaching the limits of what is reasonable…

4.3.5 Reciprocating Scrapers

Reciprocating bridge-mounted surface scrapers, also known as reciprocating scrapers, are used primarily for removing small volumes of floated sludge. They have a relatively more complex mechanical design compared to chain scrapers. This does not make them any less reliable.

Figure 4.12 shows schematically the steps in the operation of a reciprocating scraper. The flights (1) are mounted on hinged flight supports (2) with a hinge point (3). These supports are fitted with a flights position adjuster (not shown). The scraper is mounted on a carriage (4) which moves back and forth on the two rails (5) via the wheels (8). The rails (5) are supported by beams (7). The tilting of the scrapers is ensured by the synchronisation arms (9). A winch (11) drives the carriage via the cable (10). The system works as follows:

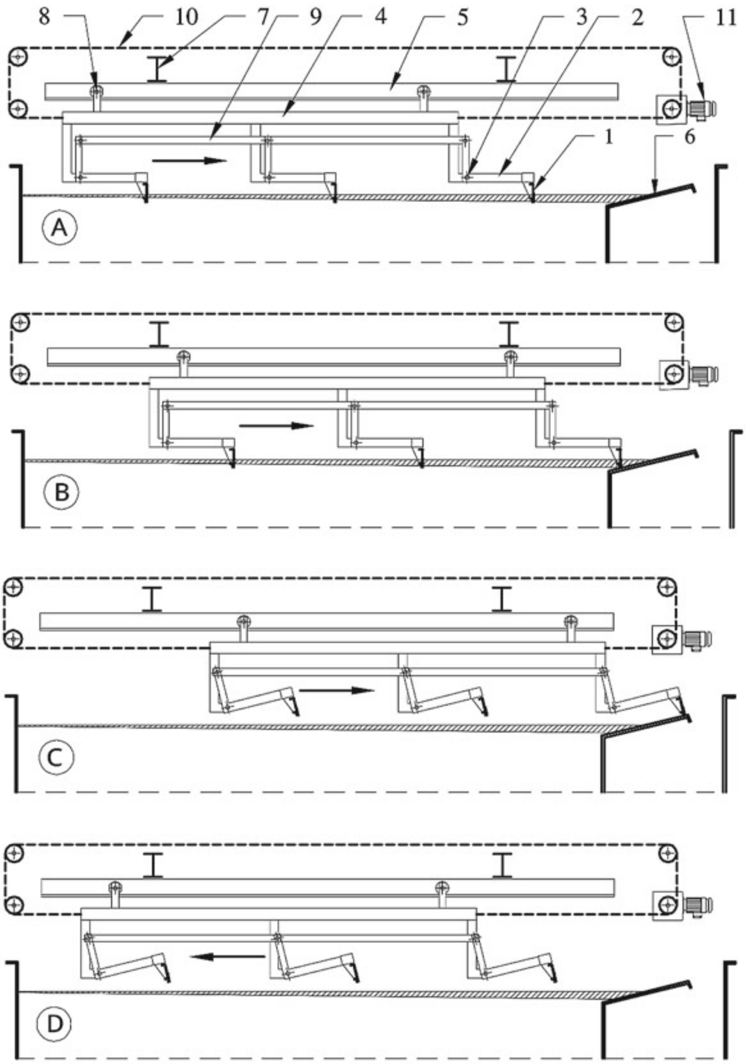

Fig. 4.12 Reciprocating surface scraper. 1—flight, 2—flight support, 3—hinge point, 4—carriage, 5—rails, 6—beach plate, 7—supporting beam, 8—wheel, 9—synchronisation arm, 10—drive cable, 11—winch

The drive cable (10) pulls the carriage (4) towards the beach (6) as shown in step A. When it arrives in position B, the front flight is lifted by the beach (6) while sliding on it to push the volume of sludge trapped between the flight and the beach until it arrives in position C. At this point all the flights are lifted above the sludge layer by the synchronisation arms (9) and are held in this position by the tilting of a simple mechanism (not shown). The direction of rotation of the winch (11) is reversed and the cable returns the carriage back to position A. During this process, the flights remain above the sludge and only fall back down at the last moment. The whole unit then returns to position A and the cable starts to pull the carriage back towards the beach. This is the back-and-forth movement where the flights push the sludge on the way forward and pass over it on the way back.

This type of scraper is used relatively rarely compared to chain scrapers. Their main advantage seems to be the fact that the entire mechanical part is permanently above water—only the flights are wet. This is an advantage for applications in seawater, as this concept allows almost the entire mechanical part to be made of non-seawater resistant materials, which is considerably less expensive than a chain scraper made entirely of non-metallic materials or duplex or even super duplex. This is because a chain scraper must be considered fully wetted by the droplets falling from the flights on the way back and must be constructed almost entirely of seawater resistant materials.

Their main disadvantage is their relatively low extraction capacity, as the return of the carriage takes time during which there is no scraping. If the speed of the carriage on the way back is the same as that on the way forward, this loss of time practically halves the extraction capacity of the scraper compared to that of a chain scraper with the same distance between the flights. This disadvantage can, of course, be partially remedied by increasing the speed of the carriage on the return, but this can only be done within certain limits. For this reason, these scrapers are mainly used for applications where relatively little floated sludge is produced, such as drinking water or tertiary treatment.

4.4 Bottom Sludge Collection

As already mentioned in previous chapters, it would be unrealistic to expect that all flocs and solid particles in the raw water would be removed by flotation. There are almost always some particles that escape flotation for one reason or another. In this case, there are two possibilities: either these particles leave the DAF clarifier with the clarified water, or they settle inside and remain in it to form a bottom sludge blanket. In the first case, the amount of sludge lost should be managed in the next treatment stage, which is often media filtration. This is, for example, the case with some drinking water flotation plants that do not have a bottom sludge collection system. It is, therefore, understood that in this case the lost flocs leave with the clarified water or accumulate at the bottom of the tank which will simply be cleaned a few times a year.

In the second case, the bottom sludge must be managed in the flotation tank itself. Depending on the case, the amount of bottom sludge varies greatly, but there is always a small volume that accumulates over time, even in drinking water clarification. The amount of sludge can be very small and the accumulation over a day or even a week or two will not cause any particular problems. But over a longer period of time this sludge can still form deposits which harden or ferment, causing corrosion and deterioration of the clarified water quality before starting to fill the flotation tank progressively. There are several methods of collecting and purging this sludge which will be described in more detail in the following paragraphs.

4.4.1 Inverted Pyramids

Two vertical sections (longitudinal and transverse) of a rectangular DAF clarifier with two inverted pyramids are shown in Fig. 4.13. This is the simplest and cheapest device for capturing bottom sludge and concentrating it in a point, from which it is easy to flush it from time to time so that its concentration is still high enough to lose the least amount of water. But it is sometimes difficult to fulfil all the best "possible" conditions at the same time, without having to make some compromises.

The first compromise concerns the slope of the pyramids. It is obvious that the steeper the slope, the better the sludge would slide to the bottom without clinging and sticking to the walls. Each sludge has its specificities, settles and thickens more or less well, but, as a general rule, it is considered that a wall inclined at an angle of about 50–55° to the horizon offers an optimal compromise regarding the clogging of the wall and that an angle beyond 55° does not bring a significant advantage. The problem is that an angle of about 50° is far too restrictive, as a pyramid with a side of about 2 m (and even 1 m!) becomes far too deep and makes the flotation tank too high compared to the reasonably transportable and tolerable dimensions in an installation space. In addition, the hydrostatic pressure of the water would become too great and would require the tank to be reinforced. In fact, the ideal design for a metal tank (and even a concrete tank) tank would be to have flattened inverted pyramids at the bottom, occupying as little height as possible. The compromise between the optimum angle and the acceptable angle in practice is usually in the range of 25–35°, depending on

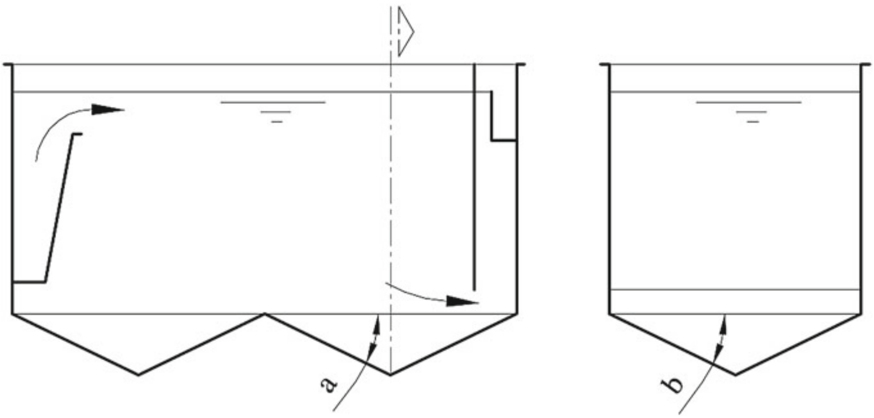

Fig. 4.13 Inverted pyramid bottom

the size and design of the apparatus. The best is to have angles (a) and (b) equal, but this means that the length of the tank must be a multiple of the width, i.e. two, three, four etc. times the length, which is not very practical. In reality the angles (a) and (b) are slightly different, but the aim is that they should be as close as possible.

The second compromise concerns the frequency of purging the bottom sludge. In order to thicken the sludge, it would be advantageous to store it for as long as possible. However, the small inclination of the walls of the inverted pyramid does not result in a large volume and, in addition, favours the clinging of the sludge to the walls and the formation of hardened deposits. Therefore, it would be wiser to purge the sludge more frequently, even if the concentration of the sludge suffers.

The extraction of the bottom sludge is, of course, done from the bottom of the inverted pyramids. The main rules to be followed are three:

– Use a fast opening and closing valve that provides a high flow rate for a short time. This allows a larger area around the outlet to be cleaned. Some manufacturers use a screw pump that operates at a very low flow rate, which does not allow for a powerful flush. This can lead to the formation of a "funnel" of deposits around the outlet and a gradual clogging of the rest of the inverted pyramid. This is a risky solution and is best avoided.
– Flash each pyramid individually, one after the other. Usually the drains from each pyramid are collected in a common pipe and if one were to open all the drain valves at the same time, the water will flow more through the place with the least resistance. In other words, if the outlet of one pyramid is blocked by sludge, the water will flow through the others and the operator will have no way of detecting that one outlet is blocked.
– Have sufficient hydrostatic pressure to ensure powerful flushing. A liquid level difference between the flotation tank and the sludge tank of at least 60–80 cm would be recommended.

4.4.2 Bottom Chain Scrapers

Chain bottom scrapers are reserved for large, flat-bottomed flotation tanks, usually made of concrete. This type of scraper can in fact be adapted to all sizes of equipment with concrete or metallic tanks. As with all chain scrapers, both variants can be used - with chain support or with flight support. However, this specific use of the scrapers gives them some special characteristics.

Firstly, these scrapers generally have widely spaced and low height flights, as the amount of bottom sludge is negligible. Therefore, it would be advantageous to use rather the two-shafts concept and the chain-supported variant, as shown in Fig. 4.14a. This configuration allows the number of flights to be reduced to a strict minimum, i.e. only two or three flights (even one flight would be sufficient to fulfil the function in the vast majority of cases). However, it would be recommended to equip the scraper with a chain tensioner and to avoid long lengths (more than 5–6 m), in order to avoid the risk of the chains floating on the return support (7). For greater lengths, it would probably be better to use a two or three shaft scraper with flights support, as shown in Fig. 4.14b. In this case, on the outward direction, the flights would slide on guides at the bottom of the tank, but the spacing between them would be limited to a maximum of 2.5–3.5 m (depending on the height of the scraper), as otherwise the belly of the chain hanging down between two scrapers might touch the bottom and be damaged by the friction. On the return side, the third shaft and the guide sprocket (8) would prevent the flights from being supported and the chain belly hanging between the guide sprocket (8) and the return sprocket (9) would naturally ensure sufficient and self-regulating chain tension.

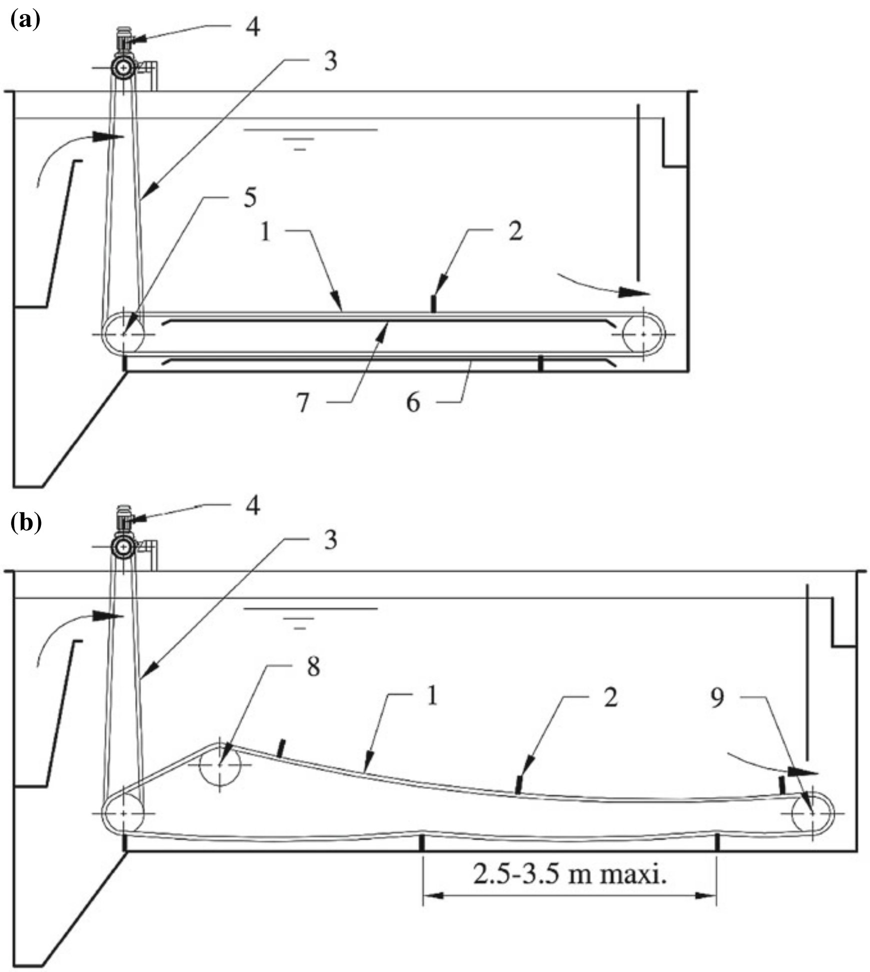

Fig. 4.14 Bottom chain scrapers. 1—chain, 2—flights, 3—drive chain, 4—drive-reducer, 5—drive sprocket, 6—chain support, 7—return chain support, 8—guide sprocket, 9—return sprocket

Secondly, the permanent immersion of all mechanical parts, including the bottom slides, requires careful consideration of all component materials of construction. After all, most plastics are known to absorb water over time and eventually swell slightly. Not to mention the fact that wastewater can contain various solvents and other aggressive chemicals. These factors can have a serious impact on the choice not only of construction materials, but also on the design of certain parts and, ultimately, on the cost of the scraper.

The above examples are, of course, far from representing all the possibilities and cases encountered on the field. The design of each scraper also depends on the type of chains used. For example, supported chain scrapers most often use metallic chains with rollers, so that the links can roll on the supports. A non-metallic chain without rollers will be damaged by the friction on the supports. On the other hand, a metallic chain with rollers would be unsuitable for the concept of supported scrapers, as it would be too heavy and create too much tension. The profile of the flights also varies. The low volume of sludge to be conveyed allows the use of fairly low profile scrapers, which are designed primarily to provide sufficient rigidity to limit bending on return.

The sludge pushed by the bottom scrapers is collected in one or more inverted pyramids of varying volume depending on the size of the tank. They are periodically purged by automatic valves or pumped out (more rare).

These scrapers have two main advantages:

– They perform the function perfectly by cleaning the entire surface and all the corners of the tank bottom. Their efficiency is even more appreciable for large flotation tanks, for which inverted pyramids are not practical to implement and operate.
– They allow the use of a flat bottom, which is simple and inexpensive to build, and require only a small amount of space for installation.

However, the mechanical part has a cost. These scrapers also require visual inspection from time to time and a minimum of maintenance, which leads to some unavoidable operating costs.

4.4.3 Bottom Reciprocating Scrapers

These bottom scrapers have been made popular mainly by the company Zickert for sedimentation applications. They work in a similar way to reciprocating surface scrapers, but are much simpler as they do not have to perform the function of sludge extraction.

The concept marketed by the Zickert is shown schematically in Fig. 4.15. The scraper consists of a number of doctor blades (1) spaced a few tens of centimetres apart. These scrapes are typically placed on two or three parallel supports, perpendicular to the doctor blades, one flat support (2) at each end and one in the middle of the doctor blades. A central support (3), fixed above the scrapes, transmits the movement. Each flat support (2) slides on plastic slides (4) fixed to the bottom of the

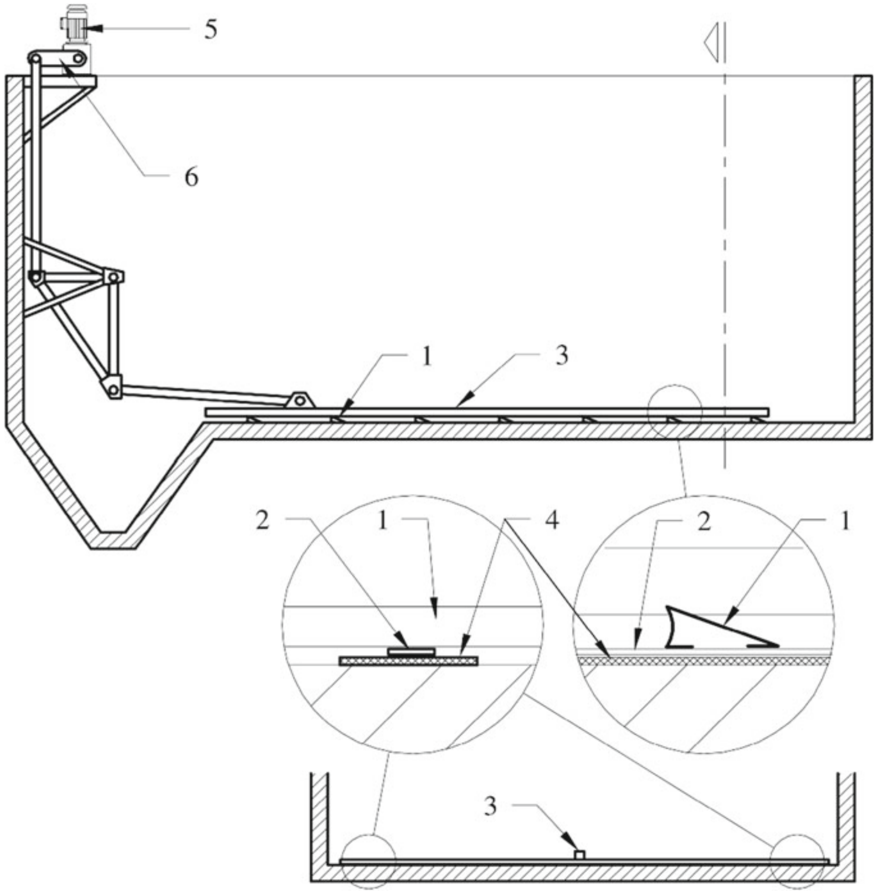

Fig. 4.15 Reciprocating bottom scraper-1. 1—doctor blade, 2—flat support, 3—central support, 4—plastic slide, 5—drive reducer, 6—eccentric

tank. The "back and forth" movement is obtained by means of a pneumatic cylinder or a drive reducer (5) (as shown in the diagram) driving an eccentric (6) which transfers the movement to the central support (3) by means of a set of levers. The essential trick of the operation lies in the profile of the doctor blades. The sludge is pushed by the vertical and concave part of the doctor blades (1). During this phase the scraper moves slowly to optimise the grip of the doctor blade and not to stir up the sludge excessively. On the return stroke the movement should normally be faster, so that the inclined side of the blades can (theoretically) "slide" under the sludge layer without displacing it. In practice, the system works even if the two speeds (back and forward) are the same—the profile of the blades "pushes" more sludge forward than it "pulls" on the return. In the end, this permanent, or at least fairly frequent, reciprocating movement of the scraper ensures that the sludge layer is progressively moved towards the extraction point.

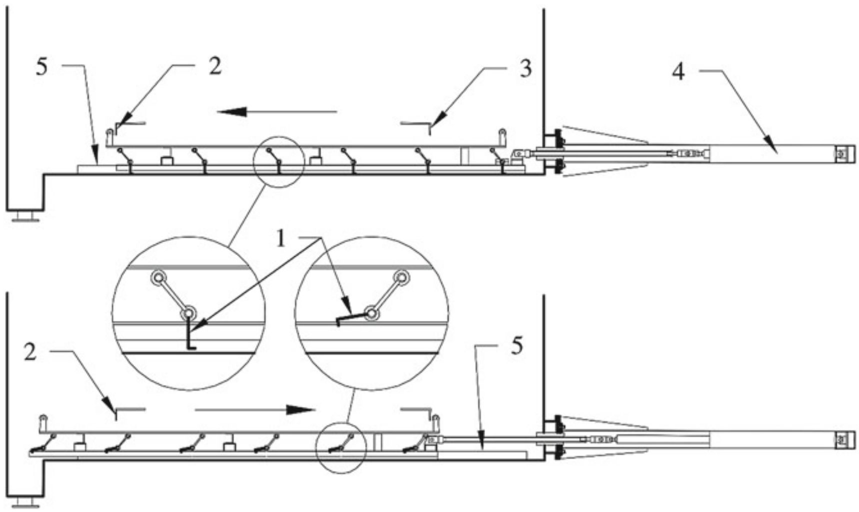

Fig. 4.16 Reciprocating bottom scraper-2. 1—doctor blade, 2—forward stopper, 3—back stopper, 4—pneumatic jack, 5—plastic slide

The versatility of these scrapers means that they can be fitted to all sizes of equipment, both large and small, in concrete or metal tanks.

Another reciprocating scraper, used by KWI, uses tilting doctor blades, which are well suited for pushing large volumes of heavy sludge, usually from industrial effluents (paper, food, etc.…). This is shown schematically in Fig. 4.16. Movement is provided by a pneumatic jack (4). On the outward journey the doctor blades (1) are in a vertical position and push the sludge. Towards the end of the journey a forward stopper (2) swings them into a horizontal position for the return journey, so that they remain above the sludge layer. Towards the end of the return journey the same type of back stopper (3) causes them to swing back to the vertical position for a new operating cycle.

This scraper is well suited for metallic tanks, but can also be used on large concrete tanks. It may look slightly more complicated than the Ziekert scraper, but it is no less reliable. And it operates periodically—one revolution per hour or even every two hours is enough to push even fairly compact sludge in the vast majority of cases.

4.4.4 Screw Conveyors

This bottom sludge collection technique is used mainly in small and medium sized metal tank DAF clarifiers. Such a device is shown schematically in Fig. 4.17. The bottom of the tank is in the form of a 'V' shaped channel, at the bottom of which is installed a screw conveyor that transfers the trapped sludge to a small sump at the end

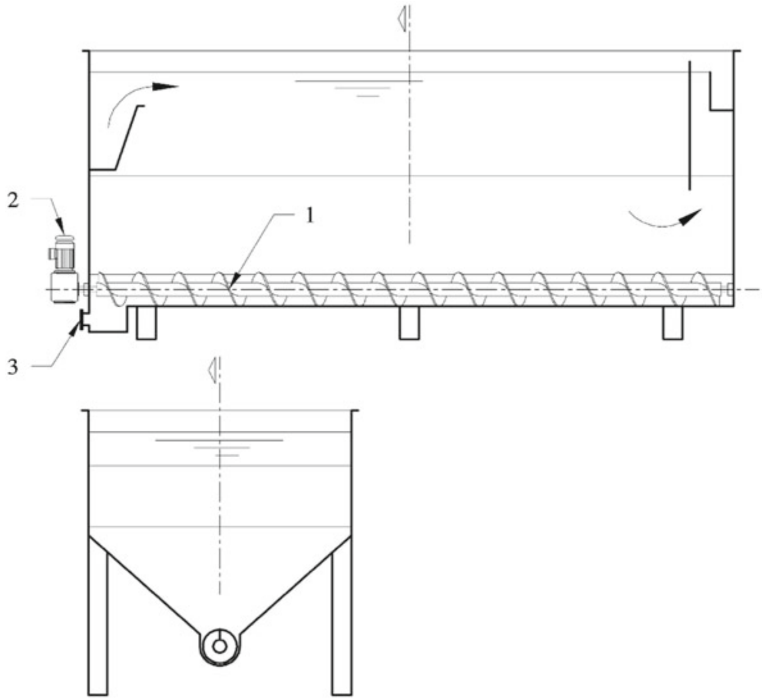

Fig. 4.17 Screw conveyor. 1—screw, 2—drive reducer, 3—bottom sludge outlet

of the tank, usually on the inlet side. The sludge is periodically drained or pumped out. The screw (1) can be either shaftless or with a shaft as shown in the diagram. Its rotation is ensured by a drive reducer (2).

The efficiency of this concept is halfway between that of inverted pyramids and scrapers. Sludge collection is better than with inverted pyramids, but not as good as that offered by bottom scrapers which mechanically clean the entire bottom surface. It has some advantages over inverted pyramids and bottom scrapers, in particular:

– This allows the angle of inclination of the bottom slopes to be increased slightly, thereby reducing the risk of sludge catching on the walls.
– It allows for a single sludge outlet with a single automatic valve, regardless of the length of the flotation tank.
– The construction of the bottom is simpler than that with inverted pyramids.

There is a small disadvantage related to the maintenance of the mechanical part of the screw, i.e. one or two bearings, a seal, the drive…

Chapter 5
Rectangular DAF Clarifiers with Assisted Clarification

As previously mentioned, the hydraulic concept of simple rectangular DAF clarifiers rarely allows hydraulic loads above 8 m/h, in some cases up to 10–12 m/h. This limitation of the hydraulic load is mainly due to the currents caused by the introduction of the water on one side of the tank, rather close to the surface, and the collection of the clarified water which takes place at the end of the flotation zone, rather in depth. This current between the inlet and the outlet, combined, on the one hand with the shallow depth of the water (imposed by transport constraints, but also by space, and budgetary constraints…) and, on the other hand, with an irregular rise of the cloud of air microbubbles along the length of the flotation zone, causes considerable turbulence that disturbs the separation of the flocs. In some cases of oversized pressurisation flow the rise of the microbubble volume, introduced in the contact zone and at the beginning of the flotation zone, is so fast and intense that it even becomes the main cause of these turbulences, more than the longitudinal flow between inlet and outlet.

There are two approaches to reducing this turbulence, improving the hydraulic conditions in the flotation zone, and ultimately, increasing the capacity of the clarifier. The first is to implement lamellar separation by providing the flotation zone with a package of inclined lamellae or 'U' shaped profiles. The second is simply to increase considerably the depth of water in the tank and, more importantly, to provide a homogeneous collection of clarified water covering the entire flotation area so as to reduce direct preferential currents between the inlet and outlet.

These tips allow a very good level of clarification to be maintained at hydraulic loads of 20–30 m/h, and sometimes up to more than 40 m/h in exceptional cases when the adhesion between the flocs and the microbubbles is particularly strong. It must be emphasised that flotation velocities of this range can only be achieved with a chemical treatment that is well adapted to the properties of the water and the flocs formed. It is not uncommon to see promotional literature extolling the virtues of DAF clarifiers operating at 30 or even 40 m/h, without clearly stating that this performance is achievable, in the vast majority of cases (not to say always…), only

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
https://doi.org/10.1007/978-3-031-51869-0_5

with a carefully selected chemical treatment. In practice, the performance of a DAF clarifier depends, of course, on the proper design of each one of its components, but also on the behaviour of the flocs that one seeks to eliminate and it is not very correct to attribute all the merit of success to the DAF clarifier alone. Many experiences show that a mediocre DAF clarifier, working with a well-chosen chemical treatment, can give better results than an excellent DAF clarifier used with an unsuitable chemical treatment.

5.1 Lamella DAF Clarifiers

Before presenting lamellar DAF clarifiers, it would probably be useful to recall some basic elements of lamellar clarification. This technique for separating solids from water was originally developed for sedimentation and was later adapted for flotation. The following description is for flotation, but in reality both are the same phenomenon. The main difference between the two applications is the direction of particle separation. In sedimentation the particles slide downwards on the bottom plate, whereas in flotation the image is, as it were, turned 180°—they slide upwards, under the upper plate of the channel formed by each pair of plates. The aim of this description is to explain the concept and practical side of this technique. The reader who wants to know more theoretical details can find information in the literature available on the subject (especially for the application in sedimentation).

When a few rare particles with a specific weight less than that of water are present in a static volume of water, they can rise without obstacles and their flotation velocity V_f (see Fig. 5.1a) will depend only on their specific weight and the resistance that the water exerts on each particle as it rises. This resistance depends mainly on the viscosity of the water (which depends mainly on the temperature) and the shape of the particle.

The situation changes gradually as the concentration of particles increases. Two phenomena are involved:

- The closer the particles are to each other, the more the microturbulence caused by the rising of each particle disturbs the rising of neighbouring particles.
- As the concentration of particles in the water increases, the volume occupied by these particles increases. At any moment of its ascent, each particle frees the volume it occupied the previous moment. If, at the end of their ascent, all the particles gather in a layer on the surface of the water, then it is obvious that the volume they occupied at the beginning of their journey must be occupied by part of the water that was initially above these particles. In this case, it is easy to see that the rising of the particles forces a certain volume of water above them to descend to occupy the volume deserted by the particles. This results in two currents—an upward flowing cloud of particles rising at a velocity V_p and a downward flowing stream of water at a velocity V_w. In a static volume, the two currents flow through each other, which inevitably slows them down. Thus, the actual ascent velocity

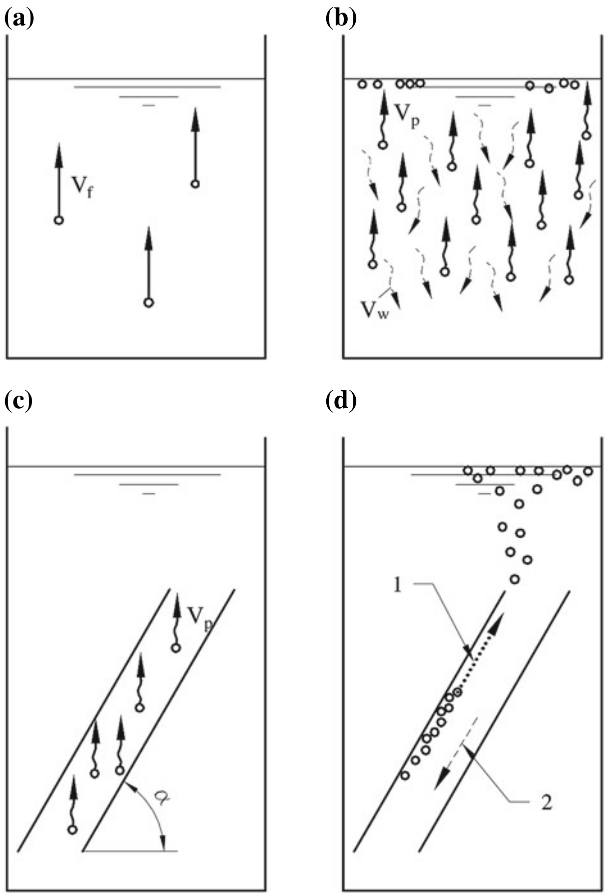

Fig. 5.1 Lamellar separation of floating particles. V_f—flotation velocity of a single particle, V_p—real flotaion velocity of the particles cloud, V_w—downward velocity of water, 1—upward velocity of the particle layer, 2—downward velocity of the clarified water

of each particle is equal to its floating velocity minus the downward velocity of the water ($V_p = V_f - V_w$). And as the concentration of the particles in the water increases, their actual rising velocity decreases (see Fig. 5.1b).

The situation will be different if the separation of the same floating particles described above is made to occur between two parallel inclined lamellae as shown in Fig. 5.1c. In this case each of the particles located between the two lamellae will rise with a velocity V_p until they touch the lower surface of the upper plate. From this moment on, all the particles that have touched the plate will form a layer of sludge that will start to slide under the surface of the plate with a velocity close to the flotation velocity V_f. Once all the floating particles are concentrated in the thin layer of sludge, there will be nothing to disturb the descent of the water. Thus, the channel formed by the two lamellae has created two opposite currents—an upward flow of sludge and a downward flow of water that no longer pass through each other, but cross each other (Fig. 5.1d) with only little disturbance at the frictional interface between them.

If the same experiment is carried out under dynamic conditions, i.e. if the block of lamellae is traversed by a downward current of water (6) (see Fig. 5.2), the same phenomenon is observed. The floating particles entrained by the current between the lamellae descend at a velocity expressed by the vector (2), but their tendency to float V_p deviates from this vector, finally giving them a resultant trajectory expressed by the vector (3) which ends up approaching the upper lamella up to the contact point (4), as shown in the first two channels "a" and "b" of the diagram. The layer of particles (5) accumulated under the surface of the upper lamella goes back upwards in the direction of the vector (1), and the water flow goes down in the lower part of the channel in the direction of the vectors (2), as shown in the channels "c", "d" and "e" of the diagram.

What can be concluded from this diagram and what advantages does this separation technique offer? There are several:

Firstly, it undoubtedly accelerates the flotation of the particles. Initially, the floating particles located between the lamellae rise slowly in the flow at a velocity V_p, but this time lapse is relatively short because the path they have to travel is short. They rise at this velocity only until they touch the bottom surface of the lamella. From this point onwards, the ascent of the layer of particles sliding in the upper part of each channel under the lamella accelerates significantly, as it rises without being strongly resisted by surrounding turbulences and the downward flow of the water.

Secondly, the lamellae package makes it possible to trap floating particles even if the downward velocity of the water flow (6) is very high, much higher than the upward velocity of the particles V_p. In other words, this technique allows the hydraulic load of the flotation surface to be increased significantly. An illustration is given in channel "g" of the diagram. A particle entering the channel formed by the two lamellae is shown in the most unfavourable position, i.e. in the right-hand part of the channel. This particle is in a flow of water, the velocity of which, expressed by the vector (7), is very high. In spite of this very high velocity, the trajectory of the particle allows it to touch the upper lamella, before the water flow which carries it leaves the channel in the lower part. The particle is thus trapped and can rise under the lamellae against a descending water flow at a velocity that would have carried it away if the lamellae were not there.

This demonstration leads to the conclusion that there are two ways of increasing the velocity of the water flow between the lamellae, while keeping the certainty of trapping the particle:

– Reduce the distance between the lamellae. Even if the flow velocity increases, the particle will still be trapped, as its trajectory will hit the upper lamella faster.
– Increase the length of the lamellae. Again, even if the flow velocity increases, the particle will still touch the upper lamella, if the channel formed by the lamellae is long enough.

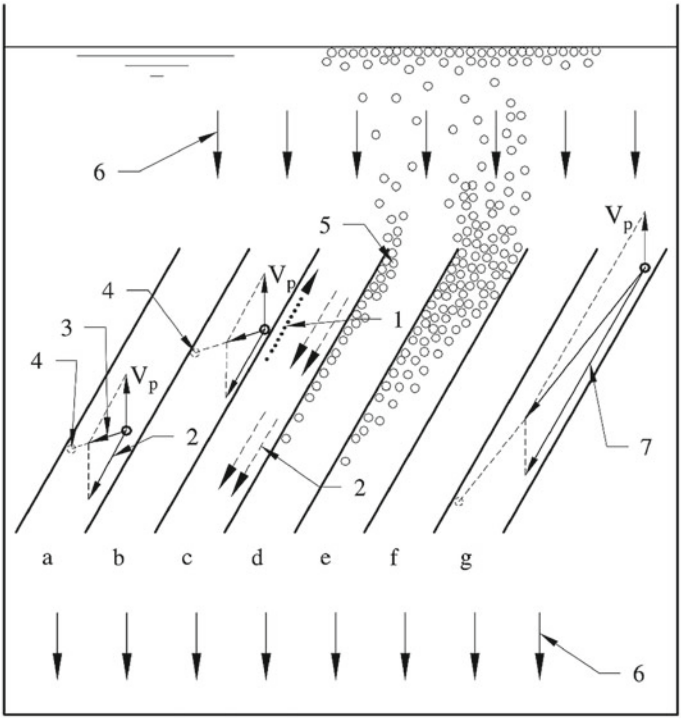

Fig. 5.2 Lamellar seperation of floating particles—details. V_p—real floatation velocity of a particle, 1—upward velocity of the particle layer, 2—downward velocity of the clarified water, 3—resulting trajectory of the particle, 4—contact point of the particle with the lamella, 5—particles layer, 6—water stream

In practice one can use either one or the other, or a combination of both, but always with moderation, because pushing the concept too far leads to embarrassing consequences. For example, it is obvious that the process works well as long as the flow conditions between the lamellae of the two streams remain close to laminar. Reducing the distance between the lamellae too much would end up giving too much importance to the turbulences created by the friction between the water and the surface of the lamellae and, above all, by the friction between the two currents (downstream and upstream). This turbulence would occupy too much space and would ultimately disrupt the laminar flow conditions of each of the layers. In fact, in flotation, a distance between the lamellae of less than 50–60 mm does not significantly improve the separation capacity of the lamellar pack. Usually the optimum distance is considered to be around 70–80 mm. Therefore, increasing the length of the lamellae should theoretically increase the separation capacity of the lamellar pack to infinity. In reality, too high a downward velocity of the water between the lamellae will eventually become incompatible with a more or less laminar flow regime. In practice, the length of the lamellae rarely exceeds 1200 mm, even with a distance between the lamellae of 80 mm. To summarise, one can say that most often the distance between the lamellae is in the range of 70–80 mm for a length of 10–15 times this distance, i.e. 700–1050 mm for a 70 mm distance between the lamellae and 800–1200 mm for an 80 mm distance between the lamellae. The optimum angle of inclination (α) is usually 50–60° to the horizon. Increasing it would reduce the benefit of the design and decreasing it below 50° would increase the friction of the floated sludge layer on the top plate too much.

Thirdly, it is easy to see that this separation technique works well as long as the layer of particles, moving up the lamellae, remains relatively thin, as shown in channel "d" in the diagram. If this layer becomes too thick, as shown in channel "e", it will start to obstruct the channel inlet and the incoming water flow will tend to push it back between the lamellae, preventing it from exiting. The process then becomes unstable and easily stalls. This is why, in practice, this separation technique is mainly dedicated to waters with low TSS concentrations—a few dozen to a few hundred mg/l at most.

And fourthly, the concentration of the particles below the surface of the upper lamella of each channel allows them, in most cases, to cling to each other in such a way as to form larger and more solid agglomerates, which could float to the surface more easily than each individual particle. Otherwise, even if the clarification between the lamellae works well, when returning to the "inlet" space above the lamellar block, the particles will be re-dispersed by the flow and re-entrained between the lamellae. The technique will then lose some of its effectiveness.

The configuration in Fig. 5.2 shows a lamellar pack with a downward flow through it. Water enters at the top of the block and exits at the bottom. The separated sludge flows upwards back into the inlet space. This configuration is called "counter-current"—the clarified water and sludge form opposing streams. In this configuration these two currents slightly disturb each other, but it has the major practical advantage of clearly separating the two phases. The clarified water is collected at the bottom and the floated sludge—at the top of the lamellar pack. For this reason it is by far the most commonly used configuration in practice.

However, there are two other configurations in which the lamellar separation technique can also work. The first of these is called "co-current" and consists in introducing the water under the lamellar pack and exiting it above the pack. In this case, the lamellar separation works even better than in the counter-current configuration, because the two streams of floated sludge and clarified water no longer cross each other, but go together in the same upward direction. The friction between the two streams is lower and causes less disturbance to the separation. In addition, this configuration allows a large amount of particles to be separated, without the layer formed being able to “clog” the flow inlet. In short, this configuration has its advantages, but it has a major disadvantage: the floated sludge layer and the clarified water stream exit from the same side of the lamellar pack. And the separation of the two phases, exiting from each channel, is a headache that has never found a “real” solution easily applicable in practice, despite the few attempts to implement this separation method. It is not that it is impossible to do, but the compromises to be accepted are quite discouraging… The second configuration is called “cross-flow” and consists of introducing the water through the sides of the lamellar pack. The clarified water is then collected at the bottom of the lamella pack and the sludge—at the top. This configuration has its advantages and has many applications in lamellar sedimentation, but is difficult to implement in flotation. The reason for this is that the hydraulic loads in flotation are much higher than in sedimentation. Therefore, by introducing a large flow of water to the sides of the lamellar block(k), it is difficult to expect a good flow distribution and change in water direction, while maintaining some semblance of a laminar flow regime. Not to mention the additional turbulence caused by the powerful upwelling of the microbubble cloud near the water entry zone.

The three modes of lamellar separation are shown schematically in Fig. 5.3. It shows a flat lamella implementation, but in reality manufacturers often opt for corrugated lamellas or honeycomb structures forming different inclined tube profiles. These profiles offer two advantages over flat lamellas. Firstly, they have a larger developed surface area and the corrugations (or honeycombs) form rising channels that facilitate the aggregation and collection of floc clusters. Secondly, corrugated plates, and even more so honeycomb structures, give a much better rigidity of the lamellar block than flat lamellae, which facilitates their installation. On the other hand, corrugated sheets and honeycomb structures are almost always made of plastics with a sometimes slightly rough surface. In addition, some plastics have hydrophobic properties and can interact with the electrostatic charges of the flocs. It should not be forgotten that coagulants and especially polymers are often used in flotation, which can be deposited on the lamellae over time and have electrostatic charges, which can make the flocs a little sticky on certain surfaces. For this reason, it is essential to choose the material of construction of the lamellae carefully in order to avoid too much and too fast fouling of their surface. Corrugated sheets are more difficult to clean than flat sheets, but honeycomb structures are even more difficult to clean.

For the counter-current configuration, which is by far the most commonly used one, the sizing of the capacity of a lamellar pack is done according to three parameters:

– The angle of inclination of the lamellae—most often 60°, sometimes 50°, to the horizon.
– The distance between the lamellae.
– The length of the lamellae.

These three parameters are used to calculate the projected area of the lamellae in relation to the bottom of the flotation zone. The ratio of the plan area of the flotation zone to the sum of the projected areas of the lamellae of the lamellar pack, covering this zone, gives the multiplication coefficient of the clarification capacity of the lamellar pack compared to a flotation zone without lamellar pack.

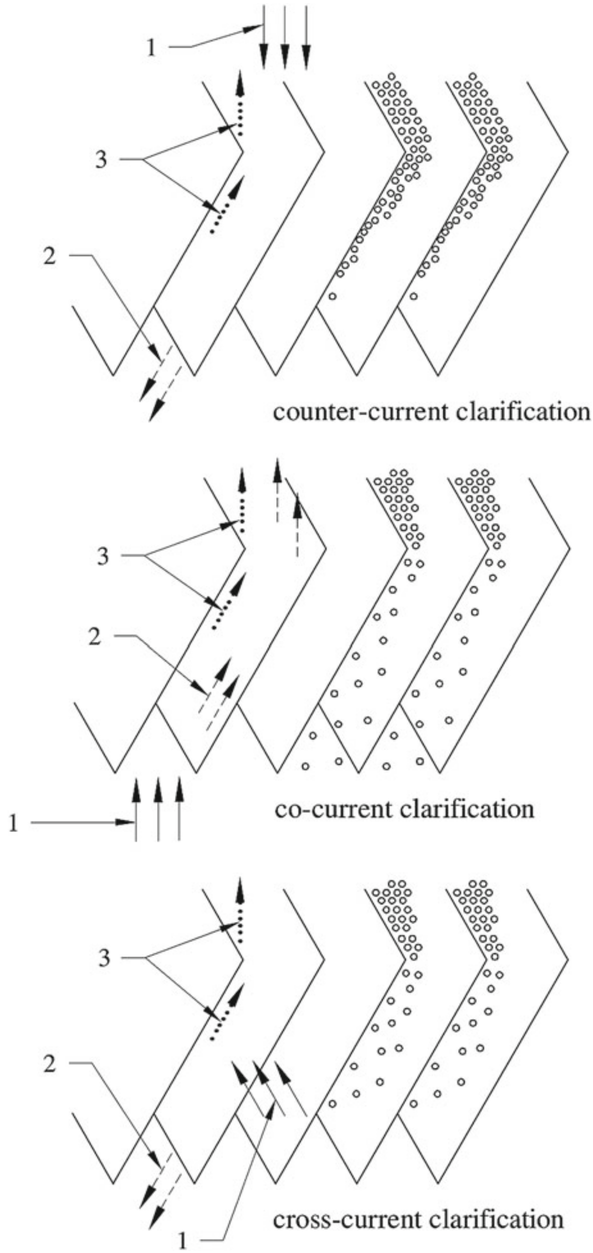

Fig. 5.3 Types of lamellar separation of floating particles. 1—raw water stream, 2—clarified water stream, 3—floated sludge

For example, if the flotation area is 10 m^2 (say 2.5 $\times$ 4 m) and the acceptable hydraulic load for a given application is, say, 8 m/h, then this DAF clarifier without a lamella pack (i.e. non-assisted clarification) will be able to handle a total flow of 8 $\times$ 10 $=$ 80 m^3/h. If the flotation zone contains a lamella block consisting of 1000 mm long lamellae, spaced at 80 mm and inclined at 60°, then this pack will contain 36 lamellae of 2.5 m width with a total projected area of 45 m^2. This total projected area is 4.5 times larger than the plan area of the flotation zone (10 m^2). Therefore, an increase in clarification capacity of 4.5 times can be expected, resulting in an acceptable hydraulic load of 4.5 $\times$ 8 $=$ 36 m/h, or a flotation capacity of 10 $\times$ 36 $=$ 360 m^3/h. This is, however, the theoretical calculation. In practice it would be wise to take into account some factors influencing this "ideal" picture, which will be discussed hereafter.

Figure 5.4a,b show schematically vertical longitudinal sections of the two main concepts for implementing lamellar clarification in flotation. The inlet (1) to the contact zone and the white water injection are similar to those of non-assisted DAF clarifiers. The collection of floated sludge by the surface scraper is done in co-current (Fig. 5.4b) or, probably more often, in counter-current (Fig. 5.4a).

According to the concept shown in Fig. 5.4a, the water exits the contact zone above the lamella pack (6) and then descends between the lamellae. The clarified water exiting below the lamella block is discharged through the collection channel (7) located on the opposite side of the inlet. It leaves the unit through an outlet channel (8) equipped with a weir to maintain the level in the tank. This concept works well, as long as the distribution of the water above the lamella pack and, respectively, the collection of the clarified water below said pack remain relatively homogeneous with respect to the surface, so that the water flow is distributed in equal portions between each pair of lamellae. In reality, it is difficult to balance this distribution perfectly, but if the horizontal velocity of the water leaving the contact zone remains low, if the water layer above the lamellar pack is deep enough to ensure a smooth change of direction of the water, and if the space below the lamellar pack is also large enough for the same reasons, then the water can be considered to flow through the lamellar pack more or less homogeneously over the whole flotation surface. The constraints of transport and height limitation of rectangular tanks (hydrostatic pressure requires large reinforcements of the tank walls) reserve this concept for small flows. It is difficult to set precise limits on the proportions to be respected, but one can say that the shorter the lamellar block, the deeper the water layer above it, the lower the inlet of the clarified water channel (7) and the better the distribution of the water through the lamellae. This hydraulic problem is best understood by looking at the second concept shown in Fig. 5.4b. It is obvious that if the lamella block is very long, collecting the clarified water in a single point, opposite the inlet, would not be the optimal solution, as it must be kept in mind that the water follows the path of least resistance. If the block of lamellae is not there, the water will go directly, in a straight line, from the outlet of the contact zone to the point of collection of the clarified water, without worrying about passing in equal portions between each pair of lamellae, as one would wish.

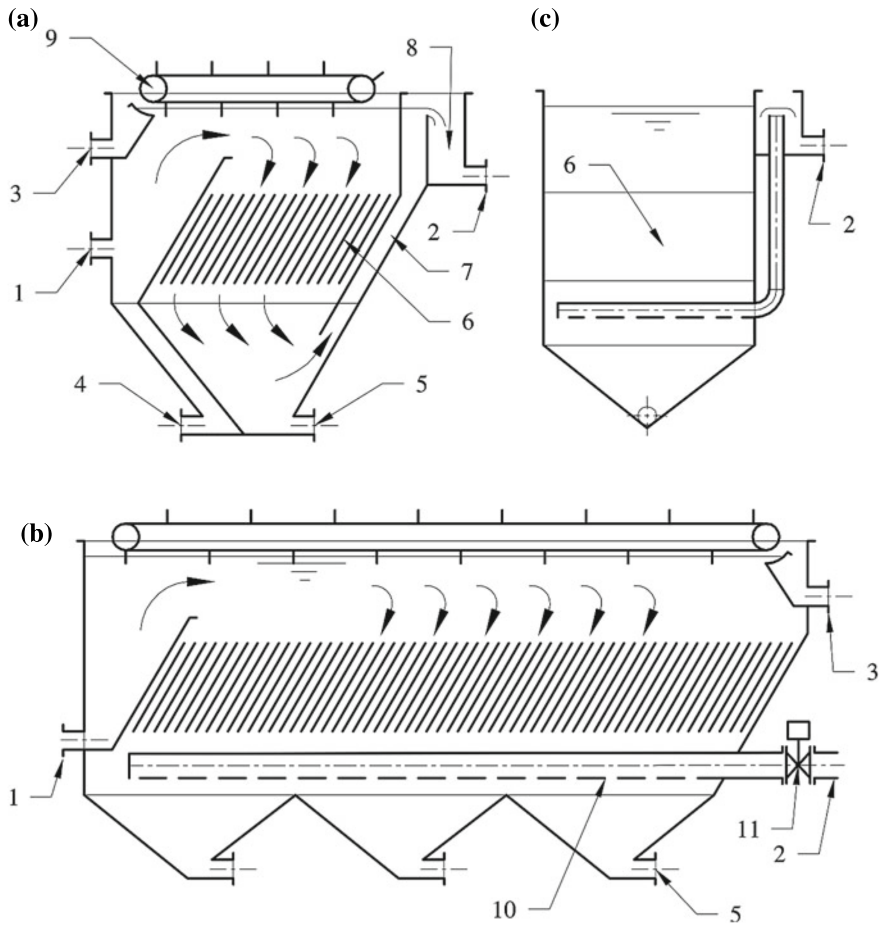

Fig. 5.4 Counter-current lamellar DAF clarifiers. 1—inlet, 2—clarified water outlet, 3—floated sludge outlet, 4—heavy sludge outlet, 5—settled sludge outlet, 6—lamella pack, 7—clarified water channel, 8—clarified water outlet channel with weir, 9—surface scraper, 10—clarified water collector, 11—automatic level control valve

Therefore, it would be better to force it to follow the desired path. The best way to do this would be to have a homogeneous distribution of the water above the lamellar pack and, respectively, a homogeneous collection of the water under the pack. A homogeneous distribution device above the lamellae is, unfortunately, difficult to design without creating turbulences incompatible with the flocs rising through this zone. However, there are a few attempts to implement such a concept, but they do not fully solve the problem. They consist of introducing water through several orifices arranged along the side walls of the tank just below the water surface. Pressurised water is injected upstream of each orifice.

On the other hand, it is quite possible to install one or more perforated clarified water collectors (10) offering an acceptable compromise of relatively homogeneous water collection under the entire surface of the lamellar pack. In this case, the maintaining of the water level is usually entrusted to an automatic control valve controlled by a level sensor, as the installation of a mechanical weir sometimes causes some hydraulic problems. A clarified water collector (10) shown in Fig. 5.4b is arranged along the length of the tank in the direction of the water distribution. Depending on the size of the unit there may be several of these collectors. Some manufacturers prefer to install several collectors across the width, perpendicular to the direction of the water distribution, and to raise these multiple collectors into a channel arranged at the top, along the tank. The outlet of each manifold also acts as a weir to maintain the level. This concept is illustrated in Fig. 5.4c, showing a vertical cross-section, widthwise, of a variant as described in Fig. 5.4b. In both cases the end result is the same, only the modes of maintaining the level differ.

As mentioned earlier, the most commonly used configuration is the counter-current configuration, as it allows a clear separation of clarified water from floated sludge. However, its operation has some specificities that deserve a more detailed examination.

1. The longer the lamellar pack, the more important it is to have a deep water layer above this lamellar pack. This is because the longer the lamellar pack, the greater the flow to be treated and the shallower the depth of water above the pack, the higher its velocity above the pack as it leaves the contact zone. Therefore:

   – This horizontal velocity will strongly disturb the ascent of the separated flocs in the first part of the lamellar pack, as this is where it will be the highest. It will be very low towards the end of the lamellar pack where the conditions for the rise of the flocs will be much more favourable. On the other hand, the concentration of free air bubbles at the exit of the contact zone is very high, which partially compensates for the negative effect of turbulence, because the presence of a large number of free bubbles strongly favours flotation, which takes advantage not only of the air bubbles associated with the flocs, but also of the mass of bubbles rising towards the surface which drags the flocs in their ascent.
   – This horizontal velocity will disturb the homogeneous distribution of the water equally between each pair of lamellae, the disturbance being stronger at the beginning of the lamellar pack and much less pronounced towards the end of the pack where the horizontal velocity is low or almost zero. The greater the water velocity, the more energy is required to change its direction. The change of direction will be much easier towards the end of the block and it is the last pairs of lamellae that will receive the most flow, even if the collection of clarified water under the lamellar pack is perfectly homogeneous.

2. The mass of free air bubbles slowly rises to the surface as the water moves over the lamellar pack, so that the thickness of the bubble cloud gradually decreases. It is important that this cloud is not completely depleted towards the end of the

pack, as it plays an important role in the rise of the flocs separated by the lamellae. In reality, these flocs return, as it were, to the inlet space where their ascent is not assisted by the lamellar effect. Thus, their entrainment towards the surface by the free bubbles is very beneficial.

3. The phenomena and the course of the process described above also depend on the sizing method and especially on the quantity of white water. In most cases, the majority of the sludge will rise to the surface directly, thanks to the air bubbles associated with the flocs and their entrainment in the mass of free bubbles. Thus, the lamellae, most often located under the microbubble cloud, only serve as a "finishing treatment" to trap the last few flocs remaining under the bubble cloud, which have a somewhat reduced buoyancy since, to rise, they can only rely on the air bubbles trapped in their structure or attached to their surface. At the same time, if the pressurisation rate is very high (say over 300–400 L of air per hour and per m^2 of flotation area) and if the microbubbles hold well, then the cloud of microbubbles can descend inside the lamellar pack. In this case the result can be impressive as the efficiency of the lamellar separation is visibly boosted by the free air bubbles rising between the lamellae. Such a configuration is, of course, very efficient, but requires a high pressurisation rate, which may be oversized in many cases. This is easier to achieve in a short lamellar flotation tank (Fig. 5.4a) than in a long flotation tank (Fig. 5.4b).

In conclusion, it is important to underline that the description of some aspects of the process proposed above is based on the author's personal observations and experiences. It is far from covering all possible applications and configurations that may be encountered in the practice. There are so many factors involved that it is difficult to propose a method for sizing this type of DAF clarifiers. Usually, the developed surface of the lamellae and the Hazen velocity (V_{HZ}) are used as a basis

$$V_{HZ} = \frac{Q}{S_P},\ \mathrm{m/h}$$

Q—flow rate, m^3/h.

Sp—sum of the projected area of the lamellae, m^2.

If the size of the lamellae, the distance between them and the arrangement of the lamellar pack in the tank are well chosen, the Hazen velocity (V_{HZ}) can vary within the limits of 18–20 to 30 m/h, but these are only indicative values that are difficult to use as they are without taking into account the specificities of the effluent, the chemical treatment etc.

Lamellar DAF clarifiers can also be classified according to the arrangement of the lamellae in the lamellar pack. Those shown schematically in Fig. 5.4 have a horizontal arrangement, as the row of lamellae runs horizontally. However, it is possible to use the same clarification technology by arranging the lamellae in a vertical row. There are even two different types of lamellae used in this configuration. It is possible to use flat lamellae as shown in Fig. 5.5 or stacks of cones forming a kind of lamellar pack as shown in Fig. 5.6a,b.

Figure 5.5 shows a conceptual sketch of a DAF clarifier with a cylindrical tank (5) (stronger and lighter than a rectangular tank requiring reinforcements) in which a lamellar pack (10) of plane lamellae is installed with a clarified water collection space (8) at the lower side of the lamellae. The raw water mixed with white water is introduced into the lower part of the cylindrical tank and circulates outside the lamellar block which is closed on all sides except the water inlet side (9). The water level is controlled by an automatic level control valve (11) and a level transmitter. The floated sludge, separated by the lamellae, passes back through the inlet space and rises to the surface. The sludge collected at the top of the tank can be scraped by a rotating scraper or a chain scraper (as shown) or by paddle wheels. In the last two cases the cylindrical tank (5) is equipped with a transition piece from round to rectangular (6) allowing the installation of the chain scraper or the paddle wheels. The sludge settled at the bottom is periodically flushed out through the outlet (4).

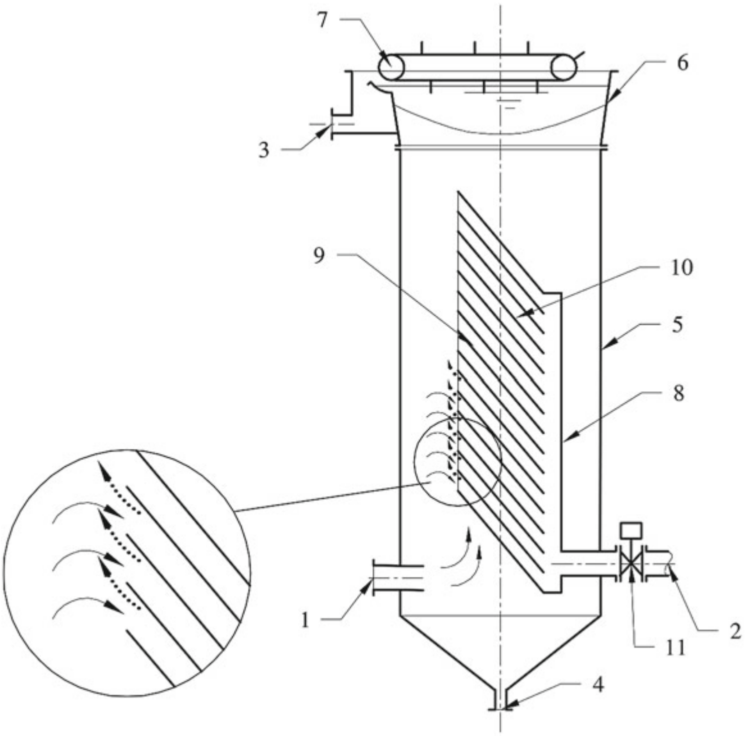

Fig. 5.5 DAF clarifier with vertical lamellar pack. 1—raw + pressurised water inlet, 2—clarified water outlet, 3—floated sludge outlet, 4—settled sludge outlet, 5—cylindrical tank, 6—rectangular top of the tank, 7—surface scraper, 8—clarified water collector, 9—raw water inlet in the lamella package, 10—lamella pack, 11—automatic level control valve

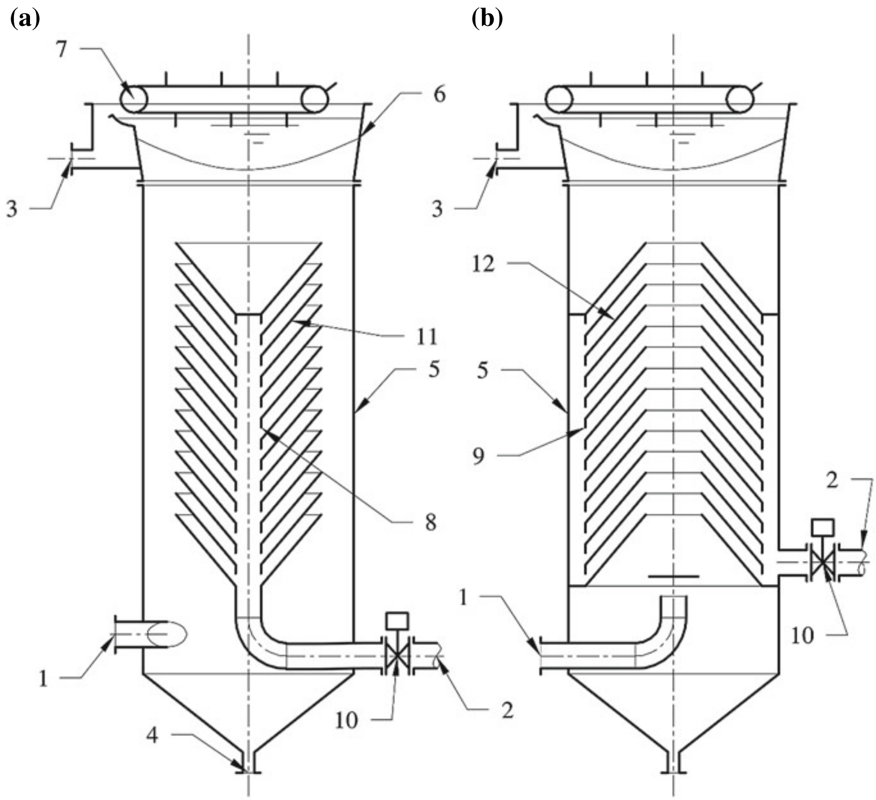

Fig. 5.6 DAF clarifiers with conical lamella pack. 1—raw + pressurised water inlet, 2—clarified water outlet, 3—floated sludge outlet, 4—heavy sludge outlet, 5—cylindrical tank, 6—rectangular top of the tank, 7—surface scraper, 8—central clarified water collector, 9—double clarified water collection wall, 10—automatic level contol valve, 11, 12—conical lamella pack

The two possible vertical configurations using cone stacks are shown schematically in Fig. 5.6.

The first, shown in Fig. 5.6a, has a stack of conical lamella (11). Raw water, mixed with white water, flows between the conical lamella pack (11) and the cylindrical wall of the tank (5). It enters from the outer side of the cones and the collection of the clarified water is achieved by the central clarified water collector (8) located in the axis of the cone stack. The velocity of water flow between the cones is variable - it is low towards the entrance of each channel and increases as it moves down towards the centre. Water level control and floated sludge collection can be achieved as in the previous case.

The second possible configuration shown in Fig. 5.6b is, in a way, the reverse of the first. The raw water + white water mixture flows along the axis of the cylindrical tank (5) and enters between the cones on the small diameter side. The clarified water is collected on the large diameter side of the cones in the space between the tank wall

(5) and the double clarified water collection wall (9). The velocity of the water is high at the inlet of the cones and decreases as it descends towards the double baffle (9).

A comparison between the two stacked cone concepts leads to the conclusion that, at equal distances between the cones and equal lengths of the lamellar channels, the projected area of the cones in the second, internally-fed configuration is about 30–40% larger, which is considerable. On the other hand, the water entry velocity into the lamellar channels in this second, centrally fed design, is about 2.5 times higher compared to the externally fed design, which is clearly a disturbing factor, even though this higher velocity could lead to more free microbubbles inside the channels, which is rather beneficial… Thus, it is difficult to give a clear and unquestionable preference to one or the other of the two concepts, as it is difficult to evaluate the impact of both factors on the performance of lamellar separation. Is it better to have more developed surface area, even if the inlet to the channels is more turbulent and the flow pushes the floated sludge inside the channels preventing it from exiting, or is it better to have less developed surface area, but a smooth entry of the water between the cones, favouring the exit of the separated sludge. In both cases an accurate calculation of Hazen velocities is impossible, as the velocity and flow regime of the water within the channels is variable and the design must surely be based mainly on the experience of the manufacturer. It would seem that there is no precise method for sizing this type of lamellar pack, especially as the separation behaviour in either design could be expected to vary with the amount of TSS at the entrance to the lamellar channels, the specific properties of the flocs, the amount of free air bubbles entering the channels, etc. However, it would appear that the first, externally fed configuration (Fig. 5.6a), is more commercially successful than the other two (Figs. 5.5 and 5.6b).

All three configurations have the advantage of further reducing the footprint of the DAF clarifier, since as the flow rate increases, the DAF clarifier grows mainly in height. On the other hand, the rise of the floated sludge along the row of lamellae (or cones respectively) means that, as it rise, each lamellar channel recovers at least a small part of the floated sludge separated by the lamellae below. Thus, the TSS concentration in the inlet space increases on the way up, which inevitably disturbs the clarification, as more and more sludge penetrates between the lamellae making it more and more difficult to remove the separated flocs. The design in Fig. 5.6a is the least affected by this problem because the water inflow velocity into the lamella channels is the lowest due to the large circumference of the cones.

The first attempts to use lamellar clarification in flotation probably date back to the early 1960s, with varying degrees of success depending on the application. Over the years, the technique has evolved and shown its advantages, but also its limitations. Experiences in drinking water clarification were generally positive, until it was realised that it was possible to achieve comparable hydraulic loads without the use of lamellae. Applications in wastewater have been quite successful and this type of DAF clarifier, especially the small ones (Fig. 5.4a), has found a market in the clarification of many industrial effluents. However, there is still the problem of fouling of the lamellae, the need for periodic cleaning resulting in the shutdown and emptying of the plant and some associated maintenance costs. This constraint is even more pronounced with vertical clarifiers, whether with flat or conical lamellae—their cleaning is very difficult if not impossible. For these reasons, some applications should be avoided if possible, especially those involving effluents containing a lot of waxes, fats and other sticky materials that are difficult to flocculate. Having said that, there are nevertheless many references of this type of DAF clarifiers in such applications as their small footprint is a very valuable advantage in certain cases.

5.2 DAF Clarifiers with "U" Shaped Elements

This clarification technology has been developed and commercialised by KWI. It offers a configuration that aims to avoid, at least partially, some of the disadvantages of conventional lamellar clarification described in the previous chapter. The core of the concept is a row of U-shaped profiles (see Fig. 5.7). Each U-shaped profile (6) has, at the bottom of the U, a clarified water collection channel (7) extending along the profile. This channel opens into one or two lateral clarified water collectors (9) through an outlet (8) in the side wall of the tank. Arranged side by side, these profiles, inclined at an angle of 50°–60° (like the lamellar plates), form a succession of lamellar channels. Each U-shaped element forms a channel operating in counter-current and each pair of profiles forms a channel operating in co-current clarification. The raw water, mixed with the white water, enters under the U-profile pack via one or more perforated feeding pipes (5), which allow a homogeneous distribution under the whole U-profile pack. The water first passes between the profiles, the walls of which form a co-current lamellar channel in the direction of the arrows (12).

During this first upward passage, a first lamellar separation takes place according to the co-current principle. The floated sludge separated in this channel rises to the surface in the direction of the arrows (13) and (14), guided by the long plate of the left side profile of each pair of profiles. At the end of the co-current channel the water, partially or almost completely clarified, makes a 180° turn in the direction of the arrow (15) to enter the U-shaped profile and head towards the collection channel (7) located at the bottom of each profile. During this second downward passage, a second lamellar clarification takes place according to the counter-current principle. The clarified water leaves the DAF clarifier via the collection channel (7), the outlet (8), the side collector(s) (9), the main collector (10) connecting the side collectors (9) and via the automatic level control valve (11). The floated sludge separated in the counter-current channel rises in the direction of the arrow (16) to mix with the floated sludge in the co-current channel (13) and reach the surface in the direction of the arrow (14). In real operation, the water clarified in the co-current channel and entering the counter-current channel is almost completely clarified and contains only a very small amount of flocs. These flocs are easily separated in the counterflow channel, resulting in a small volume of floated sludge.

This configuration using the U-shaped profiles offers several advantages compared to the "traditional" counter-current lamella pack.

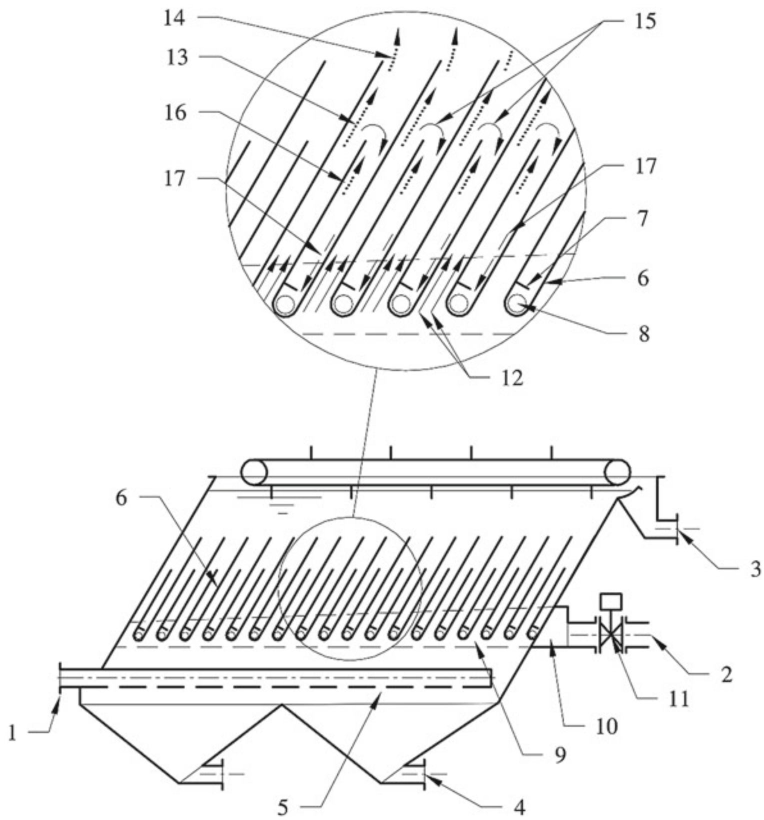

Fig. 5.7 DAF clarifier with horizontal “U” shaped profiles pack. 1—raw + pressurised water inlet, 2—clarified water outlet, 3—floated sludge outlet, 4—bottom sludge outlet, 5—perforate feeding pipe, 6—“U” shaped profile, 7—clarified water channel, 8—clarified water outlet, 9—clarified water side collector, 10—main clarified water collector, 11—automatic level control valve, 12—raw + pressurised water introduction in the “U” shaped profiles pack, 13—co-current floated sludge, 14—floated sludge, 15—co-current clarified water, 16—counter-current floatead sludge, 17—counter-current floated sludge

Firstly, it allows for a homogeneous distribution of raw water under the entire flotation surface, without the distribution device causing any interference with the clarification. The collection of clarified water is also homogeneous over the entire flotation surface, as each “U” shaped element collects an equal portion. Therefore, there are no horizontal currents in the flotation zone that interfere with water distribution and the floated sludge upwelling.

Secondly, this configuration allows the two modes of lamellar clarification to be used optimally, taking full advantage of each. For example, co-current clarification offers an excellent separation capacity for large quantities of sludge, especially as the concentration of air microbubbles in the co-current channels is very high (in fact they all pass through there…). On the other hand, the separation of clarified water from sludge is not optimal. But this is not very important, because the following counter-current clarification channel is perfectly comfortable with some recalcitrant flocs which are separated there without difficulty.

Thirdly, the floated sludge separated by the lamellae does not return to the “inlet” space upstream of the lamellar pack. It is collected in the space above the U-shaped element pack, which is reserved exclusively for it. In this space there are no currents and the sludge thickens in the best possible conditions.

The main disadvantage (which is common to all lamellar DAF clarifiers) is the risk of fouling of the plates forming the U shaped elements and especially the collection channels for the clarified water. Here this problem is partially solved by the use of stainless steel plates with a special surface treatment that strongly reduces the adhesion of sludge on the plates. Thus, cleaning with a simple water jet is efficient and relatively easy.

These advantages allow this type of DAF clarifiers to operate at a hydraulic load of the flotation zone from 20 m/h to over 30 m/h and up to 50 m/h in certain applications. Sizing is based on a specific, specially developed test or by experience. Because it is not really possible to consider this technology as a simple lamellar clarification, even if it uses this technique in a certain way. Calculating the projected area of the U-shaped elements components is not very useful, as the two clarification modes do not work in the same way and, in addition, the flow is interrupted when the water passes from one to the other.

Figure 5.8 shows schematically the vertical version of this technology. The concept is the same: raw water is distributed at the closed side of the U-shaped profiles and floated sludge is collected in the space at the open side of the elements. The water circulation inside the profile pack is identical with the horizontal version. The floated sludge is collected by a spiral scoop (18). Small and medium size units (up to 150–200 m^3/h) have a cylindrical tank, as shown in Fig. 5.8. For larger sizes, the “U” shaped elements are installed in two or four rectangular modules joined at the top by a cylindrical section for the floated sludge collection. This configuration allows the construction of clarifiers with a capacity of up to 1000 m^3/hr for a footprint of only 4500 × 4500 mm. It is, however, relatively more expensive, as the flat walls of the rectangular tanks require a lot of strong reinforcement.

This technology has also been adapted to concrete tanks. In this case, only the modules containing the U-shaped profiles are made in stainless steel. This allows the flotation tank to be incorporated into the structure of other concrete tanks, such as the aeration tank, but also, more generally, to build very large flotation tanks, especially based on the vertical version. This is the case, for example, for clarification applications of municipal effluent after biological treatment in MBBRs or for clarification of biofilter wash water. For clarification of such effluents containing a few hundred mg/l of TSS with in-line flocculation, the concept allows to operate at hydraulic loads of 30 to 40 m/h in relation to the flotation area, with almost no limit to the individual capacity of the clarifier, which can reach more than 2000 m^3/h. In biological sludge thickening, the SS load at the flotation surface varies from 30 to 50 kg/m^2.h with standard flocculant dosing of 1.2–2 kg/ton DM.

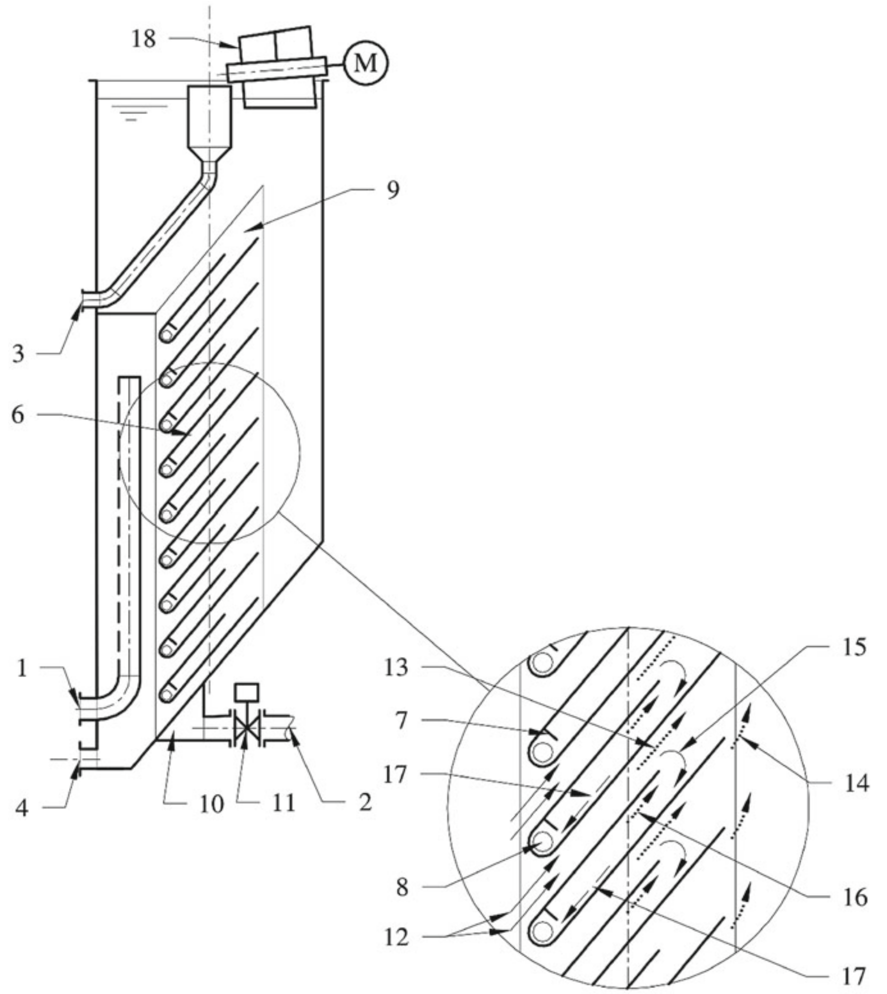

Fig. 5.8 DAF clarifier with vertical "U" shaped profiles pack. 1—inlet, 2—clarified water outlet, 3—floated sludge outlet, 4—bottom sludge outlet, 5—perforate feeding pipe, 6—"U" shaped elements, 7—clarified water channel, 8—clarified water outlet, 9—clarified water side collector, 10—main clarified water collector, 11—automatic level control valve, 12—raw + pressurised water introduction in the "U" shaped elements package, 13—co-current floated sludge, 14—floated sludge, 15—co-current clarified water, 16—counter-current floated sludge, 17—counter-current clarified water, 18—spiral scoop

The majority of these clarifiers are used for wastewater clarification. They are installed in many plants in the paper, food and oil industries, both in refinery effluent treatment and in produced water treatment. There are also many references in clarification and thickening of all kinds of biological sludge.

Chapter 6
High Hydraulic Loading Rectangular Clarifiers with Non-assisted Clarification

Although there are many forms and designs of different types of rectangular DAF clarifiers, the focus of this chapter will be on large ones, operating at high hydraulic loading (20–40 m/h), which are used for the clarification of natural waters and seawater for drinking water production. These clarifiers have certain design and operational features that differentiate them from the simple rectangular non-assisted clarification DAF clarifiers described in Chap. 5. Their development over the years has been favoured by the growing importance of the issues related to their use. Indeed, several factors have come together:

- The flows to be treated in this domain of application are often very large—several thousand, or even, in some cases, several tens of thousands of cubic metres per hour. Thus, the financial stakes in terms of construction costs, space occupied by the facilities and operating costs become sufficiently motivating to justify a substantial investment in research and development.
- The nature of the application imposes a strict obligation of results in terms of performance and operational reliability.
- Large drinking water production facilities are, logically, the domain of large water companies, which have the resources to invest in the development of these flotation systems. It would be fair to point out, however, that the pioneers were, as is often the case, a few small companies who laid the foundations of the concept which was then taken up and developed by some of the major players in the water sector.

As a result, several of the major equipment manufacturers have developed their own versions, which have their own commonalities, differences and specificities.

Let's recall the main challenges that these clarifiers have to face:

- They must be as compact as possible, in order to reduce construction costs and occupied space (which is often a major issue) as much as possible. In other words, the coagulation and flocculation time must be reduced to the strict minimum necessary to reduce the volume of these tanks. In the same way, the hydraulic load of the flotation zone must be increased as much as possible (but within

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
https://doi.org/10.1007/978-3-031-51869-0_6

reasonable limits) to reduce not only the volume of this part of the apparatus, but also the cost of the corresponding equipment.

- They should have as few moving parts and 'sensitive' equipment that require maintenance and replacement as possible. This implies careful design and construction material selection.
- They should consume as little energy as possible, mainly for pressurisation. The efficiency of the saturators should be as high as possible and the pressure relief devices—the most efficient, but also the most reliable. It may also be advantageous, in some cases, to have some flexibility in the pressurisation rate to adapt it to varying operating conditions.

Reducing the volume of the coagulation and flocculation tanks is not a simple thing and it is difficult to establish precise sizing criteria. This is demonstrated by the different sizing methods encountered in practice. Thus, depending on the quality of the water and the allocation of coagulation and flocculation times, coagulation tanks can be sized for a residence time ranging from a few tens of seconds to ten or even fifteen minutes. Flocculation can also last from a few minutes (5–8 min for water that is easy to flocculate) to 20–30 min, or even longer for cold and soft water. Whether or not flocculant is used for flocculation can also change the conditions and time of flocculation.

The hydraulic loading of the flotation zone has also evolved considerably. There are still installations operating at 10–12 m/h, but also large installations operating at nearly 40 m/h. Obviously, it is recommended, and in the case of large installations even mandatory, to confirm all the sizing parameters in real conditions with a pilot plant, covering a period of several months, to test possible seasonal variations in water quality. In any case, it is important to underline, once again, the importance of a thorough analysis of the water characteristics and the chemical treatment to be implemented, as only a proper chemical treatment would allow the DAF clarifier to reach its best performance and offer the best possible clarified water quality.

As mentioned above, there are several versions of this type of DAF clarifiers, implementing different combinations and designs of the main elements. For a better understanding of the specifics of their operation, it would be simpler to consider each of these elements separately in the following paragraphs.

6.1 Coagulation and Flocculation Tanks

The first step in chemical treatment, after an eventual pH correction, is coagulation. Even if there are installations that use a static mixer for mixing the coagulant (which, by the way, can give complete satisfaction in many cases), the "classic" tank with a mechanical mixer remains the reference device for cases that require a coagulation time of more than a few tens of seconds, especially when one seeks to obtain a well-formed microfloc. There are three different ways to achieve coagulation.

The first, and least expensive, is a simple static mixer. This type of device ensures a satisfactory distribution and mixing of the coagulant in the water flow, but does not always generate sufficiently strong and sustainable shear forces and turbulence for optimal coagulation, especially for more difficult waters. This shortcoming is particularly noticeable when the flow rate decreases significantly from the maximum design flow rate. This can be remedied by using several parallel lines, each equipped with its own static mixer, which allows the isolation of one or two of the lines in the event of a drop in flow, but this solution is rarely used in practice.

The second method is flash-mixing, which uses a propeller mixer to provide a very rapid, violent and efficient dispersion of the coagulant. The residence time in the tank is in the range of 30–45, sometimes up to 60 s, with a velocity gradient G in the range of 400–1000 s^{-1} (see Sect. 2.1.4.), with low values being chosen more often for large tanks and high values for small tanks. The advantage of this concept is that it is flexible in operation and can be adapted to all flow rate variations. Due to the short residence time of the water in the coagulation tank, it is often advantageous to use a single coagulation tank for several DAF clarifiers.

The third is flash mixing followed by a longer coagulation (5–15 min) with a smoother mixing ($G = 200$–$260\ s^{-1}$). It can give a better result, especially for "difficult" waters.

As previously mentioned in Sect. 2.1.4, the optimum shape of the volume mixed by a propeller mixer remains the cubic shape. For coagulation, mixers with a single propeller or with two propeller stages can be used. In the first case the shape of the tank will be close to a cube, while in the second case it will be closer to one and a half to two cubes superimposed. This second solution saves space and takes advantage of the depth of available structures. On the other hand, mixers with two propeller stages are sometimes more fragile mechanically. For this reason, coagulation tanks with two-stage propeller mixers are relatively rare. On the other hand, for very large installations, tanks larger than 100–125 m^3 ($5 \times 5 \times 5$ m) are often considered too big and the mixers—too heavy, with installed powers that can exceed 30 kW. Several smaller coagulation tanks operating in parallel are therefore preferred. In some cases it is also possible to use two flash mixing tanks in series with (possibly) stronger mixing in the first tank and more moderate mixing in the second tank, but this configuration is more rare.

The mixing is provided by one vertical shaft mixer per tank. The propeller is usually pushing (the water is pushed to the bottom) and the coagulant is injected near the shaft of the propeller, just above it, for optimal dispersion. The water inlet is usually at the bottom of the tank and the outlet at the top. The reverse is also possible, but it is preferable to avoid a direct outlet from the bottom of the tank, so as not to break the "butterfly" circulation flow of the water (the water pushed to the centre of the bottom is deflected horizontally to go up along the side walls and return to the centre in the axis of the propeller).

Coagulation is followed by flocculation, in which the microflocs formed by the coagulant are agglomerated into larger flocs that are easier to separate from the water. This process takes longer and is carried out under slow mixing conditions and is sufficiently gentle not to destroy the fragile flocs. It can be done with or without the use of a polymer. It is obvious that flocculation will always be faster and more stable with a suitable polymer and that the better adhesion of the bubbles to the flocs will result in better quality clarified water, but it should not be forgotten that the polymer dosing involves operating costs that one would always prefer to do without if possible. In addition, the presence of a polymer in the water can lead to faster clogging of sand filters or, even more so, ultrafiltration (UF) membranes, if such filtration stages are installed downstream of flotation installation. Therefore, it is very important to minimise the polymer dosage as much as possible if its use is indispensable. In these cases the doses are usually limited to 0.05–0.1 mg/l of pure product.

Flocculation tanks can be designed in several ways depending on the time and flocculation conditions selected. They can be classified according to two criteria:

1. Depending on the number of flocculation stages, one or two flocculation stages can be used, depending on the flocculation time and the specificities of the floc. The use of three flocculation stages can be technically advantageous in some cases, but this more expensive solution remains exceptional. Due to its small "piston" effect, the two-stage concept allows a more homogeneous mixing of the water, better avoiding possible short- circuits that can always occur in a single tank. In this case, it can be advantageous to have a more intense mixing in the first stage to favour the clinging between the microflocs and a "softer" mixing in the second stage to favour the formation of larger size flocs. In drinking water the velocity gradients used for the first stage are in the range of 70–100 s^{-1} and for the second stage—in the range of 40–60 s^{-1}. For reference, in wastewater where flocs are often more solid, a single flocculation stage (velocity gradient 80–100 s^{-1}) is sufficient. It may be advantageous to equip the mixers with frequency inverters that would allow optimisation of the mixing intensity in real operating conditions. *Figure* 6.1 shows vertical longitudinal sections of a single stage flocculator and a two stage flocculator often used in drinking water flocculation.
2. Depending on the mixing technique used, flocculators can be either mechanically mixed or hydraulically mixed. Mechanically mixed flocculators most often use vertical shaft mixers with single or two-stage blade propellers or barriers with vertical or, more often, horizontal shafts. Hydraulic mixing flocculators (called around-the-end hydraulic flocculators) use simple, successive baffles that deviate the direction of water flow many times, creating sufficient turbulence to ensure mixing. The water flow can be horizontal or vertical. In all cases it is important to maintain a sufficient flow velocity (at least a few centimetres per second) to avoid settling.

The importance of mixing, or rather, the homogeneous dispersion of the flocculant in the water upstream of the flocculator must be emphasised here. The mixing in a flocculator is not always sufficient on its own to ensure a good and quick dispersion of the flocculant in the whole volume, if the said flocculant is injected in a single point. Two solutions are most often used.

The first is to install a simple ramp (5) (a perforated tube) for flocculant distribution over a long weir between the coagulation tank and the flocculator as shown in

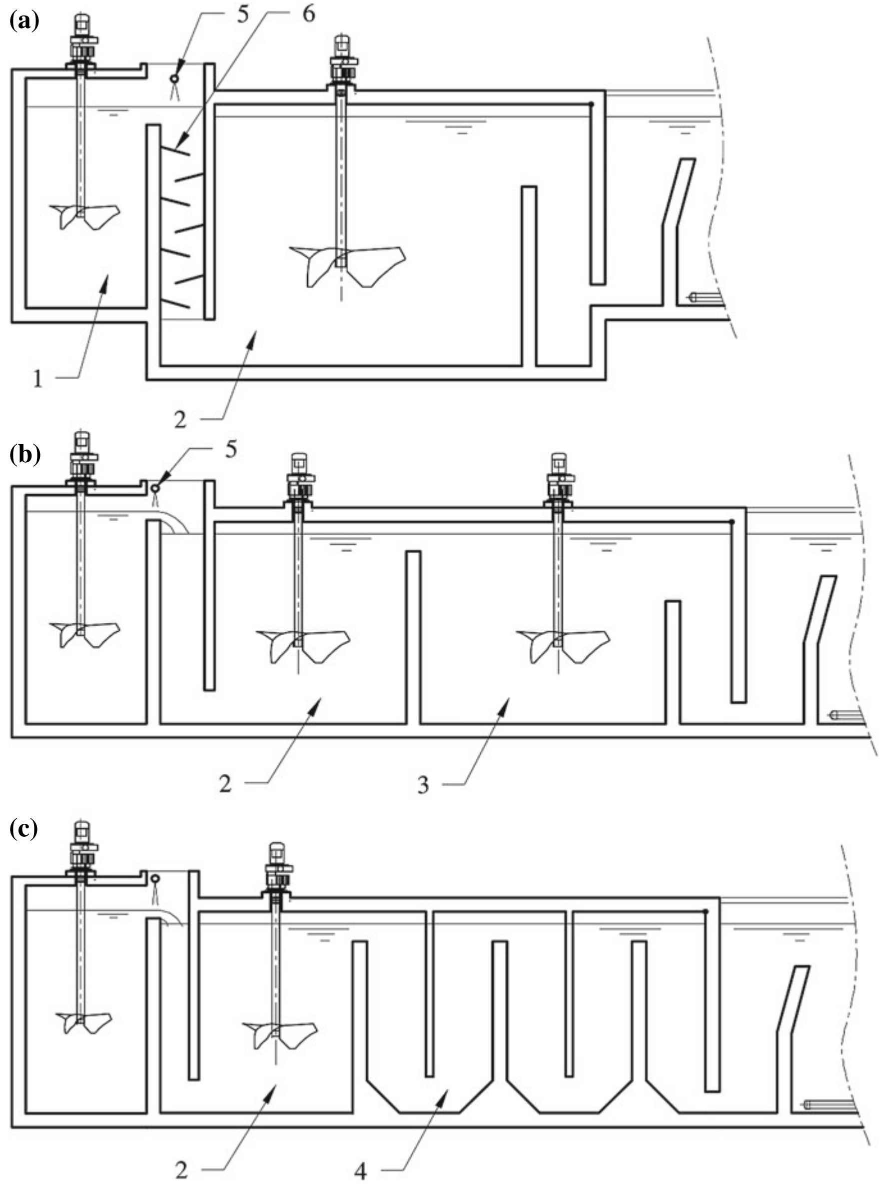

Fig. 6.1 Coagulation and flocculations tanks. 1—coagulation tank, 2—first stage dynamic flocculation, 3–second stage dynamic flocculation, 4—second stage hydraulic flocculation, 5—polymer spray, 6–static mixer

Fig. 6.1*b*. The velocity of the water over the weir followed by a small drop (15–20 cm) may be sufficient to ensure good mixing. The flocculant must be diluted enough so that dispersion through the holes can take place at a certain velocity to minimise the risk of clogging the holes.

The second is to install a static mixer (6) in a small vertical compartment at the inlet to the flocculator as shown in *Fig.* 6.1*a*. The water flow through this static mixer is sufficiently turbulent to ensure mixing of the flocculant. The installation of a flocculant distribution manifold (5) in addition to the static mixer would only be beneficial.

Some manufacturers (e.g. Degrémont) use combinations of a first flocculation stage (2) equipped with a mechanical agitator, which ensures good mixing of the flocculant in the water with rather sustained agitation, and a second around-the-end hydraulic flocculation stage (4) ensuring progressive floc growth. This combination also has the advantage of considerably reducing the number of mixers used, although it requires slightly more civil works—see *Fig.* 6.1*c*.

6.2 Contact Zone

The contact zone is where the white water is mixed with the raw water before entering the flotation zone. It is located between the flocculation tank and the flotation zone. The transfer between the flocculation tank and the contact zone is done at a sufficiently low velocity, usually less than 20–25 cm/s, so as not to break the flocs. In this zone, the pressure relief devices for the pressurised water are also installed. These must meet several criteria:

- They must expand the pressurised water and disperse it into the raw water at a relatively low velocity to preserve the integrity of the flocs, but at the same time sufficient to ensure rapid and efficient mixing with the said raw water.
- They should allow for a homogeneous distribution of the white water across the width of the flotation tank.
- They must be arranged and oriented in such a way as to avoid any risk of a preferential upward white water current parallel to that of the raw water.
- If possible, they should be removable or at least easily accessible to simplify maintenance.

In rectangular DAF clarifiers, regardless of the type of pressure relief devices, there are two ways to install them in relation to the raw water inlet from the flocculation tank.

The first is to install the pressure relief devices at the bottom of the contact zone as shown in *Fig.* 6.2*a*. Of course, the raw water inlet window is located immediately above so that it can mix immediately with the white water. This arrangement has some advantages:

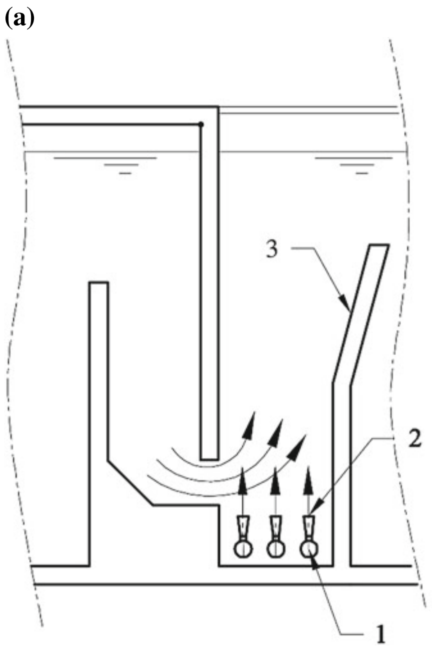

Fig. 6.2 Pressurised water injection in the contact zone. 1—pressurised water distribution pipes, 2—pressure relief nozzles, 3—inclined baffle

- It allows the pressurised water to be dispersed over the entire width of the expansion zone without really worrying about the speed of mixing with the raw water, as the speed of the white water decreases sharply to only a few tens of centimetres after exiting the pressure relief devices.
- It allows the installation of several independent pressurised water distribution ramps, which makes it possible to vary the pressurisation flow rate by cutting off the supply to one or two ramps (this is only possible if the saturator allows a variation of the pressurisation flow rate).

On the other hand, in some cases it may have a disadvantage: if the bottom of the contact zone is at a water depth greater than 4 m (which may happen for constructional reasons), then pressure relief at such a depth may lead to excessive growth in bubble size and coalescence as they rise. It seem that the optimum depth for pressure relief would be around 2.4–3 m. This depth would offer a good compromise between a gradual and not very turbulent mixing of raw and white water and a moderate growth in air bubble size.

The second arrangement is to install the pressure relief devices above the raw water inlet window as shown in *Fig.* 6.2*b*. In this case it is easier to avoid expanding at too great a depth. The injection and mixing of the white water with the raw water should be done under conditions that are not too turbulent, but still ensure homogeneous mixing. In this configuration the probably most successful concept seems to be the

Veolia Spidflow. The white water distribution ramps are placed on a perforated floor which, by creating a small pressure drop, ensures a very homogeneous distribution of the raw water across the cross-section of the contact zone.

The shape or rather the cross-section of the contact zone is also important. In the vast majority of cases, it is designed for an ascending velocity of the water at the bottom not exceeding 6–7 cm/s and it decreases, thanks to the inclined partition (3) provided at the top to widen the passage section, to less than 4–5 cm/s.

6.3 Flotation Zone

The design and hydraulic loading of the flotation zone of large rectangular DAF clarifiers has evolved considerably as experience has accumulated. In the 1960's and 1970's the values rarely exceeded 5–6 m/h (total hydraulic load). Then came the first drinking water flotation systems operating at hydraulic loads approaching 10 m/h, before the arrival in the 1990s of high hydraulic loading flotation systems operating at 15–20, then 25, then 30 and even, in some particularly favourable cases, up to 40 m/h. What are the technological advances that have made this progress possible? There are mainly two. One is in the equipment, the other—in the very understanding of the hydraulic phenomena occurring in the flotation zone, depending on the variation of different parameters such as the hydraulic load, the concentration of air bubbles in this zone, the horizontal velocity of the water leaving the contact zone, the length and depth of the flotation zone and the clarified water collection mode.

Early rectangular DAF clarifiers used for drinking water clarification had an outlet located near the bottom on the opposite side of the inlet, at the end of the flotation zone. This configuration results in preferential currents between the inlet and the outlet because, in general, the direction of a water flow in a tank is determined by the direction and initial velocity of the water at the tank inlet and the location of the outlet point. By creating heterogeneous hydraulic conditions in the tank, these currents do not allow uniform and optimal use of the entire flotation area, which may deteriorates the quality of the clarification beyond a hydraulic load exceeding 10–12 m/h. However, it is simple to observe that the upward velocity of the lower interface of the air bubble cloud in static conditions is at least 25–30 cm/min, which corresponds to 15–18 m/h.

To overcome this preferential currents problem, the water outlet at the end of the tank was replaced by a homogeneous collection of the clarified water under the entire flotation area. This was achieved by simple perforated pipes, installed parallel to each other at the bottom of the entire flotation area (a similar concept was used by Krofta in the 1960s) or by a double perforated bottom (later developed by the Finnish company Rictor Oy). This first technological advance, combined with an increase in the depth of water in the flotation zone, significantly improved the hydraulic conditions in the said zone and allowed, on its own, a significant increase in the hydraulic load without deteriorating the quality of the clarification.

The second technological advance is based, in a way, on the conclusions drawn from simple observations of the variations in the behaviour of an increasingly thick cloud of air bubbles over an increasingly small flotation area. According to Hazen's theory, the upward velocity of the bubbles or bubble/particle aggregates must be greater than the hydraulic load of the flotation zone (assuming a homogeneous downward flow, which is a somewhat idealised estimate for a tank with the water inlet on the side). And it turns out that for particles of 20–50 μ and bubbles of around 100 μ diameter the upward velocities vary from 10–12 to 20 m/h depending on the water temperature. So, how can we explain that in reality, DAF clarifiers operating at a hydraulic load of 30 and even 40 m/h maintain an excellent quality of clarification which remains, in certain cases, almost constant for a hydraulic load varying between 15–20 and 40 m/h?

The explanation that is more or less agreed among specialists is based on the appearance of stratification of the water flow in the flotation zone at high hydraulic load. To describe this flow behaviour, it should first be recalled that currents with a horizontal component in the flotation zone are unavoidable for the simple reason that the water entry is horizontal and at the surface at the beginning of the tank. If this horizontal current did not contain air bubbles, then its shape would depend mainly on the inlet velocity. If the water inlet velocity and hydraulic load are low, then the flow will go almost straight from the inlet to the outlet and would look approximately like that shown in *Fig.* 6.3*a*. A moderate increase in inlet velocity and hydraulic load would gradually change the shape of the flow as shown in *Fig.* 6.3*b*. And finally, a high inlet velocity and hydraulic load would cause a vortex similar to that shown in *Fig.* 6.3*c*.

If the same tests were carried out again with the same hydraulic loads and entry velocities into the flotation zones with water containing sufficient amount of microbubbles for flotation, the picture would be slightly different. Indeed, at a temperature of about 20°C, with a pressurisation rate of 10% and a saturation rate of the pressurised water of about 70–80%, the raw water/white water mixture would theoretically contain about 0.65–0.75% air (6.5–7.5 i of air per m^3 of water), which would modify the specific weight of this mixture from about 998 to 991.5–990.5 g/l. As a result, this water would be less dense than the water below it (which does not contain air bubbles) and would tend to "float" on top of it forming a more or less horizontal layer. At a low hydraulic load of 6 m/h, the amount of pressurised water will be 0.6 m^3/m^2.h (39–45 l of air/m^2.h). If the inlet velocity of this lighter water is moderate and the amount of microbubbles in it is not very high, the white water cloud will look approximately like the one shown in *Fig.* 6.4*a*.

In simplifying a little, one could say that increasing the hydraulic load (at the same pressurisation rate) would necessarily increase the thickness of the microbubbles cloud approximately as shown in *Fig.* 6.4*b*. Numerous observations have shown that, at a hydraulic load above 12–15 m/h (which, at the same 10% pressurisation rate, represents 1.2–1.5 m^3/m^2 · h of white water or 78–112 l of air/m^2 · h), and a certain inlet velocity of the water into the flotation zone (which seems to vary depending on the length and depth of the flotation zone), the layer of microbubbles will form a first horizontal stream of more or less uniform thickness. This first stream arrives

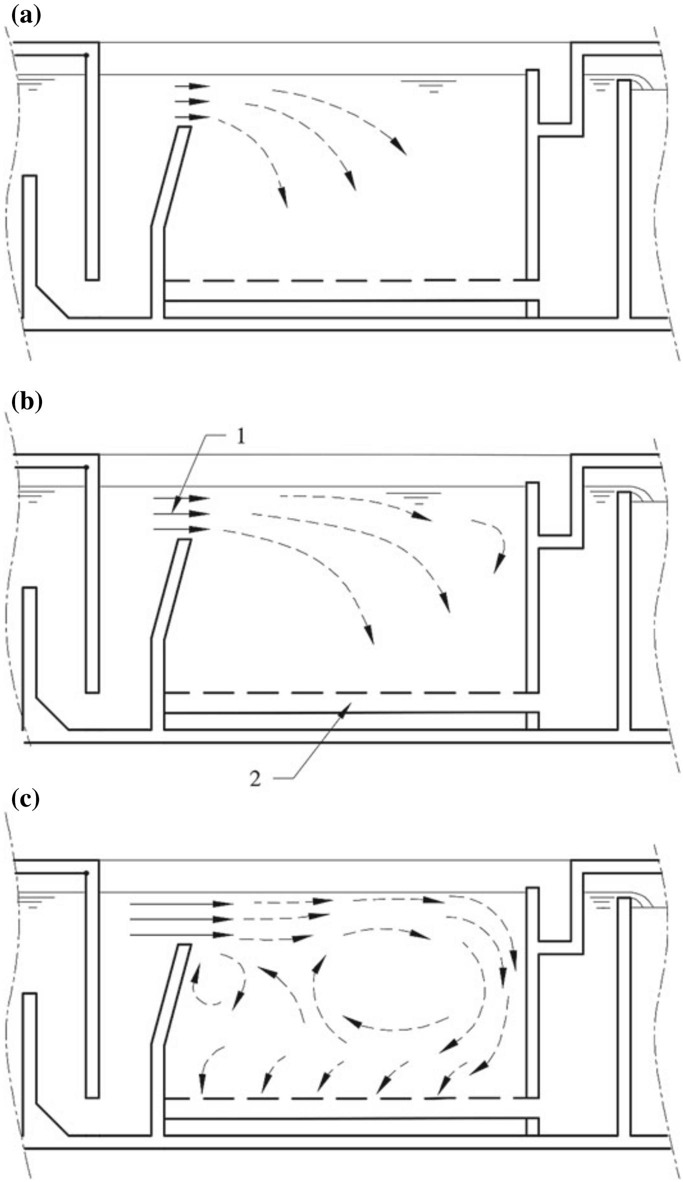

Fig. 6.3 Flow patterns without pressurisation. 1—velocity of the water entering the flotation zone, 2—water outlet

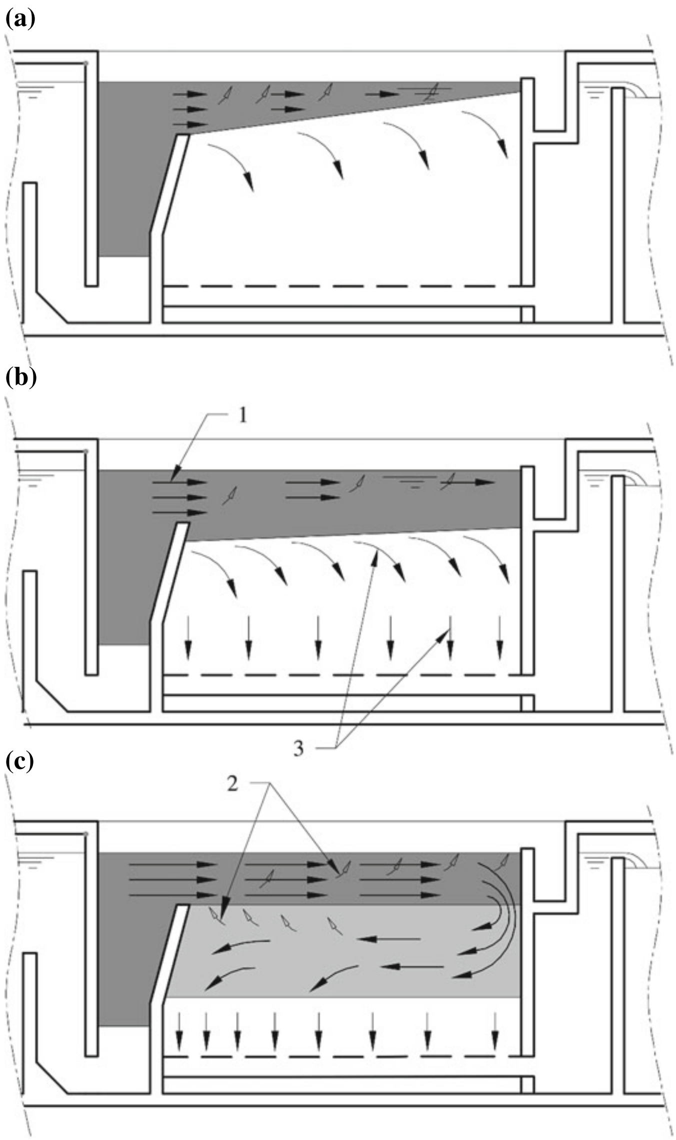

Fig. 6.4 Flow patterns with pressurisation. 1—velocity of the water entering the flotation zone, 2—floated sludge, 3—clarified water

at the wall opposite the entrance and dives down, forming a second stream that goes under the first one in the opposite direction. This second stream becomes thicker and thicker as the quantity of white water increases. At a hydraulic load of 30 m/h, and under the same conditions, the upper stream contains 3 m^3/m^2.h of white water (195–225 l of air/$m^2 \cdot h$).

This phenomenon could be explained by the fact that the surface stream progressively loses air on its way out (as many bubbles arrive at the water surface) and therefore becomes increasingly "heavier", which allows it to dive under the surface and return in the opposite direction. However, it still has enough air in it to stay above the layer of water below it, which contains almost no air bubbles. This would result in a stratification of the currents into three layers as shown in *Fig.* 6.4*c*. In such a configuration, the rising of bubbles and bubble/particle aggregates could be considered to occur not in one, but in a way in two, or even, according to some, in three layers, which would accordingly increase the flotation area. The bubbles and aggregates, which could not rise to the surface in the first stream, are found in the middle layer that still contains air. This air pushes them upwards, which would make them return to the upper stream. And so on, until coalescence and clinging allow them to reach the surface.

For more information and details on this subject the reader can refer to the studies made by the *Department of Water and Environmental Engineering* of the University of Lund in Sweden in the years 1999–2002. The results of these studies are, among others, presented and commented in more detail in the book *Dissolver Air Flotation for Water Clarification*—James K. Edzwald, Johannes Haarhoff.

While some studies have shown this stratification phenomenon, it has not been as clearly demonstrated by others. This is because the diagrams shown in *Fig.* 6.4 are still somewhat idealised. Measurements of the real water velocities in the flotation zone, as well as simple visual observations through windows, show in reality variable, much less well-ordered pictures. It has to be pointed out that there are several factors that come into play and influence the currents:

- The hydraulic load and the velocity of the water leaving the contact zone. Small variations in these two parameters can make stratification appear or disappear.
- The shape of the flotation zone (length/depth ratio).
- The concentration and dominant size of the bubbles. They significantly modify the currents. A low volume of air combined with a high hydraulic load could even, it seems, reverse the currents.
- The method of collecting the clarified water. A perfectly homogeneous collection over the whole surface of the bottom of the flotation zone is not always optimal to cause stratification. A more abundant collection at the inlet side could sometimes "stimulate" the formation of the middle current and favour stratification. It is easy to assume that this is why this trick is used by some manufacturers.
- The size of the DAF clarifier on which the studies were done. Some studies have been done on pilots only a few tens of centimetres long and as deep. Others have been done on larger and probably more representative devices—in the range of 2 m in length and about as deep.

Consequently, the simultaneous action of these influences makes the stratification unstable and somewhat fragile. It seems to appear and disappear according to the variations of all these parameters. But one can only be pleased to note that the actual performance of the clarification remains, fortunately, less sensitive to the variations of the currents in the flotation zone.

It can also be assumed that other factors related to the evolution of the bubble cloud, as well as the specificities of the bonds between bubbles and particles during clarification in the flotation zone, may play an important role. As mentioned above, various theoretical calculations show that the flotation velocities of bubbles and small bubble/particle aggregates (small means bubbles and particles of comparable size) are in the range of 15–18 m/h for a water temperature in the range of 20–25 °C. Of course, this flotation velocity of the last and finest bubbles of a bubble cloud is an average and should be considered as an approximate value. In reality, this velocity depends not only on the temperature, but also on the size and stability of the bubbles, which in turn depends on the pressure relief conditions and the availability of electrostatic surface charges likely to preserve the fineness of the bubbles. Moreover, it is not really representative of the real flotation velocity, which is what we are most interested in. Firstly, these flocs are often much larger than the few tens to a hundred microns that are frequently taken as a basis in some studies. Secondly, these flocs are often, thanks to the coagulant and flocculant, firmly bound to several fine bubbles, but also to larger bubbles resulting from the coalescence that occurs in the flotation zone. These agglomerates, which enclose several bubbles of different sizes within their structure, can be quite compact and, therefore, experience less resistance from the water as they rise. Consequently, their flotation velocity would be higher than that of multiple small dispersed flocs, each of which is more fragilely associated with a few bubbles.

The coalescence which inevitably continues in the flotation zone is also an important factor. The higher the hydraulic load and the higher the air concentration in the floatation zone (op to more than 200 l of air/$m^2 \cdot h$) and the thicker the microbubbles cloud covering the floatation zone and the higher the probability of coalescence. In such conditions, the formation of more and more larger bubbles (120 or 150 μm and probably even more), clinging to the flocs as they go, may modify the properties of the bubble/particle agglomerates and have an accelerating effect on their flotation velocity significantly over that of the 60 or 80 μ bubbles, which are often used as a reference for flotation velocity estimates.

Thus, it seems difficult to give a simple and clear explanation to the question of how a DAF clarifier works at such a high hydraulic load. So we can assume that it is probably a combination of several phenomena, like those described above (and probably others), coming into play simultaneously. But the degree of importance of the role of each of these phenomena remains, for the time being, a bit unclear.

Be that as it may, experience shows that, all other conditions being equal:

- In actual operation, enhanced pressurisation, which produces a thicker layer of microbubbles covering the entire flotation zone in depth, favours the quality of clarification. An abundant cloud of free microbubbles (not associated with flocs) allows the bubble/floc aggregates to be floated more efficiently and at a higher velocity than that obtained with only bubbles associated with flocs. It should be noted that the theoretical modelling of this phenomenon seems rather difficult. If the modelling of the behaviour of aggregates composed of a bubble and a floc of known dimensions and specific weight remains relatively feasible and precise, things become more complicated when there are, at the same time, several bubbles attached to the surface, or, even better, incorporated inside a larger floc.

- A fine pressure relief, producing many fine bubbles and little coalescence, makes it easier to achieve the result described above.
- The availability of electrostatic charges in the water influences the stability of the bubbles and the adhesion forces between the bubbles and the particles. In practice it is sometimes possible to observe, even visually, that a small change in the coagulant dosage can, in some cases, visibly alter the quality of the white water and the interactions between bubbles and flocs (bubbles stay finer longer and cling better to the flocs).
- The use of a suitable flocculant, even at a very low dose (0.05–0.1 mg/l), or an appropriate organic coagulant, can improve the quality of the clarification and allow an increase in the hydraulic load.

6.4 Clarified Water Collection

There are three ways to collect the clarified water, shown in *Fig.* 6.5. The first, and historically the oldest, is the one shown in *Fig.* 6.5*a*. The clarified water is simply collected on the opposite side of the inlet under a siphoidal partition. This design does not allow very high hydraulic loads to be achieved unless there is a very deep flotation zone (say a depth of the same order as the length of the flotation zone) that allows the clarified water to flow more or less laminar to the outlet. On the other hand, it does allow for the installation of a bottom scraper which could be useful in some cases. Nowadays, DAF clarifiers of this type are used for applications other than drinking water, for example tertiary treatment, biomass clarification after biofilters or other waters with low TSS content.

The second way of collecting the clarified water is shown in *Fig.* 6.5*b*. In this case the water is collected under the entire flotation surface by a multitude of perforated collectors (1) arranged next to each other. All these collectors (1) open into a clarified water compartment (2) from which the water overflows over a weir (3) which can be fixed (as shown) or adjustable and which, of course, determines the level of the water (and thus also of the floated sludge blanket) in the flotation area. A variant of this concept, used in Veolia's Spidflow, implements several parallel vertical partitions (6) across the headers (1)—see *Fig.* 6.5*c*. These partitions (6) force the water down vertically and prevent any horizontal currents in this area that may disrupt the final stage of clarification.

The third way is shown in *Fig.* 6.5*d*. In this case the headers are replaced by a perforated floor (5) covering the entire flotation surface (Rictor design).

The design of the collectors (1) or the perforated floor (5) can use a few tricks. As mentioned in the previous paragraph, it is possible, through the size and/or arrangement of the water collection holes (4), to influence the direction of water flow in the flotation area. A higher number (or larger size) of the holes (4) at the inlet side could

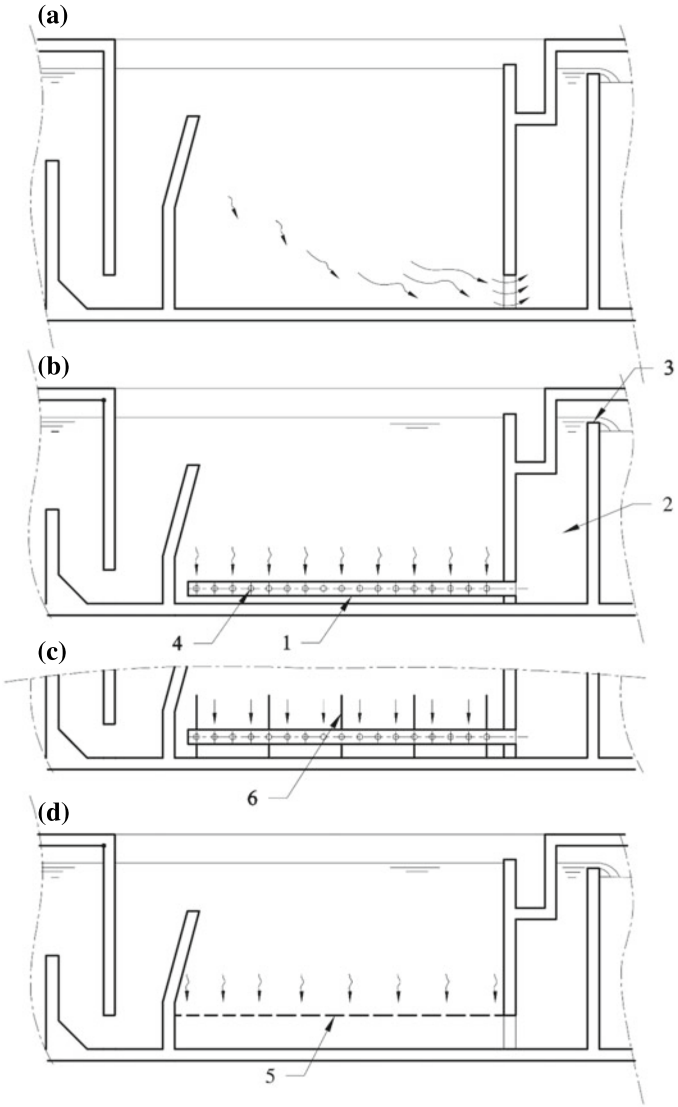

Fig. 6.5 Clarified water collection devices. 1—perforated collectors, 2—clarified water compartment, 3—weir, 4—hole, 5—perforated floor, 6—vertical partition

attract more water to this area, favour stratification of the currents (return stream) and, consequently, increase the effective floc separation area.

The two last devices (perforated collectors (1) or perforated floor (5)) actually fulfil the same function with the same efficiency. Of course, each of them has its specificities, advantages and disadvantages. The collectors (1) allow an easier and efficient cleaning of the bottom of the flotation zone, as this operation has to be done, unfortunately, from time to time even if the clarified water seems perfectly clean. On the other hand, unless a very large number of these perforated collectors (1) are installed (which increases the cost), their cumulative cross sectional area for water passage remains relatively limited. Consequently, it is sometimes difficult to avoid a relatively high head loss at maximum flow rate, which would make the level of the sludge layer vary a little too much as a function of the flow rate, if the outlet weir (3) is fixed. This means that each clarifier must be operated within a relatively narrow range of flow rates to avoid having to manage floated sludge extraction that is complicated by excessive variation in its level. These variations are less with the perforated bottom (5) which can be sized to create very little head loss. In this case, the variations in flow would lead to a variation in the sludge layer level limited to the variation in the overflow height of the water over the fixed weir (3). In addition, the perforated floor (5) allows for a more regular and dense arrangement of holes, which provides (at least theoretically) a more homogeneous and "precise" collection of the clarified water. On the other hand, any deposits accumulated in the double floor may be more difficult to clean.

6.5 Floated Sludge Collection

The floated sludge produced by large drinking water DAF clarifiers can be discharged in two ways—by scraping (mechanical mode) or by overflow (hydraulic mode). The mechanical mode produces fairly concentrated floated sludge—from 1.5–2% to over 4% in some cases. This high concentration minimises water loss and the volume of sludge to be managed and stored, and allows direct dewatering without prior thickening. However, these advantages come at a price, as the clarifiers must be equipped with surface scrapers, which are expensive and require regular maintenance. In general, the surface scrapers used are similar to those described in Sect. 5.3. Of course, the components are adapted to the larger size of the flotation tanks. A second disadvantage of the surface scrapers is the risk of causing some floc to fall off due to the movement of the flights. Indeed, a slight increase in the turbidity of the clarified water is often observed a few minutes after a sludge scraping cycle. It will disappear completely after about 10–15 min after the scraping cycle has stopped. It is therefore important to adjust the scraping cycles appropriately in order to minimise this side effect as much as possible when it occurs. In general it is not recommended to run the scrapers continuously, as they push a too thin and not very concentrated sludge blanket that easily loses flocs, even if the speed of the scrapers is close to the speed of the water on the surface. The effect is further accentuated when the flights rise on the extraction beach. It is more appropriate to operate the scrapers on a time basis. The period between scrapings can be long enough (up to more than an hour) to allow a sufficiently thick sludge layer to accumulate. The operating time of the scrapers can be limited to the time required to perform just half or, at most, a single sweep of the flotation surface at a slow speed of the range of 1–1.5 cm/s. This operating mode does not completely avoid floc stalling, but at least reduces it and limits possible losses to only a few minutes per cycle.

The hydraulic method consists in overflowing the floated sludge blanket into a channel opposite the inlet by raising the water level in the flotation tank. This method, if implemented properly, is sufficiently efficient and much less expensive than the mechanical method as it involves simpler and less expensive equipment. In addition, it has the advantage of not disturbing the floated sludge blanket and, therefore, not causing floc shedding. Its main disadvantage is the low concentration of the sludge discharged in this way—only 0.2–0.4%, even with careful management of the overflow cycles. For it is obvious that the overflow parameters (mainly the overflow height, the concentration of the sludge blanket and its thickness at the time of overflow initiation, as well as the duration of the overflow) play an essential role on the final concentration of the overflowed sludge. If the overflow height is too high in relation to the thickness of the accumulated sludge blanket and if the overflow lasts too long, the resulting sludge will be much less concentrated than the values given above.

Sludge overflow can only be efficient in two cases:

- If the sludge blanket is much thicker than the overflow height, then it could only overflow gradually if it is sufficiently liquid, i.e. not very concentrated. But it is a somewhat tricky approach to try to keep a layer of sludge that tends to concentrate naturally of its own accord through the action of air bubbles that gradually build up underneath it. It is feared that such "fragile" flotation could have consequences for the quality of clarification. This operation mode should be avoided…
- If the floated sludge blanket is relatively thin so that the overflow height is greater than its thickness. In this way the entire blanket will overflow into the sludge channel. This results in the need to overflow quite frequently, hence the low concentration of the discharged sludge.

On the other hand, if the sludge blanket is very thick (let's imagine a 100 mm thick layer that has formed and thickened for several hours) it risks being too compact and remaining stuck to the weir, letting overflow only the water sliding between it and the weir. To avoid this situation, it is recommended to overflow more frequently, even if this reduces the concentration of the discharged sludge and increases water losses.

Raising the water level can be done in three ways. The first and simplest way (see *Fig. 6.6a*) is to simply close the clarified water outlet. This causes a rapid rise in water level, but also an extremely large overflow into the sludge channel (3), resulting in a large loss of water and a very low concentration of the discharged sludge. This technique is inexpensive in terms of equipment (a simple automatic valve (1) or penstock) and can, if necessary, be used for small installations where the sludge is discharged directly without treatment. However, it is difficult to justify for large installations.

The second way is shown schematically in *Fig. 6.6b* and has the advantage of causing less water loss than the first. In this case the automatic valve (5) is at the outlet of the floated sludge overflow channel (3). In normal operation this valve is closed and the water level is kept high enough so that the said channel (3) remains

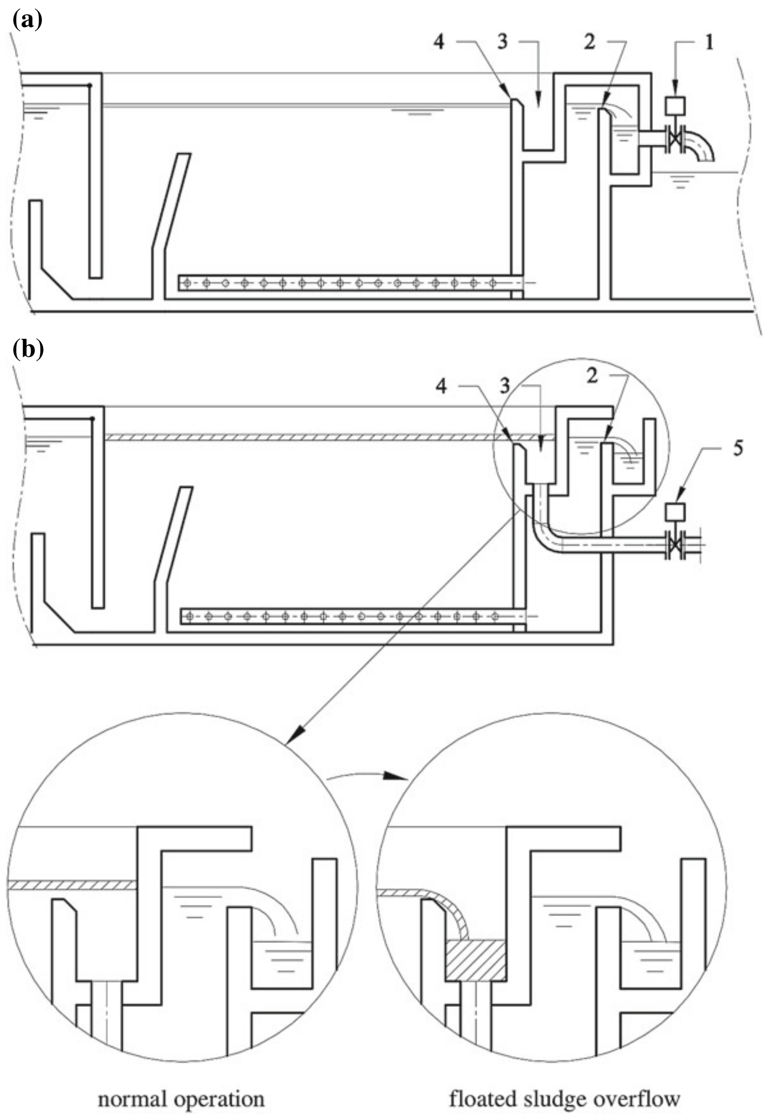

Fig. 6.6 Hydraulic floated sludge removal. 1—clarified water automatic valve, 2—fixed clarified water weir, 3—floated sludge overflow channel, 4—fixed floated sludge weir, 5—floated sludge automatic valve

permanently flooded. When the automatic valve (5) is opened, the channel (3) is emptied and the floated sludge layer is allowed to overflow. The overflow height over the weir (4) of the channel (3) must be adjusted by the difference in level between the weir (4) and the outlet (2). Of course, the valve (5) and the discharge pipes behind it must have sufficient capacity to quickly discharge all the water overflowing the weir (4) and empty the channel (3). Indeed, overflowing some of the water as sludge into the channel (3) will necessarily reduce the overflow height on the weir (2). In addition, it is necessary to take into account the possible head losses in the clarified water collectors that will necessarily decrease when the sludge overflows.

The third way of raising the water level (see *Fig. 6.7*) involves the use of one (or more) electrically or pneumatically operated (2) automatic weir (1) installed at the clarified water outlet. This automatic weir (1) allows the water level to be raised slightly so that only a (small) part of the incoming water, corresponding to the floated sludge layer, overflows into the sludge channel. Typically, the overflow height is in the range of 15 to 20–25 m^2, giving an overflow rate of 3.36 to 5.25–7.25 l/sec per metre of weir. This is the most expensive solution in terms of equipment, but also the most accurate and the one that offers the most flexibility. With a few accessories such as level detection and some automation, it could allow automatic regulation of the floated sludge overflow level in almost all circumstances.

If the sludge overflow mode is according to *Fig. 6.6a* or *6.7*, it is recommended to provide a wall spray (5) on each side of the tank during the sludge overflow cycle. This wall spray (5) can be fed by a small bypass of the pressurisation pumps. It often consists of a simple perforated pipe with a manual flow control valve and has two functions. The first is to create a thin layer of water flowing over the walls of the tank which will loosen the floated sludge layer from the wall, because if the sludge layer has been accumulating for a long time, if it is rather concentrated and if it has had time to dry out a little on the surface, then it will tend to stick to the walls and it is not certain that the weak surface water flow, when the sludge overflows, will loosen it properly. The second is simply to wash off the traces of sludge that will inevitably remain and dry on the walls after the water level has dropped at the end of the overflow cycle.

The floated sludge collection method is a strategic choice that depends mainly on two factors:

- The amount of sludge to be discharged per unit of time and flotation area.
- The floated sludge destination and further treatment.

The hourly sludge volume to be discharged from the flotation surface depends on the TSS concentration in the inlet water (including also the hydroxides produced by the coagulant), the hydraulic load and the concentration of the floated sludge. The TSS concentration of surface water is often quite variable—it is low (a few mg/l) for long periods of time, but can rise sharply (several tens or even hundreds of mg/l), for example during an algal bloom.

The concentration of the floated sludge depends on the sludge characteristics, the thickness of the sludge blanket accumulated on the surface and the time during which the blanket is accumulated. If the water contains mainly algae, if the coagulation is

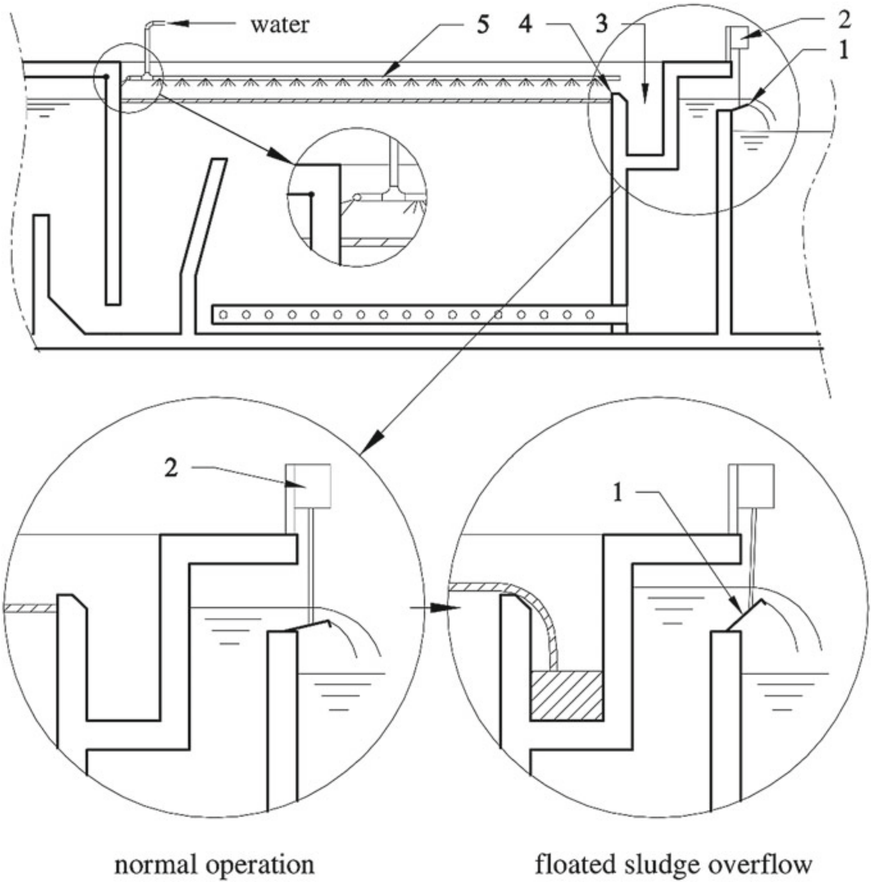

Fig. 6.7 Floated sludge overflow with automatic weir, 1—automatic clarified water weir, 2—electric or pneumatic actuator, 3—floated sludge overflow channel, 4—fixed floated sludge weir, 5—wall spray

done with an aluminium-based coagulant and if the sludge layer accumulated at the time of discharge is only a few millimetres thick, then it will be difficult to expect a concentration higher than 1–1.5%. If the water contains mainly humic matter and the floated sludge layer is several centimetres thick and accumulated over a period of one or two hours, then a concentration of the sludge blanket in the range of 2–3% can be expected. Finally, if such a layer is accumulated for several hours to a thickness of 10–15 cm before scraping, its concentration may exceed 3.5–4%. Iron-based coagulants generally give slightly more concentrated floated sludge, but the difference is often marginal and the concentration depends mainly on the other factors.

The hydraulic load also plays an important role. On the one hand, a high hydraulic load means more white water per square metre per hour, and therefore more air that can contribute to the proper thickening of the floated sludge. But on the other hand, a high hydraulic load also means a faster growth of the sludge layer thickness and, consequently, a shorter thickening time.

The treatment of floated sludge recovered from DAF clarifiers can be done in several ways. The most logical approach would be to have an on-site dewatering facility, in which case mechanical extraction would probably be preferable, especially if the volume of sludge is significant. Alternatively, the sludge could be directed to an existing wastewater treatment plant where it would be thickened and dewatered with the sludge from the wastewater. A third option is to accumulate the sludge in lagoons. In this case, only the dry weight of the sludge counts and then hydraulic collection would probably be the best solution. If the treatment of wash sludge from eventual sand filters is also taken into consideration, the task becomes even more complicated and justifies a detailed case-by-case study. Only such a study would allow a choice to be made between mechanical or hydraulic extraction of the floated sludge. A solution that could offer an attractive compromise, especially for large drinking water plants, would be to opt for a hydraulic overflow of the sludge from the DAF clarifiers and to provide an additional (small) DAF clarifier to concentrate the sludge before dewatering. In this case it would make sense to collect the floated sludge and the sand filters wash water in the same buffer tank and treat it on the additional DAF clarifier, killing two birds with one stone. This concept would eliminate the need for many expensive surface scrapers for the DAF clarifiers and at the same time concentrate all the sludge from the plant in a very compact and efficient installation before dewatering, although the energy consumption of the additional DAF clarifier is likely to be higher than that of a "conventional" thickening by sedimentation..

The rate of accumulation of the sludge layer varies according to the TSS concentration and the hydraulic load. If we imagine, as an example

- A TSS concentration at the inlet of 6 mg/l,
- A concentration of floated sludge on the surface of approximately 2%,
- A hydraulic load of 25 m/h,

then it could be calculated, as an approximation, that a 15 mm thick floated sludge blanket will be accumulated in about 2 h. Considering that an overflow cycle takes (between the raising of the level, the overflowing of the sludge and the return to the normal level) about 3–4 min, we can conclude that an overflow of sludge would be necessary every 1.5–2 h, which is quite correct. If the same approximate calculation is made for an inlet TSS concentration of 60 mg/l, it will be found that the 15 m^2 thick layer will accumulate in only 12 min. In this case, a sludge overflow would become more difficult to justify, as it would mean that the overflows would be repeated one after the other every few minutes. Not to mention the water losses…

So, where is the reasonable limit between 6 and 60 mg/l of TSS at the inlet, below which sludge overflow is possible and above which surface scrapers are necessary? It is difficult to say… Each manufacturer has his own opinion on the subject. Let's remember once again that the TSS content in drinking water is generally quite low—a few mg/l. On the other hand, it can rise sharply for a short period of time for any reason and it is this second maximum value that is often taken as a contractual reference for the sizing of the installations. So, if this maximum value is only likely to occur for a few days or weeks once over a several year period, it may not be unreasonable to opt for a sludge overflow that will provide operational comfort and accept the constraint of a more "difficult" management of the disposal of more abundant sludge for a few days or weeks. Also, examples of plants designed for such "safe" values that they are almost never reached are not so rare. And it is sometimes a pity to install heavy and expensive equipment, which might only be justified for a few fractions of a percent of the plant's operating time… But these are strategic choices that can be discussed on a case-by-case basis.

In all cases, the method of extraction of the floated sludge is one of the first choices to be made in the design of an installation, as this choice conditions the entire sizing of the works. Indeed, if surface scrapers are chosen, it is better to opt for DAF clarifiers with a shape close to a square or even elongated. This allows for a larger flotation surface of each cell, within the limits of the available width of the selected scraper, i.e. maximum 8 to 10 m depending on the manufacturer. Most often the selected width is within the limits of 6–8 m. The choice of this width also determines the dimensions of the clarified water collectors, in many cases also the width of the flocculation tank, the choice of the number and type of mixers etc.… On the other hand, a DAF clarifier with hydraulic extraction of the floated sludge would have the advantage of a rather wide and short tank (see Sect. 4.1), involving a lower water velocity, a better distribution of the air microbubble mat, less turbulence and, in the end, a slightly better clarification quality in certain cases. The clarified water collectors will be shorter but more numerous. Longer outlet weirs will provide better level stability in the event of flow variations. In short, the shape of the flotation tanks and the footprint of the plant will be quite different in the two cases.

6.6 Bottom Sludge Collection

Even if the water treated in these large DAF clarifiers, operating at very high hydraulic loads, has very little TSS, and even if the flotation works perfectly well, achieving almost immeasurable TSS levels and turbidity usually below 1 NTU, it would be unrealistic to expect to have no deposits at the bottom of the flotation zone. Over time there will always be a thin layer of sediment that will cover the bottom and the clarified water extraction headers. So, is it necessary to provide a means of collecting this 'sludge'? It would seem that the almost unanimous answer from the vast majority of major manufacturers is no. Because the quantity of this sludge is so small that it would not be worth investing in additional equipment. So even if a few small flocs settle here and there from time to time, too bad, one lets them go with the clarified water. In any case their impact on TSS and turbidity of the clarified water is, at worst, insignificant, and at best—unmeasurable. They will be trapped easily and without significant additional interference in the filtration stage that almost always follows the DAF clarifiers. And, once or twice a year, one empties and cleans the bottom of the tanks. The deposit is usually no more than a few millimetres. This solution is also suitable from a design point of view, because while it is simple to install a bottom scraper in a flotation tank like the one shown in *Fig. 6.5a*, it is more difficult for flotation tanks with collection of clarified water over the entire bottom surface of the flotation area. This can still be done relatively easily for the clarifiers shown in *Fig. 6.5b*, but for the rest it is more complicated…

Chapter 7
DAF Clarifiers with Built-in Sand Filter

There are many 'clean' or 'relatively clean' water treatment applications where the treatment process involves clarification followed by sand filtration. These can be drinking water applications, process water for industrial use or tertiary wastewater treatment. If the clarification stage is done by dissolved air flotation, then it is easy to imagine that the idea of combining the DAF clarifier with a gravity sand filter has soon occurred to many engineers. If the floated sludge is collected on the surface and the clarified water is collected at the bottom of the DAF clarifier, it would be easy to install a sand bed through which to filter the water already clarified by flotation. This combination complicates the design and operation of the equipment somewhat, but has the advantage of allowing the same tank to be used for both facilities, even if it needs to be a little deeper and have some additional features. In addition, this concept allows the flotation to be operated only when necessary—if the incoming water is clean enough, then the pressurisation can be switched off and only the sand filtration function used. Finally, it allows the surface area of the two units to be more or less halved if they were independent. Indeed, in many applications the hydraulic load of a "classic" flotation plant is quite close to that of the gravity sand filter installed downstream of the said plant. Generally this load varies between 6–8 and 12–15 m/h depending on the type of filter, which makes it easy to combine the two functions in the same tank. Of course, there are cases where the two hydraulic loads are quite different—DAF clarifiers operating at 20 or 30 m/h are followed by sand filters operating at 10–12 m/h, and sometimes even at only 6-8 m/h, loaded with very fine filter media to produce very high quality filtered water. This is the case, for example, in seawater treatment when the filtered water is sent directly to the reverse osmosis membranes, without going through an ultrafiltration stage. In this case, the advantages offered by the combination of the two devices in one may look less obvious, but remain defensible in a context of lack of space or implementation difficulties, especially in the event of hydraulic floated sludge overflow. Furthermore, even if flotation systems operating at 30 m/h give excellent results, it would be difficult to state with certainty that these results would be better than those obtainable at 8 m/

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
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h. For example, if the filtration velocity chosen is only 8 m/h over a very fine filter media, then a flotation system arranged in the same tank would operate at 9–9.5 m/h because the flotation surface will probably be reduced by the backwash water collection troughs. Of course, it is necessary to make some additional adaptations to the tank and the pressurisation circuits, but their cost remains significantly lower compared with that of a separate flotation installation.

Although the idea of combining the two technologies seems attractive, it has taken several decades to come up with sufficiently efficient and reliable concepts. It has to be admitted that the first versions put on the market suffered from various design flaws that somewhat dampened the enthusiasm of many.

Obviously, the main problem with this combined unit is the backwashing of the sand filter. On the one hand, the flotation has to work without interruption and on the other hand, the sand filter has to be stopped for washing. So, how to ensure continuity of the treatment while satisfying these two constraints? Two concepts ware developed.

The first consists of dividing the sand filter into several independent compartments and washing them separately one after the other. Each compartment has its own filter floor and its own outlet for the filtered water to the common tank collecting the filtered water from all compartments. Each of the compartments receives a portion of the water that has already been clarified by flotation and discharges its filtered water into the said common tank. In this case, while the flotation is running continuously, both sides of one compartment (its inlet and outlet) can be isolated, washed, and put back into operation before moving on to wash another compartment. The number of compartments must be large enough to ensure that the surface area of each one is small enough to ease washing and, above all, that the compartments in operation can easily absorb the additional hydraulic overload received during the washing of a compartment that no longer filters water. Isolation of the inlet side of each compartment is achieved by a hood that moves from compartment to compartment. This hood is mounted on a mobile bridge, which allows it to be stopped above a compartment, so that it can cover this compartment and create a seal around its edges. Its purpose is twofold: firstly, it isolates the compartment, preventing the water from the flotation zone from entering it and, secondly, it collects the sand backwash water from the isolated compartment and transfers it either to an external tank or to the contact zone at the entrance to the flotation zone, so that this water can be re-flocculated and re-floated with the raw water, thus carrying out an "internal" treatment of this backwash water.

The critical element here is the sand filter backwash method. Some manufacturers have started by installing a submersible pump on the hood which, after positioning the hood over the compartment to be washed, starts up and sucks the water inside the hood. The vacuum caused by the pump would in turn suck in the filtered water below the filter floor and, consequently, the water from the common filtered water tank to which the filter floor of the washed compartment is connected. This concept could work pretty well, but would require, firstly, a good sealing between the hood and the edge of the compartment and, secondly, a backwash pump with an operating curve that is not very sensitive to suction side pressure drops. Unfortunately:

- The sealing between the hood and the edge of the washed compartment was often lacking and the pump also sucked some water from outside the hood.
- The behaviour of the low pressure submersible pumps that were used was quite sensitive to suction side pressure drop. Therefore, the more the sand is clogged, the more the suction flow rate decreases, becomes unstable and moves away from the expected operating point on the curve.

Both of these factors made the actual flow through the sand bed somewhat uncertain, resulting in unreliable and often poor backwashing. So an attempt was made to improve the concept by adding a second submersible pump attached to the same mobile bridge. It sucked water from the filtered water collection channel and pumped it in the outlet of the backwashed compartment, trying to assist the suction pump mounted on the hood. Of course, the flow rate of this second pump was slightly lower than that of the hood pump so that the suction line remained under a slight vacuum, in order to secure the leak-free collection of the backwash sludge. Despite this attempt at improvement, the problem was not reliably solved as the backwash flow rate remained difficult to control.

This technology was available in two versions—in a rectangular tank with a travelling bridge, and in a circular tank with a rotating bridge. In any case, given the washing difficulties described above and the fact that this concept did not allow for air or air + water backwash, it was practically abandoned with one exception, which will be described in Sect. 7.2.

The second concept, combining flotation and filtration in the same tank, which is suitable for higher flow rates, consists of implementing several independent flotation/filtration cells. In this case each cell has its own flotation part and its own gravity sand filter. When the cell is washed, everything is stopped, including the flotation part. The water level is lowered and the sand filter is washed in the most conventional way. The continuity of the system is ensured by multiplying the cells so that the cells in operation can easily absorb the hydraulic overload when one of them is washed. The more cells there are, the more insignificant this overload is and the less oversizing is required for each cell. But also, the more cells there are, the more expensive the installation. So where is the limit? What is the optimal number of cells that ensures, at the same time, sufficient operational flexibility and minimal installation costs? It is difficult to recommend a precise number, as the costs depend on the floated sludge collection method (surface scrapers or hydraulic overflow), the number of saturators and pressurisation pumps, the tanks, piping and backwash pumps to be used, the cost of civil works, variations in the flow rate, the specificities of the project, etc. If one wants to be sure not to make a mistake, it is best to make the evaluation on a case by case basis.

This second concept has virtually no technical weaknesses. It may sometimes disturb some people by its "all in one" aspect, but if each of the devices (flotation part and sand filter part) is designed properly, there is no reason to think that sharing the same tank is, in itself, a disadvantage or induces any additional risk of malfunction. Except, of course, for the possibility of physically bypassing the flotation part and

Table 7.1 Recommended minimum depth of water above the sand

Hydraulic load of the flotation zone, m/h	Depth at which the last microbubbles are found, mm	Recommended minimum depth of water above the sand, mm
5	400–600	1000
9	700–900	1400
12	1000–1200	1800

going directly to the filtration. But this remains an easily manageable constraint that only concerns, in fact, maintenance interventions on the flotation part.

However, there is one specific detail that is important to consider, which is the depth of the water above the sand bed. It is best to avoid letting the cloud of microbubbles from the flotation zone reach the sand bed, as this would cause a kind of "false" emboli on the sand surface. Microbubbles plastered onto the sand by the downward flow of water would have the same effect as solid particles and would cause a rapid increase in head losses and a shortening of the filtration cycle. According to observations on real installations and pilot units, with a pressurisation rate of the range of 12-15%, the depth at which the last free microbubbles can be found varies according to the hydraulic load and is around the values proposed in Table 7.1. These observed depths do not quite correspond to the theoretical flotation velocities of the finest bubbles, because, theoretically, the free bubbles smaller than 70 μ should leave with the clarified water, if the hydraulic load exceeds 10-12 m/h at 20 °C. However, it can be estimated that in reality, coalescence in the flotation zone greatly reduces the number of bubbles below this size and that, even if a few rare, even finer bubbles remain and arrive on the filter, they will cause a fairly moderate, or at least acceptable, increase in pressure drop across the filter. Furthermore, it should be noted that in many conventional installations, consisting of separate flotation and sand filters, the transfer of water between the two is done through channels or even pipes, without a long overflow to ensure good degassing, and it is quite possible to find a few rare micro air bubbles in the water above the sand. This phenomenon can be noticed by a small difference in turbidity between the water leaving the DAF clarifier and the water above the sand bed.

Respecting these water depths above the filter should normally avoid the danger of creating conditions for the occurrence of a real embolism, but it is a parameter to be taken into consideration in all cases of operation of any gravity sand filter. The phenomenon deserves some more detailed explanations:

As a reminder, in a gas-saturated liquid, embolism is the appearance of gas bubbles caused by a drop in pressure. In a sand filter the water above the filter bed is normally saturated with air at atmospheric pressure. With increasing depth, the hydrostatic pressure gradually increases the solubility of air in the water and therefore eliminates the risk of spontaneous air bubble formation. However, the situation changes when the water passes through the filter bed. The head losses caused by the clogging of the filter bed cause a drop in water pressure and, if the clogging is excessive, the water pressure can even drop below atmospheric pressure. This depression created inside

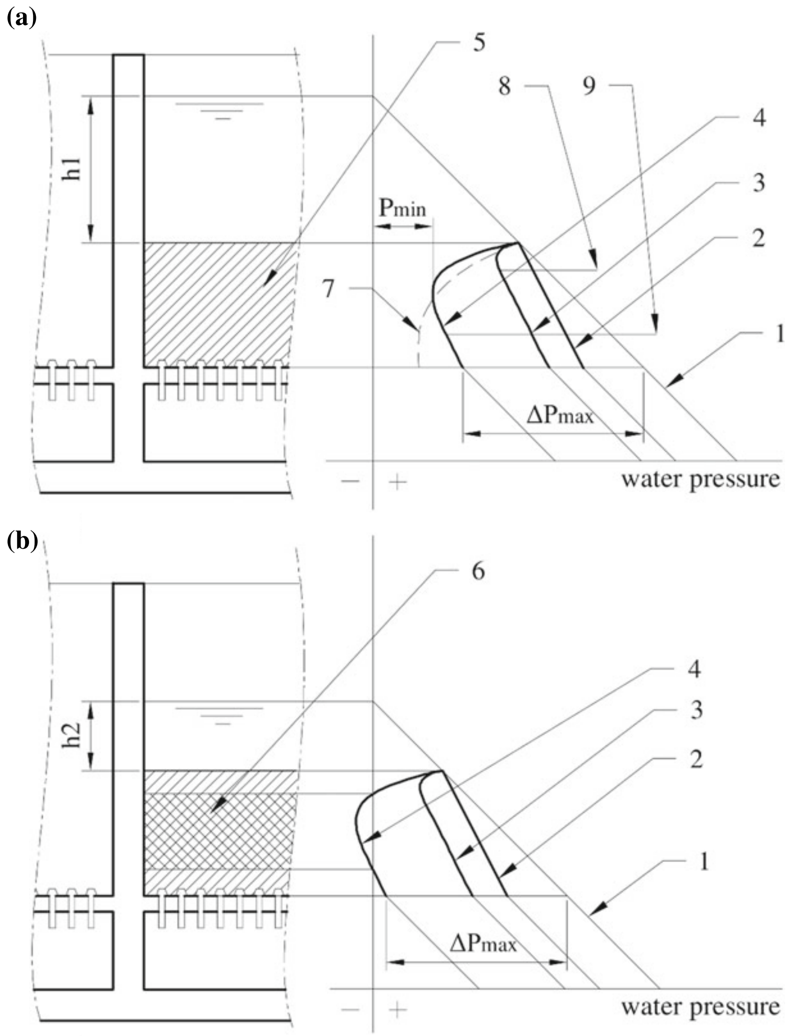

Fig. 7.1 Evolution of the pressure in the filter as a function of the head loss, 1—piezometric line in a stopped filter, 2—piezometric line in perfectly clean sand, 3—piezometric line in clogging process, 4—piezometric line with maximum clogging, 5—sand, 6—Depression zone in which air bubbles are formed, 7—piezometric line of a punctured filter, 8—filtration front corresponding to line 3, 9—filtration front corresponding to line 4

the filter bed will inevitably cause some dissolved air to become excedentary at this pressure, which is lower than the atmospheric pressure. The air bubbles formed at this point fill the spaces between the grains of the filter media and cause further clogging of the filter bed. This is illustrated in Fig. 7.1.

Figure 7.1a shows the evolution of the static water pressure in a sand filter with a water height h1. When the filter is not in operation, i.e. when there is no flow through it, the static pressure evolves along the line (1). The piezometric line (2) corresponds to a filter in operation, i.e. with water flowing through the filter bed when the sand is perfectly clean. The part of the line (2) in the sand layer is steeper, because the sand resists the water flow. Line (3) corresponds to a filter in operation with the upper part of the sand bed slightly clogged. After a first zone of pressure loss on the surface of the sand, the line resumes a slope parallel to line (2) corresponding to the still clean sand at depth. The level at which this line (3) becomes parallel to the line (2) corresponds to the filtration front (8). Above the filtration front (8) the sand starts to become clogged, but below it the sand is still clean. The piezometric line (4) corresponds to a filter at the end of its filtration cycle, which it is time to wash. It can be noted that the minimum pressure inside the filter bed (Pmin) remains positive and that the last lower part of the line (4), which corresponds to the bottom of the filter bed, remains parallel to the line (2), indicating that there is still some clean sand at the bottom of the filter bed. In this situation, the filtration front (9) of the line (4) is still in the filter layer. This corresponds to a total pressure drop ΔPmax that must not be exceeded during operation.

If the same situation (same filter, same filtration rate, same maximum pressure drop ΔPmax) were to be reproduced in a filter like the one shown in Fig. 7.1b with a water depth h2, which is significantly lower than the depth h1 in Fig. 7.1a, one would see that a part of the piezometric line (4) would be in the zone of pressure lower than the atmospheric pressure. This depression extends into the depression zone (6) of the filter bad and is likely to cause degassing with the formation of air bubbles there. This is the gas emboli that should be avoided either by increasing the depth of the water above the filter bed or by reducing the maximum permissible pressure drop ΔPmax, which means shortening the duration of the filter cycle.

Finally, curve (7) corresponds to an “overexploited”, or so-called “punctured” filter. All the sand is clogged and the filtration front has exceeded the bottom of the filter bed. This situation should be avoided at all times, as the quality of the filtered water has already started to deteriorate.

The sizing of the filter bed should satisfy two criteria—the pressure drop across the bed and the duration of the filtration cycle. Ideally, the desired filter cycle time (for operational reasons) should be slightly less than the time for which the maximum pressure drop ΔPmax is reached. This allows the desired filter cycle time to be maintained, optimising the filter’s absorption capacity as much as possible, so that the backwash can take place before the maximum admissible clogging. If the concentration of TSS likely to be retained in the filter and the compactness of these flocs inside the filter bed are known, then it is possible to determine the volume of filter material to be used. As an indication, one can consider that 1 m^3 of filtering medium composed of spherical grains (whatever the particle size) can retain about 1 kg of dry matter from iron or alumina hydroxides and organic matter. This is the most frequent application of this type of equipment combining flotation and filtration. In this case, for a first approach, there are two parameters to vary—either the duration of the filtration cycle is fixed and the hydraulic load of the filter is determined accordingly, or the reverse. For a more precise calculation, there are empirical formulas, such as those proposed in Degrémont's Memento Technique de l'Eau, which allow, on the basis of a few filtration measurements, to calculate the evolution of the head losses according to the main parameters of the filtering material and the dimensions of the filter.

In any case, the best method of defining the parameters of the filter bed remains, if possible, the pilot test with a combined flotation and filtration unit, or, simpler still, with a flotation pilot and a separate filtration column which will offer more facility for testing several types of filters. This type of filtration column, often made of plexiglass, allows direct visual observation, as well as determining the backwash flow rate causing the desired expansion of the filter bed. Some filter material suppliers provide expansion curves for different backwash rates and water temperatures. For single-layer filters washed with water alone (increasingly rare due to layer stratification), good washing generally requires an expansion of at least 15–20% of the layer thickness. For two-layer filters (e.g. sand/anthracite) it is important to carefully determine the "high flow" wash rate, allowing sufficient expansion of the entire filter bed, without loss of anthracite at the intended level of the backwash sludge collection troughs, and the "low flow" wash rate, which allows for re-stratification of the layers, i.e. allowing the sand to settle gradually, but keeping the anthracite in suspension so that it can re-form a homogenous layer above the sand.

The same applies to the selection of the hydraulic load. Il possible, a pilot plant would allow a more precise definition of the evolution of the head losses in the filter media and of the duration of the filtration cycle. In the vast majority of cases, the limiting factor is more on the filtration side than on the flotation side. Of course, increasing the hydraulic load could possibly result in a slight decrease in the quality of the floated water which would shorten the filtration cycle, but experience shows that in the range between 6 and 10–12 m/h the flotation performance remains almost constant, if the chemical treatment is well selected. On the other hand, increasing the hydraulic load shortens the filter cycle time almost linearly. Ideally, 24-h filtration cycles are preferred, as this allows the filters to be washed at night when electricity is cheaper. However, this condition sometimes requires a reduction in the hydraulic load in order to be able to "last" 24 h. Otherwise, the hydraulic load can be increased and the cost and size of the works can be reduced, but the filters will have to be washed more often.

The backwashing of the sand filter of combined flotation and filtration plants is done in a very classical way, depending on the type of filter and the filter media. As already mentioned above, the filter can consist of a single layer of homogeneous sand backwashed with air and then air + water, or it can be of the two-layer type with a layer of anthracite on top of a layer of sand backwashed with air only, then backwashed with water at a high flow rate and finally with water at a low flow rate to re-stratify the two layers. Single-layer filters have some advantages over dual-layer filters in terms of simplicity of backwashing and backwashing rate. Air + water backwash is usually done with an air flow rate of 40–60 m/h and only 10–20 m/h of water depending on the sand grain size. This type of backwashing causes practically no stratification of the filter bed and keeps the sand layer homogeneous,

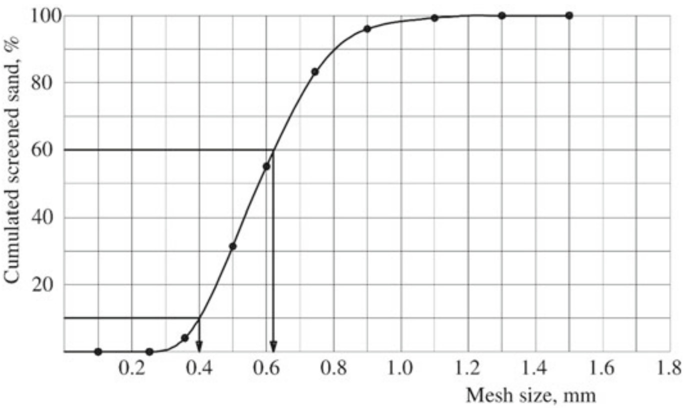

Fig. 7.2 Effective size and coefficient of uniformity of sand. E.S—Effective size = 0.4 mm, C.U—Coefficient of uniformity = 0.62/0.4 = 1.55, • —measurement point with a meshe

unlike backwashing with water alone, which stratifies the sand by pushing the finest grains to the surface, thus forming a superficial layer of fine sand. This layer of fine sand retains more TSS on the surface and prevents the filter bed from being used in depth, which results in a reduction in the duration of the filtration cycle. In contrast, two-layer filters allow good utilisation in depth of the filter bed because the anthracite, whose effective size is usually more than twice that of the sand, retains mainly the larger particles, leaving only the finer particles for the sand. This concept allows for a considerably longer filter cycle.

Another rule of thumb for single-layer filters is that the thickness of the filter bed should be more than 1000 times the effective size of the filter media when flocculant is used, and 1200–1500 times when no flocculant is used. This rule is applied less often and within wider limits for two-layer filters depending on the materials used, but these values can still be used as a benchmark.

Finally, to complete these few basic notions on filtration on granular media, it would be appropriate to recall the two main granulometric characteristics of a filtering material which are:

- The effective size, which corresponds to the mesh size of the sieve allowing only 10% by weight of the sieved material to pass. Usually it is noted as ES (or SES—Standard Equivalent Size). It is expressed in m^2 and is considered to determine the filtration threshold of the filter material.
- The uniformity coefficient, which is equal to the quotient of the 60% diversity by the effective size, or more simply, the mesh size allowing 60% of the grains to pass divided by the effective size. A uniformity coefficient of 1 indicates a perfectly homogeneous material.

The meaning of these two parameters is illustrated in Fig. 7.2 which shows, as an example, a particle size curve of a sand sample.

The two most commonly used filter media are sand (true density 2.5–2.7 t/m^3) and anthracite (true density 1.45–1.75 t/m^3). Pumice (true density 2.4 t/m^3, but high porosity of about 50%) is also increasingly used in drinking water and seawater, alone or in combination with fine sand. There are also filter materials made of glass grains with or without surface treatment conferring them hydrophobic properties

7.1 Rectangular DAF Clarifiers with Built-in Sand Filter

As mentioned above, the rectangular version of the combined units with a common flotation space and compartmentalized sand filter with compartment-by-compartment backwashing has been phased out in favour of the concept involving a multitude of independent cells comprising a flotation system and a single sand filter. In this case, when the filter in a cell needs to be backwashed, the floated sludge is removed, the feed is stopped, the water level is lowered and a conventional filter backwash is carried out before the cell is put back into operation. Since the beginning of this chapter we have been talking about a sand filter, but in reality it is a single or double-layer granular filter, which can be made up of a single layer of sand or anthracite, or two layers of sand + anthracite. In some cases it is also possible to use other filter materials such as pumice alone or in combination with fine sand. It has to be mentioned that this type of combined device (flotation/filtration) does not impose any special requirements on the sand filter. For example, almost all types of granular gravity filters can be combined with a flotation space above the filter. The same applies to filter floors—for a rectangular tank a prefabricated filter floor would be just as suitable as a filter floor with strainers on a cast-in-place slab.

The first concept that deserves attention is very similar to a conventional gravity sand + anthracite filter—see Fig. 7.3 showing a conceptual vertical longitudinal and vertical transverse cross-section of a cell of such a device with hydraulic floated sludge overflow. Coagulated raw water is distributed through a channel (1) connecting all cells. The purpose of this channel is to ensure an equal distribution of the flow between the cells, whatever the number of cells in operation. This flow distribution is done either through a calibrated submerged orifice or through a weir. This second solution causes a loss of 150–200 mm of water height on the piezometric line, but has the advantage of being more accurate and reliable than the first, as it is not influenced by small differences in water level between the cells. Each flotation/filtration cell usually has its own flocculation tank (3) with one or two mixers (4) depending on the shape of the tank.

Pressurised water is distributed by a device (6) as in a conventional flotation tank. In general, it is preferable to have one saturator per cell, but it is quite possible (as shown) to have a common supply of pressurised water (5) supplied by one or more saturators not assigned to a particular cell. When the sand filter is being backwashed, the pressurised water supply to the cell is cut off by means of an automatic valve (21).

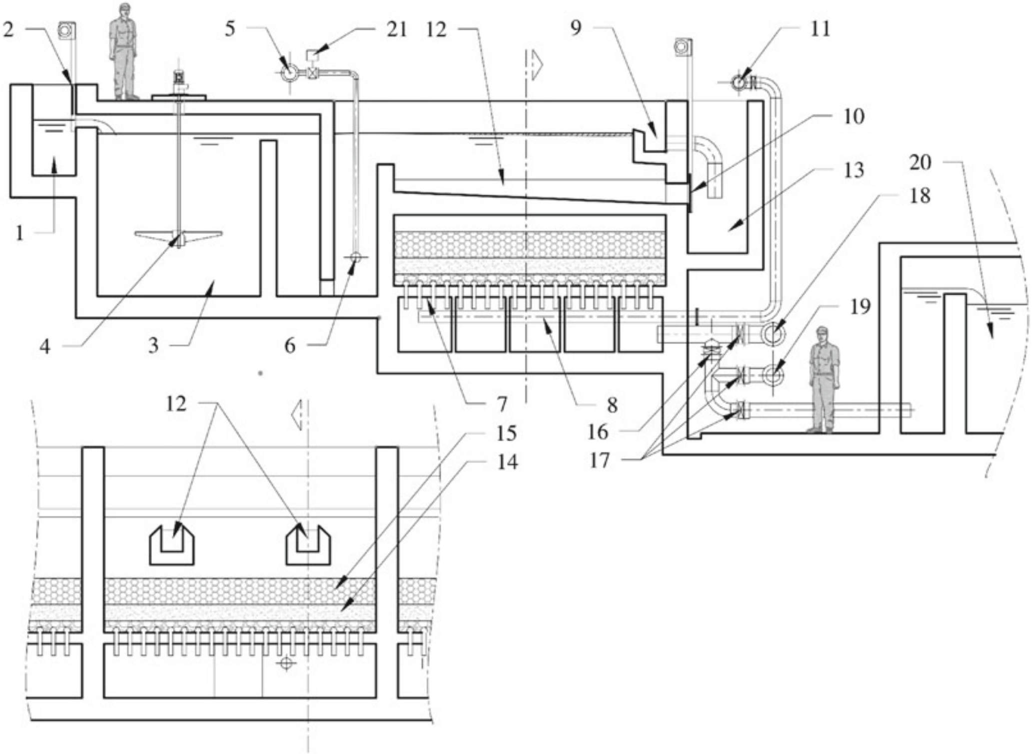

Fig. 7.3 Rectangular DAF clarifier with inbuilt filter bed, 1—coagulated raw water feeding channel, 2—automatic penstock, 3—flocculation tank, 4—mixer, 5—pressurised water, 6—pressurised water distribution, 7—filter floor, 8—air scouring pipe, 9—floated sludge overflow channel, 10—backwash sludge automatic penstock, 11—air for scouring, 12—backwash sludge troughs, 13—backwash and floated sludge channel, 14—sand, 15—anthracite, 16—automatic level control valve, 17—isolation valves, 18—backwash water feeding, 19—first filtrate removal, 20—filtered water tank, 21—automatic valve

An automatic penstock (2) isolates each cell for washing its filter. In normal operation the water level is maintained slightly below the weir of the floated sludge overflow channel (9). Depending on the build-up rate of the floated sludge layer this level is periodically raised so that the sludge overflows into the floated sludge overflow channel (9). The level is raised either by simply closing the automatic level control valve (16), or by partial closure (controlled by a level sensor) of this valve. The choice depends on the inflow and the length of the channel weir (9), the aim being to reliably ensure the desired overflow height in order to control the concentration of the discharged sludge as best as possible. In the case shown, the floated sludge and the sand filter backwash sludge are discharged into a common discharge channel (13) for all cells, as the floated sludge is collected by hydraulic overflow. However, it is quite possible to equip this type of cell with a surface scraper that pushes the floated sludge into a channel (9) almost identical to the one shown in Fig. 7.3, but connected to a separate collection tank for "concentrated" floated sludge. This would avoid diluting the "concentrated" floated sludge (2–3%) with the sand filter wash water, which contains only a few hundred mg/l of TSS at most. Concerning the type of surface scraper, almost all options are possible—two- or three-shafts scraper or paddle wheel. In case of hydraulic overflow of sludge or if only a paddle wheel is used (without a scraper pushing the sludge), it would be recommended to provide a washing ramp for the walls of the tank as shown in Fig. 6.7.

In any case, before air scouring, the water level is lowered to 100–200 mm above the sand level. The automatic penstock (10) opens to discharge the backwash water during the backwash and then closes to seal the flotation chamber. Of course, as in every sand filter, the automatic valves (17) allow the first filtrate to be separated before the filtered water is directed to the filtered water tank (20).

There is nothing really special about the piezometric line compared to a conventional sand filter, apart from the requirements on the depth of water above the filter bed. The difference in water level between the feed channel (1) and the filtered water tank (20) is usually in the range of 2.5–3 m, but the design can be adapted on a case-to-case basis depending on availability.

The same applies to the filter floor—there are no special requirements imposed by the flotation part. Most constructions can be used.

The second concept worthy of attention was developed during the years 1990. It is known by the trade name Coco-Daff ("Counter-current dissolved air flotation/filtration"). Overall it is similar to the previous one—the installation is composed of several independent cells designed generally on the same principle. The difference with the previous concept is mainly in the flotation part. The flocculated water is distributed evenly over the entire flotation surface at a level relatively close to the surface. The white water is distributed separately, also homogeneously over the entire flotation surface, but at an intermediate level between the filter layer and the flocculated water distribution level. In this way, as the microbubbles rise towards the surface, they pass through the mass of flocculated water which descends towards the filter bed, hence the name counter-current. This approach has the ambition to offer some advantages compared to introducing the flocculated water + white water mixture on one side of the flotation zone as done in the previous concept. Firstly, it creates less current in the flotation zone and should normally ensure better clarification conditions on the surface. Secondly, the mutual crossing of the two currents (up and down) causes an intimate mixing that provides additional flocculation, which in some cases allows the installation of mechanical mixers to be avoided and only hydraulic flocculation to be used. Thirdly, any floated sludge settling is taken up by the rising microbubble layer. Finally, the introduction of pressurised water is made low enough in a zone where normally there are no more flocs. Thus, the mixing of the water caused by the pressure relief and the injection of the pressurised water is not expected, in principle, to cause significant floc destruction in this zone.

Figure 7.4 shows two vertical cross-sections (one longitudinal and one transverse) of a conceptual example of this type of apparatus. As shown, each cell can have its own flocculation tank, but it is possible to have a common flocculation tank for all cells, provided that the flocs are sufficiently strong and the water distribution is done in a sufficiently "soft" way to avoid their destruction.

The coagulated water arrives through a common channel (1) to be distributed among the operating cells. Homogeneous water distribution is achieved by means of a feed channel (5) and several distribution tubes (6), each equipped with two (as shown) or three flocculated water diffusion cones (7). The pressurised water supply is provided by the pipes (8). The pressure relief nozzles (9) are located just below each diffusion cone (7). These nozzles are designed to diffuse the pressurised water radially, rather upwards than downwards, to keep air bubbles away from the filter bed as much as possible. In the shown version, the floated sludge is removed by overflowing into the channels (10) leading to a common discharge channel (13). Alternatively, these channels (10) can be omitted and a surface scraper can be installed to push the floated sludge directly into the channel (13). In normal operation the water level is maintained by the automatic control valve (16) which is controlled by a level sensor (not shown).

The initiation of a backwash cycle starts by closing the automatic Inlet penstock (2), isolating the pressurised water supply to the cell (automatic valve not shown) and lowering the water level below the edge of the backwash sludge throat (12), so that air scouring can be carried out. Then the automatic penstock (11) is opened and the filter bed is washed in the way that corresponds to the types and characteristics of the filter material(s). The backwash sludge is collected by the throat (12) and discharged through the common collect channel (21). When the washing is finished, the penstock (11) is closed and the air from the channel (18) is purged. The tank is filled with filtered water up to the level of the feeding pipes (6). After this, the pressurised water supply is restored, the penstock (2) is opened and the tank is filled with flocculated water. The first filtrate is discharged, as usual. Finally, the shown unit is equipped with a prefabricated filter floor which has the advantage of being very economical in terms of height, since it occupies less than 300 mm under the sand bed, compared to at least three times more for a filter floor with strainers on slab.

These two rectangular units, combining flotation and filtration, are mainly used in drinking water treatment for relatively high flow rates—usually over 1000 or 2000 m^3/h. The first concept described above is also successfully used in tertiary

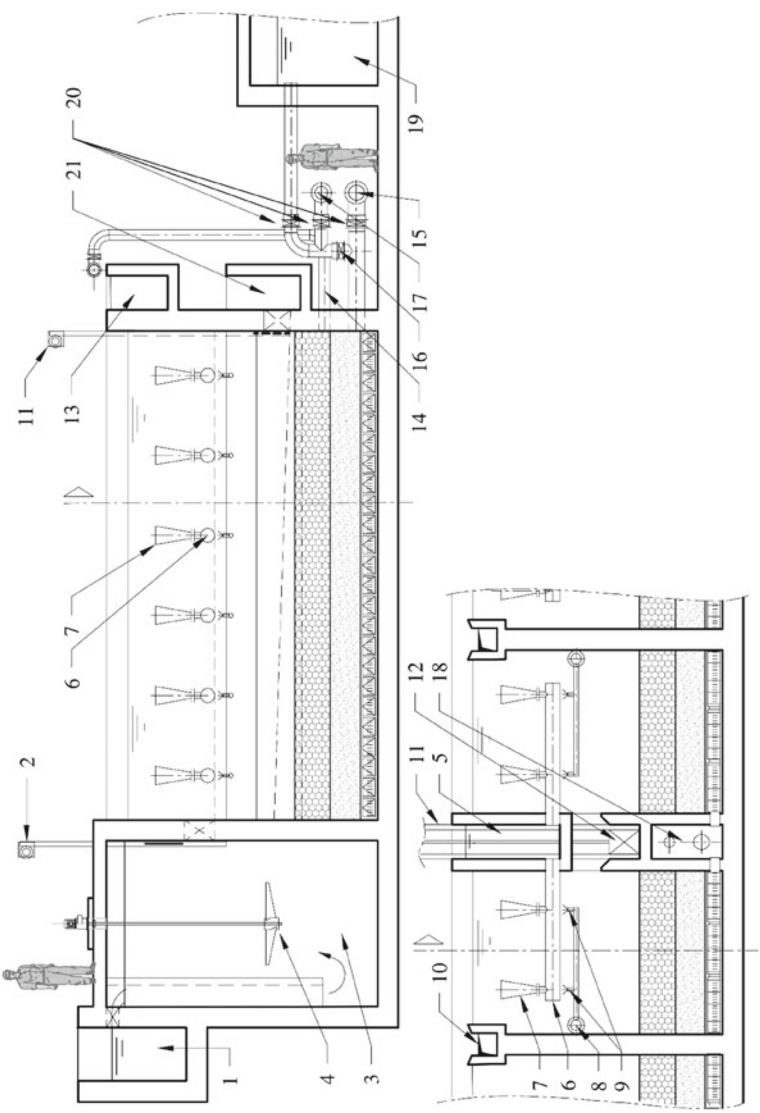

Fig. 7.4 CoCo-DAFF clarifier, 1—coagulated raw water feeding channel, 2—automatic inlet penstock, 3—flocculation tank, 4—mixer, 5—distribution channel, 6—feeding pipes, 7—diffusion cones, 8—pressurised water feeding, 9—pressure relief nozzle, 10—floated sludge overflow channel, 11—backwash sludge automatic penstock, 12—backwash sludge throat, 13—floated sludge collect channel, 14, air for scouring, 15—backwash water, 16—automatic level control valve, 17—first filtrate removal, 18—filtered and backwash water channel, 19—filtered water tank, 20—automatic valve, 21—backwash sludge collect channel

Table 7.2 Filter materials—flotation/filtration

	Filter type	Filter material	Effective size, mm	Layer thickness, mm	Hydraulic load, m/h
Drinking water	Single layer	Sand	0.6–0.8	800–1000	6–9
	Double layer	Anthracite Sand	1–1.4 0.5–0.7	400–600 300–600	8–12
Tertiary treatment	Single layer	Sand	0.8–1	800–1000	5–8
	Double layer	Anthracite Sand	1.4–1.8 0.7–0.9	400–900 300–600	6–9

wastewater treatment, for example in the municipal wastewater treatment plant of Astana (Kazakhstan) treating 265,000 m^3/day. It is apparently difficult to find information about the use of Co-Co-Daff in tertiary treatment, but there are no technical reasons why such installations should not exist. For more information on this topic see Sect. 8.4.4.

Table 7.2 summarises some of the characteristics of the filter materials and hydraulic loads used for this type of equipment. These are, of course, indicative values that may vary significantly depending on the flotation performance, the quantity and specificities of the flocs that may arrive on the filter bed (size, compactness), the possible presence of other clogging factors such as the use of high doses of flocculant, the quality of the filtered water, the duration of the filtration cycle, etc.

7.2 Circular DAF Clarifiers with Built-in Sand Filter

While large rectangular clarifiers combining flotation and filtration are more suitable for relatively large flow rates, circular units with a common flotation space for all filter cells are mainly used for small flow rates—from 100–1000 m^3/h for most references. There are two main reasons for this. The first is that this type of unit is ideally suited to a fully metallic construction assembled on site requiring very little civil works, which is quite appreciable in some cases. The second is economic—the stainless steel construction of a circular tank is cheaper than that of a multitude of independent rectangular cells, each equipped with floated sludge and backwash water recovery facilities, level control, automatic valves and piping, access walkways etc.

Several versions of circular clarifiers have been developed by Krofta and later KWI, the creator and almost sole specialist in these units. The last, most advanced version (known by the trade name Klaricell) is shown schematically in Fig. 7.5. As one can see, the flotation part is very similar to that of a conventional circular DAF clarifier. The feeding of flocculated water and white water takes place in the inlet space (4) surrounding the central filtered water tank (6) via several raw water inlet pipes (7). The flotation area (5) is common and covers the entire surface of the tank. The bottom of this flotation area is divided into filtration sectors (1), which are separated from each other by partitions with flat with edges (3). Each sector is equipped with its own filter floor which communicates with the central filtered water tank (6) via an inlet/outlet pipe (2). This pipe plays a double role. In "filtration" mode, it allows the discharge of the water filtered by the sector. In the "washing" mode of the sector it serves as an inlet for the air and wash water.

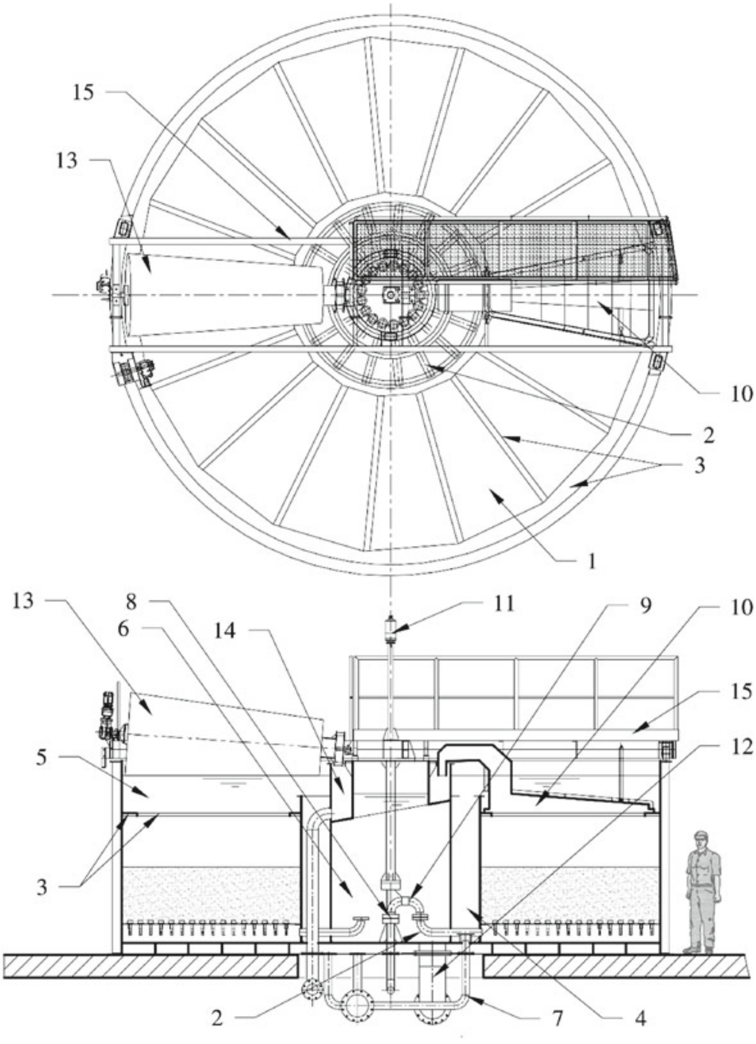

Fig. 7.5 Klaricell—cicular DAF clarifier with inbuilt sand filter, 1—filter sector, 2—inlet/outlet of the filtration sector, 3—sector's partition edge, 4—inlet space, 5—flotation chamber, 6—central filtered water tank, 7—raw water inlet pipes, 8—rotary joint, 9—bridge, 10—backwash sludge collection hood, 11—electric slip-ring, 12—filtered water outlet, 13—spiral scoop, 14—floated sludge channel, 15—rotating bridge

The unit is equipped with a rotating bridge on which are installed:

- A spiral scoop (13) discharging the floated sludge into the floated sludge channel (14).
- A hood (10) to collect the backwash sludge from each sector.

The system works as follows:

Flocculated water and white water, introduced into the inlet space (4), are floated over the entire flotation area as in a conventional circular DAF clarifier. The floated water is then filtered through a multitude of independent filter sectors (1). The filtered water from each sector is collected in the central filtered water tank (6) from where it leaves the unit. The water level in the flotation space is maintained by an automatic level control valve (not shown) installed in the filtered water outlet pipework. The driving force for filtration is provided by the difference in water level between the flotation chamber (5) and the filtered water tank (6). Of course, this difference expresses the average degree of clogging of all sectors in operation and not that of a particular filtration sector. In reality, the degree of clogging of the sectors tends to balance out quickly on its own. This is because having a common flotation space means that a recently washed sector filters more water than the average of the sectors, because its sand is clean, which makes it easier to filter a higher flow rate. As a result, this sector clogs up faster than average. And vice versa—a sector that has not been washed for a long time filters less water because its sand is already more clogged than the average. This self-balancing operation works well at a relatively lower pressure drop than conventional filters—it is recommended that the average pressure drop (the difference in levels between the flotation chamber (5) and the filtered water tank (6)) is kept below 400–500 mm for stable and reliable operation. This requires more frequent washing and sometimes leads to some increase in wash water losses, but this is the price to pay for a compact and efficient flotation/filtration unit. In addition, in industrial water treatment applications, tertiary treatment and even in some drinking water applications, the backwash sludge is recycled to the flocculation tank. This allows the sludge to be re- flocculated and, ultimately, removed by flotation at a high enough concentration to be send directly to dewatering. In addition, this sludge can, in some cases, improve flocculation and reduce polymer consumption as it already contains polymer. This recirculation of the backwash sludge also represents a hydraulic overload that must be taken into account when sizing the ancillary equipment, but it also allows the sludge to be treated in the same unit without additional works.

The filter bed of each sector is washed individualy. When a sector is to be washed, the rotating bridge (15) stops by positioning the backwash hood (10) above the sector so that its edges are above those of the sector. A simple mechanical device allows the sealing between the edges of the hood (10) and the edges (3) of the sector. The connecting bridge (9), which rotates with the rotating bridge (15), is positioned above the outlet of the inlet/outlet tube (2) of the corresponding sector at the same time as the hood (10) and creates a seal between the rotary joint (8) and said inlet/outlet tube (2). Thus the space under the hood (10) is completely isolated hydraulically from the rest of the apparatus. Then, through a set of automatic valves, the water under the hood is sent to the pressurisation system until the water level under the hood (10) reaches 100–200 mm above the sand surface. This allows for an air scouring followed by an air + water backwash. The wash water can be taken directly from the filtered water tank (6), as it is easily supplied from all other sectors that remain in operation. The backwash sludge is discharged into the floated sludge channel (14) and then, through a second set of automatic valves, sent to the flocculation tank or to an intermediate tank. When the washing process is finished, the seals of the hood (10) and the connecting bridge (9) are uncoupled, so that the rotating bridge can be switched on again towards another sector to be washed.

Depending on the application, it is (very) rarely necessary to wash all sectors one after the other. In the vast majority of cases, the rotating bridge has the time to pass several sectors (sometimes up to 10 sectors) between two washes. This makes it possible to extend the time between two washes of the same sector and, consequently, to lengthen the filtration cycle of all the sectors. This mode of operation implies choosing a prime number of sectors, i.e. 17 for small units, 19 for middle size units and 23 for large units. Thus, regardless of the number of sectors being bypassed, no sector will be rewashed until all others have been washed first.

Figure 7.5 shows a single-layer sand filter, but often this type of unit is equipped with two-layer anthracite + sand filters. In this case, the washing sequence will, of course, be adapted accordingly.

Chapter 8
The Main Applications of Dissolved Air Flotation

The few domains of dissolved air flotation application discussed in this chapter are the best known, the most "traditional" and the most frequent. But they are far from covering all the cases in which dissolved air flotation can be used successfully. In fact, it is applicable in almost all cases of clarification, provided that the suspended solids to be separated meet some basic conditions:

1. Preferably, the SS should not be too heavy or form too heavy and compact flocs. It is obvious that flocs with a settling velocity of more than 4–5 m/h would be easily separated by sedimentation at a lower cost, especially if this is possible without chemical treatment. In this case the use of flotation would probably not be economically justified. But there may be special cases, especially in industrial effluent treatment, where a fraction of the TSS flocculates easily and settles very well at high velocity, but another fraction remains in suspension, or worse, tends to float. In this case it is essential to find an adapted chemical treatment in order to trap the maximum of SS in flocs with more homogeneous properties. In other cases, it can happen that flocs that settle well undergo chemical reactions causing degassing that can bring the flocs to the surface after only a few tens of minutes. But these are rare and particular cases that must be studied individually.
2. The flocs formed must have an electrostatic charge to attract the air microbubbles and attach them firmly to their surface. If flocculation is rapid, it will sometimes be possible to form the flocs in the presence of the microbubbles so that some of them are trapped inside the flocs. This significantly improves the buoyancy of the flocs, but is only possible when the first condition is met, i.e. when there is good adhesion between the microbubbles and the flocs. A case in point is the clarification of sand filter wash water in a drinking water plant. During the commissioning, it was noted with embarrassment that the sludge flocculated well, forming light flocs, but these flocs were unable to retain any air bubbles on their surface, so that after the passage of the microbubble cloud they remained in suspension in the water without any of them floating on the surface. This was a bitter and unexpected failure against the background of the experience of about

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
https://doi.org/10.1007/978-3-031-51869-0_8

fifteen perfectly functioning sand filter wash water clarification plants, some of which were built for the same customer… It turned out that, in this particular case, the wash sludge contained mainly decarbonation sludge, some powdered activated carbon and finally very little organic matter (the raw water contained only 1–3 mg/l of TOC). Even with significant polymer overdosing, these mineral flocs were unable to fix any air bubble on their surface.

3. The TSS concentration should be within a few grams per litre, 10–12 g/l at most. Beyond this, the amount of sludge to be floated becomes too much and flotation is unlikely to be the most appropriate clarification technique. Unless the sludge floats on its own without pressurised water or at least floats particularly easily…

8.1 Paper Industry

The production of pulp and different types of paper is probably the first industrial application of dissolved air flotation. The first installations date probably from the 1920s–1930s. The paper industry is still a major user of this clarification technology which offers many advantages over competing techniques in many applications. To better understand the wide range of possibilities for the use of flotation in this industry, it is first necessary to briefly explain what the paper industry is. It has two main branches.

The first is the production of pulp, which consists mainly of cellulose fibres. Virgin pulp is mainly made from wood, but for some special purposes straw or cotton can be used (e.g. for banknote paper). The main manufacturing step is the separation of the cellulose fibres from the lignin. Two methods are most often used:

- The chemical method of "softening" the lignin with chemicals and high temperature cooking. Depending on the conditions under which the wood is cooked, two types are distinguished:
  - Acid cooking, known as "bisulphite cooking". This method produces fine pulps that are usually bleached and used for high quality papers.
  - Alkaline cooking, known as the "Kraft process". The pulps obtained generally have better mechanical strength than those obtained by bisulphite cooking and are used primarily for packaging paper and cardboard.
- The mechanical method allows the production of several types of pulp, including:
  - Mechanical pulp used for printing and writing papers and for newsprint.
  - Thermomechanical pulp (TMP). This type of pulp has more or less the same applications as mechanical pulp.
  - Chemical-thermomechanical pulp (CTMP). Used for printing and writing, but also for tissue paper.
  - Bleached chemical-thermomechanical pulp (BCTMP).

In general, most pulps produced in this way have a more or less pronounced unbleached colour. This colour is acceptable for certain uses such as packaging paper and board, but for the vast majority of applications these pulps are bleached for aesthetic reasons or so that they can be dyed in other colours, colour printed etc. Bleaching is done either with chlorine (a highly polluting practice generating large quantities of AOX dioxins, but unfortunately still the predominant method worldwide) or with oxygen - hydrogen peroxide or ozone. This second technique offers many advantages over chlorine bleaching and its use is increasingly favoured and encouraged by environmental authorities.

Another method of producing pulp is to use recycled paper. This paper is collected from professionals, such as transporters using packaging, or office waste collectors, or from municipal waste collection centres. Recycled paper collected by professionals is generally of better quality, cleaner and better sorted than that collected at waste disposal sites. Manufacturing can be done in two different contexts. The first is to use the recycled paper without special treatment to produce paper or cardboard for packaging on site. In the second, recycled paper is used to produce white pulp bales, similar to virgin pulp bales. These are then sold to paper manufacturers who can use them to make almost any type of paper by mixing or not this recycled pulp with different virgin pulps. In the latter case, it is essential that its mechanical and aesthetic characteristics are as close as possible to those of virgin pulp. In other words, it must contain the maximum amount of long, strong fibres and it must be white. The manufacturing technologies are therefore more complex and almost necessarily include a de-inking stage (which consists of separating the ink particles from whatever was printed on the recycled paper) and a bleaching stage.

The second branch of the paper industry is paper manufacturing. Depending on the type of paper produced and the raw material used, the design of the stock preparation plant and the paper machine can vary considerably. It is safe to say that each paper mill is unique, as there are so many combinations and technological details in the production process.

The raw material can be bales of virgin pulp or de-inked pulp, or recycled paper. Paper production starts with the stock preparation plant. The raw material is mixed with water and mechanically defibrated in a pulper. This concentrated pulp (3–6%) then goes through a grading stage followed by a refining stage (in hydrocyclones). The concentrated and purified pulp is stored in a tank in which additives, mineral fillers (talk, kaolin, calcium carbonate, titanium dioxide, etc.) and other products (starch, latex, colouring agents, etc.) may be added depending on the production process. This concentrated paste is then diluted with water to the exact concentration required for the manufacturing process. This concentration depends on the speed of the paper machine and the desired paper grammage, and can vary from a few tenths of a percent to 1–1.5%. This diluted pulp is pumped at a controlled rate to the headbox of the paper machine.

Figure 8.1 shows a generic diagram of a paper machine. The pulp, diluted to the right concentration, arrives in the headbox (1) to be spread on the forming wire (2), which runs at a precise and constant speed. By the force of gravity, the water contained in the pulp starts to pass quickly through the forming wire (2), whose mesh is open enough to let it through, but at the same time tight enough to retain the fibres. The dewatering in this first area is facilitated by a suitable support of the forming wire (2). The dewatering section ends with several suction boxes (4) which suck under vacuum, under the filter cloth, to recover some more water. At the end of this dewatering section the paper sheet is formed, but it still contains about 22–24% water. To dewater the sheet further, it is taken over by a felt which passes it into the press section equipped with press rolls (6) to mechanically dewater it and reduce its water content to about 16–18%. The remaining water is removed by evaporation in the drying section, which consists of a single (tissue) or multiple steam-heated cylinders. The sheet still containing about 6–7% water is finally wound into a reel (8).

It is therefore obvious that the use of water is ubiquitous in all stages of pulp and paper production, as it is the universal fibre carrier. The volumes of water involved are very large and at the same time the quality of the water used in the core of the manufacturing process is crucial not only for the quality of the final product, but also for the operating and maintenance costs, not to mention the environmental impact of this industry.

The treatment of the various effluents produced by the paper industry has two purposes. The first is to recover the fibres present in the waste. This allows, on the one hand, to limit the loss of precious and costly raw material and, on the other hand, to limit environmental pollution. The second is to recycle as much water as possible in the production process. This allows, on the one hand, to reuse the chemicals and calories (heat) already present in the process water and, on the other hand, to reduce as much as possible the discharged volumes. It is therefore logical to think that the best solution would be to recycle all the water over and over again and add only the bare minimum to compensate for evaporation losses. Some paper makers achieve this, but at the cost of many compromises.

In order to characterise the water problems at each production stage, its use should be considered from two different points of view. On the one hand, it is certainly preferable to recycle as much water as possible in order to reduce the specific water consumption, which is expressed in m^3 of water (at the factory inlet) per tonne of final product. On the other hand, it is obvious that no internal water treatment is 100% efficient and that with each passage through the circuit, the water becomes increasingly loaded with mineral salts, dissolved and colloidal matter, and increasingly fine SS that are more and more difficult to separate. This accumulation of salts and pollutants results in a progressive decrease in the effectiveness of the chemical products used for water treatment, so that once a certain threshold is reached, the coagulants and flocculants no longer work at all, or produce increasingly poor results with increasingly high doses, producing increasingly polluted and untreatable clarified water. Not to mention the effects on the quality of the paper produced, the increase in the chemical aggressiveness of the water (corrosion) and the inevitable development of biomass throughout the circuits leading to fouling and odours. It is, of course, possible to fight against these undesirable effects by adjusting the pH of the circuit in certain cases, by using 316 stainless steel equipment rather than 304 stainless steel, by using all sorts of biocides, but the benefit of these actions is limited and depends on the constraints and specificities of the fabrication. It is best to find the reasonable limit and accept a compromise between water consumption, paper quality

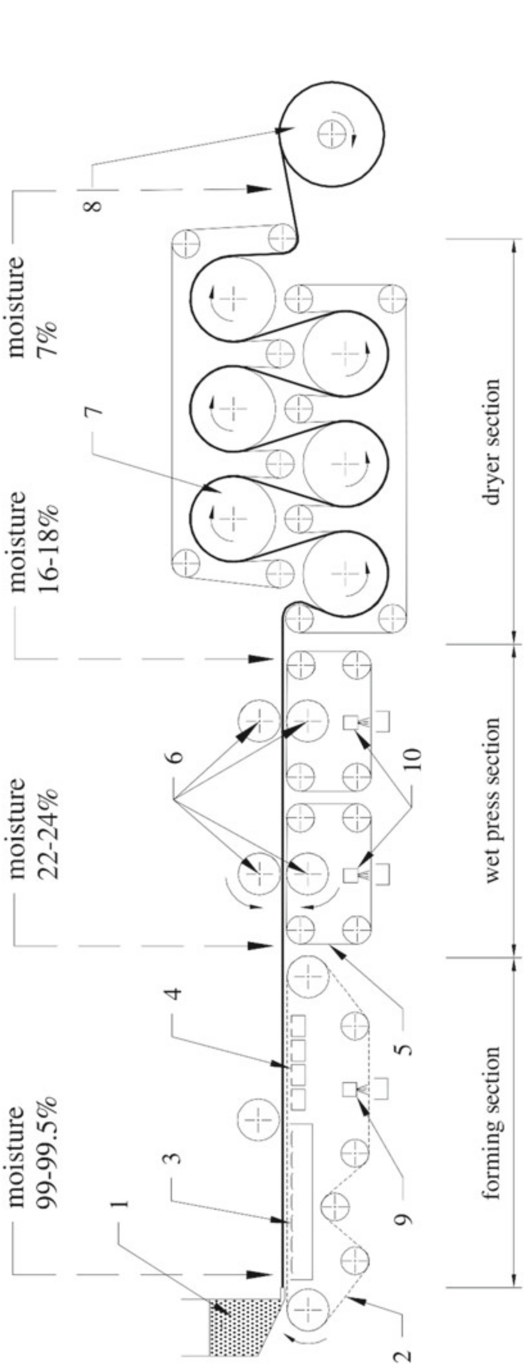

Fig. 8.1 Generic diagram of a paper machine. 1—head box, 2—forming wire mesh, 3—drainage section with water collection under the wire, 4—suction boxes, 5—felt, 6—press rollers, 7—steam-heated cylinders, 8—reel, 9—wire showers with water collection, 10—felts showers with water collection

and operating costs. During the last 30 years of the twentieth century manufacturers have invested a lot of money and effort to reduce specific water consumption, both in the pulp production process and in the papermaking itself. These efforts are to be commended, as the progress has been very significant, leading to reductions of up to several times in specific water consumption in most manufacturing processes. As an indication, according to the data adopted by the European Commission (2015, BREF "Pulp&Paper"), the specific water consumption for the manufacture of the different types of pulp is most often around 20–60 m^3/tonne of pulp, with some exceptions concerning bleached pulps for which the specific consumption can go up to 100–110 m^3/tonne of pulp in certain cases. According to the same source, the specific water consumption in paper production is between 5 and 20 m^3/tonne of paper, with some exceptions for certain special papers that can reach 30 m^3/tonne.

Another aspect of the water recycling issue is the input of pollutants by the various raw materials. Each production process produces a certain more or less incompressible quantity of pollutants, most of which are in liquid form, which also influences the specific water consumption. The management of these two parameters (specific water consumption and input of liquid pollutants) is at the heart of the management of water circuits in a paper mill. The main aim of this management is to reduce the amount of water used in the production process, while ensuring optimal recovery of raw materials and acceptable quality of water recycled in the production process. If one parameter changes, the other will inevitably change and a new equilibrium will be established. It is important to keep this in mind, as any change in the operation of the water systems, as well as the implementation of a new treatment of one or more effluents, will upset the existing equilibrium and lead to a new one, the characteristics of which are sometimes difficult to predict in advance. In practical terms, it is difficult to predict the characteristics of the clarified water that a DAF clarifier added locally to a circuit might obtain once the circuit is stabilised. And a pilot test, treating only a fraction of the flow, will only give indicative information, as treating a fraction of a highly closed circuit or treating the whole circuit are two different things.

There are three possible approaches to the treatment of the different effluents from pulp and paper production.

The first is to collect all the effluents in a common network and then treat the mixed effluent. This method has several major drawbacks: the recovered fibres are often polluted by waste, products or effluents discharged accidentally, the mixed water is often "buffered" and more difficult to treat, etc. Nowadays this concept has been abandoned almost everywhere.

The second approach is to separate "polluting" discharges from "clean" manufacturing effluents containing recyclable fibres and reusable water. The former goes directly to the effluent treatment plant from which nothing returns to manufacturing. The latter are mixed and treated to recover the raw material they contain and produce clarified water that can be recycled in full or at least partially to manufacturing.

The third approach is to separate individually the circuits so that the "polluting" effluent can be sent directly to the treatment plant and the different "clean" circuits can be treated locally without necessarily mixing them. This method is the most efficient because it offers several advantages. Firstly, it is generally easier to clarify a specific circuit, for which it is possible to choose the most appropriate chemical treatment, rather than having a mixture of different effluents. Secondly, the recovered fibres (and possibly fillers) and clarified water are directly recyclable as they come from the same circuit and are at the same temperature. Thirdly, it gives the possibility to use a fraction of the high quality clarified water from one circuit in specific points of another circuit.

Finally, it should also be remembered that dissolved air flotation is not the only option for the recovery of raw materials and clarification of process effluents. It has two competitors.

The first, and in many applications the oldest, is sedimentation. Its main advantage is that it usually works without the addition of chemicals—the retention agents already present in the water (aluminium sulphate, various polyamins) are usually sufficient to allow proper settling of the pulp. On the other hand, it has several disadvantages which have led to its progressive abandonment, except in a few rare and very specific cases:

- Sedimentation is a slow process requiring a long residence time, and therefore large volumes that are not always easy to implement.
- For the above reason, this method is mainly used for the treatment of mixed effluents in a single large settler. This can lead to pollution of the recovered fibres which makes their direct reuse difficult.
- In the absence of oxygen, the long residence time of the pulp at the bottom of the settler often leads to the onset of fermentation resulting in odours that remain in the finished product. This phenomenon clearly runs counter to efforts to reduce water consumption, since it increases with the progressive closure of the circuits, as the water inevitably becomes increasingly loaded with putrescible organic matter.

The second is filtration. The equipment used in the paper industry for this purpose are usually disc filters using filter cloths that are backwashed after each filtration cycle. Disc filters have three clear advantages:

- They work without the addition of chemicals.
- They give good quality clarified water and a high concentration of recovered fibres.
- They are compact and easy to install.

Criticisms are mostly related to their cost and especially to the maintenance costs, because the cloths are expensive and their frequent replacement requires the stop of the production and long working hours. They are well suited to virgin pulp-based production with relatively clean circuits. They have more difficulty managing circuits with high organic and colloidal matter content, and the use of clogging retention agents such as certain coagulants and flocculants.

Compared to these two competing techniques, flotation offers a compromise that is often considered optimal. Compared to disc filters, flotation systems are less expensive in terms of investment and maintenance costs while producing water of sufficient quality. They also aerate the water and reduce fermentation and the associated odours. On the other hand, they often require the addition of chemicals, especially flocculant, to achieve their maximum performance level, which increases operating costs. The energy consumption of a flotation plant is comparable or slightly higher than that of a disc filter, but the difference is not significant.

In the end, the choice between flotation and filtration is made on a case-by-case basis according to the specificities of each production. There is no one factor that gives an unquestionable, universal and decisive advantage to either of these two techniques. They each have their advantages and disadvantages only in the context of each application.

As mentioned before, each production line has its own specificities and it is difficult to list precisely the performance of flotation clarification in the different possible applications within the paper industry. Nevertheless, the main and most frequent ones can be mentioned.

8.1.1 Paper Pulp Manufacturing

In paper pulp manufacturing, there are few points where effluents that might be of interest for local treatment for fibre recovery, water recycling, or both, are generated. The only relatively frequent application is for water used for debarking and preparing wood for cooking. This water gradually becomes loaded with resins and lignin and turns a dark brown colour. Instead of using clean water, some manufacturers use this water during grinding, chipping and possibly leaching. To remove the colour, a DAF clarifier with coagulation and flocculation can be used. Very good coagulation can be achieved with aluminium sulphate or PAC. Flocculation with an anionic flocculant in small doses (1–1.5 mg/l) gives a solid floc that is perfectly suited for flotation. The quality of the clarified water is sufficient for it to be recycled to a large extent.

8.1.2 Paper Manufacturing

This is the main application of flotation in the paper industry. It concerns the water under the drainage section (3) and the water from the suction boxes (4) of the paper machine (see Fig. 8.1). This water, called white water, is collected in a tank, from which part is pumped directly to the stock preparation plant for dilution before the headbox. The rest is pumped to one or two flotation clarification stages (depending on the type of production). Depending on the speed of the paper machine and the retention on the wire, this water contains between 500 and 1500 mg/l of SS (fibres + fillers) in the vast majority of cases. This concentration can be much higher in tissue production, as the retention on the wire is lower to obtain a thin, light and airy sheet.

For some bleached virgin pulp and/or de-inked pulp products (e.g. writing paper) the retention products in the water may be sufficient for proper clarification by flotation without additional additives. It is sufficient to provide a rather abundant pressurisation and a rather moderate hydraulic load of the DAF clarifier. But in most cases an additional cationic flocculant addition of 1.5–2.5 mg/l (virgin pulp) and up to 4–5 mg/l (recycled paper) results in better clarified water and more concentrated floated pulp—3–6%, depending on pulp characteristics. The addition of flocculant can be done in-line just at the inlet of the DAF clarifier as flocculation is very fast—only about 10 s. Depending on the design of the DAF clarifier the flocculant is added either to the raw water just before the injection of the white water or to the white water after the pressure relief device and before it is mixed with the raw water. Both ways work well, provided that the flocs form in the presence of air bubbles so that some of the air bubbles can be trapped inside the flocs.

The recovered stock is recycled in the storage tank upstream of the headbox. Some of the recycled water is used for the wire mesh showers (9), known as "low pressure showers", for the pump glands and for the liquid seals of the vacuum pumps. To avoid any risk of wear of these mechanical parts and also of clogging of the wire mesh showers, it is recommended to filter this part of the clarified water on a police filter (a simple wire mesh filter with a mesh size of 100–200 μ). The aim is not to remove more solids, but simply to retain large particles that may accidentally end up in the water or as a result of a few rare losses at the DAF clarifier. Some papermakers try to use this water for the felt showers (10) known as "high pressure showers" in the press section, at least for the first felt. However, washing the felts (5) with this water is not always a good idea, as the organic matter it contains becomes embedded in the felt and reduces its longevity. It is more sensible to supply these showers, if possible, with the clean hot water obtained by condensing the water evaporated in the dryer and the steam used to heat the heated cylinders (7).

The water squeezed out of the press section is not recycled, as it contains too much colloidal organic matter which is best disposed of. The same applies to the rinse water from the wire mesh and felts. The remaining clarified water is recycled to the stock preparation plant. Of course, the unused part of this water overflows and joins the non-recyclable wastewater and ends up in the mill's wastewater treatment plant. This partially opens up the production circuit, as this water is replaced by clean water used at the most sensitive points, i.e. for steam production, chemicals dilution, felt rinsing etc.

As mentioned above, in some cases, especially in the manufacture of recycled paperboard and when the circuits are very closed (specific fresh water consumption less than 6–7 m^3 per ton of paper), it can be advantageous to have two stages of clarification by flotation. The first stage is designed to recover mainly long fibres for direct recycling in production. In this case only a cationic flocculant is needed. But the water clarified by this first flotation stage still contains a lot of short and fine fibres, mineral fillers and organic matter that it is often better to eliminate, as much as possible, to deconcentrate the circuit and also to produce clarified water of better quality. To do this, part of the water clarified by the first DAF clarifier is coagulated with an aluminium-based coagulant (preferably a basic aluminium polychloride type coagulant which does not alter the pH, or very little) and flocculated with an anionic flocculant. Coagulation is rapid (about 15–20 s may be sufficient) and the flocculant can be dosed in-line at the inlet of the DAF clarifier. The clarified water from the second DAF clarifier can be used for wire mesh showers, pump glands and possibly also for the liquid seals of vacuum pumps. The floated sludge, on the other hand, must be removed from the circuit.

In some cases, such as the manufacture of decorative papers or cigarette papers, the recovery of fibres, and especially fillers, from white water can be more difficult. For example, titanium dioxide (TiO_2), used in some decorative papers, is very easy to flocculate and float, but the flocs formed are sometimes so compact that it becomes difficult to re-disperse them afterwards for recycling, without the risk of having "residual" lumps. This phenomenon can also occur with certain special papers. For this reason, it is very important to find a chemical treatment that allows the recovery of fine particles without causing irreversible flocculation. Sometimes the best solution is to avoid any chemical treatment and to use a simple flotation process. In this case a lot of air must be supplied for the flotation to work properly and it may even be that full pressurisation is the best solution. There are a number of white water clarification plants in cigarette paper production that operate in this way. And attempts to switch to partial pressurisation to simplify the flow variations management and, more importantly, to save energy, have often failed…

8.1.3 De-inking

The removal of inks from pulp produced from recycled paper is completed by washing and thickening the de-inked pulp. If the pulp is intended for the pulp bale production, it is pressed on pulp presses. This process produces effluents containing mainly fillers (up to 60–70% of TSS) and fine fibres, as well as a significant amount of organic matter. Flotation clarification is particularly well suited to the treatment of this effluent, as it is easy to coagulate and flocculate, and the resulting flocs float so well that it is sometimes possible to increase the hydraulic load of the DAF clarifier very significantly without losing efficiency. Cases can be cited of DAF clarifiers handling 60 and even 80% more flow than their "standard" rated capacity. It is therefore strongly recommended that the effluent is thoroughly tested before choosing the design parameters.

Chemical treatment consists of coagulation and flocculation. Coagulation is rapid (20 s is sufficient) and can be carried out in the flotation feed pipe, if it is long enough and sized to provide this residence time. Coagulant can be added either at the inlet or in the outlet reduction of the feed pump to ensure good mixing. The most commonly used coagulants are bentonite and organic coagulants of the polyamine type. The flocculant, normally anionic, is added in-line to the inlet of the DAF clarifier. In this application only the clarified water is recycled to the process. The floated sludge is removed from the circuit.

8.1.4 Mill Effluent Treatment

So far we have discussed the treatment of the internal circuits of pulp and paper production. But some of these effluents, as well as other non-recyclable direct discharges, tank overflows and pulpers drains, end up in the mill's effluent treatment plant. This effluent is necessarily screened on a rotary screen or other type of fine screen to separate bulky waste. A buffer tank is used to homogenise this effluent before primary treatment followed, ideally, by biological treatment. Again, for primary treatment, the most commonly used clarification technology is flotation. The competing technique is sedimentation, but this has been progressively abandoned on most sites for more or less the same reasons it was abandoned for process water—too space consuming, anoxic fermentation of water and sludge, odours etc.

The treatment almost always includes coagulation and flocculation prior to flotation to recover as much organic matter as possible before the final discharge or before the biological treatment. The buffer tank plays an important role here, because if the coagulation is to function optimally and, above all, stably, it is essential to feed the DAF clarifier with an effluent whose characteristics change as little as possible over time. If the buffer tank is too small or poorly managed, the characteristics of the effluent will change permanently as a result of variations in discharge, pulpers draining, tanks overflows etc., and the chemical treatment will give results that vary with these changes. In most cases the volume of the buffer tank corresponds to the average volume discharged for a period of 6–12 h, sometimes more. Depending on experience, part of the volume is used for homogenisation and the rest is kept empty for flow equalisation. It is obvious that it is advantageous to keep the homogenisation volume as high as possible to have the best possible stabilisation of the effluent characteristics. At the same time, the equalisation volume, which is attempted to be left available, must still be sufficient to absorb the largest possible discharge surplus (the sum of the volumes exceeding the average flow through the buffer tank). The buffer tank must be equipped with sufficiently powerful mixing means to ensure rapid homogenisation of the volume. This mixing can be provided by mixers (minimum 5 W of dissipated power per m^3 of volume of the buffer tank) or by an aeration system. In this case floating surface turbines seem to be a good solution, as they avoid the formation of floated sludge crusts on the surface. Aeration also has the advantage of stripping out part of the COD (sometimes more than 10–15%!) in some cases such as effluents from recycled paper based productions. In the case of aerobic biological treatment, especially for effluents from mills using recycled paper, it may be advantageous to recycle the excess biological sludge into the buffer tank to take advantage of the adsorption of organic matter by the biomass. This improves the flotation capture rate of the primary treatment and reduces the COD loading of the biological treatment.

What type of equipment should one choose for the clarification of white water and de-inking effluent? Generally speaking, compact DAF clarifiers are preferred in the paper industry, as space is often at a premium as mills evolve. Therefore, "classic" DAF clarifiers, whether circular or rectangular, operating at 6–8 m/h with deep and large tanks, are not really suitable for paper applications. The same applies to floated sludge collection devices. Conventional surface scrapers (see Figs. 4.5 and 4.9) require too much maintenance, as the lips or brush seals are chemically attacked by the water and deform quickly. Clarifiers with spiral scoops or paddle wheels without seals are preferred.

Circular DAF clarifiers with radial distribution (see Fig. 3.10) were very successful throughout the paper industry in the years 1975–2000. They operate at a relatively low hydraulic load (7–8 m/h), but have two major advantages. The first is their lightness, as the water depth is only 400 mm, which allows them to be installed on top of other equipment or on the roofs of buildings. Their second advantage is the very low volume of water (only the equivalent of 2.5–3 min of flow), which offers the possibility of quick emptying with little water loss and easy cleaning, which is very appreciated in case of frequent colour changes. Their operating principle even allows, in some cases, to change the colour without stopping the feeding of the clarifier. All that is required is to divert the clarified water and the floated mass into the drain for one minute.

From the 1990's onwards some models of assisted clarification DAF clarifiers have also found many users in the paper industry. Their extremely compact size and small footprint (see Figs. 5.6a, 5.7, 5.8), as well as their high clarification efficiency, are decisive arguments for choice in many cases, despite the fact that they can often be slightly more expensive than "conventional" DAF clarifiers. However, these clarifiers are not the ideal solution for cases of frequent colour changes, as thorough cleaning is sometimes difficult, especially for vertical clarifiers. In paper mills, the main applications of these vertical clarifiers are for effluent from recycled paper production and de-inking, which change little over the year.

Regarding the choice of saturator type, the following recommendations can be made:

- Avoid large-volume saturators, which are generally expensive and cumbersome. They are, of course, usually very efficient in terms of saturation rate, but it is not certain that this is really very useful, as this type of effluent contains a lot of organic matter which favours the "preservation" of the microbubbles and avoids their coalescence quite well after the pressure relief. In addition, in the vast majority of cases, the pressurisation rate is oversized for concentration variations and safety reasons. Thus, a saturator offering a saturation rate of 50–60% is fully sufficient and provides enough air. It should even be pointed out that saturators operating at 35–40% saturation are very common in the paper industry.
- Low volume saturators in which the water circulates at high speed in every corner of the vessel are preferable. This avoids the formation of deposits that are very frequent in these effluents containing fibres, glues, starch, flocculants and other clogging products, not to mention the development of biomass favoured by the abundance of organic matter and oxygen.
- In view of the above recommendations, saturators using any kind of packing should be avoided at all costs.

– Air dissolving pumps may work well in terms of dissolving air, but their channels are sensitive to clogging, and the presence of fibres and mineral fillers in the water significantly reduces the longevity of the turbines.

As far as pressure relief devices are concerned, it is obvious that all kinds of pressure relief nozzles with holes or slots of a few millimetres are to be definitely excluded. These devices, which are intended almost exclusively for drinking water, will inevitably clog up quickly. Automatic or manual pressure-relief valves are much better suited to difficult operating conditions and are to be recommended, even if their performance in terms of pressure-relief quality is not as good as that of the said nozzles, especially if a single large pressure-relief valve is used. It is better to multiply the pressure relief points and to avoid as much as possible the pipes after the pressure relief devices, as they favour the coalescence of the bubbles. In any case, it would be wise to leave easy access to these devices, which are often the most sensitive part of the pressurisation installation.

8.2 Food Industry

Compared to the paper industry, here the volumes discharged are much lower—from less than 10 m^3/h to 100–120 m^3/h at most, with an average range of 20–40 m^3/h covering the vast majority of cases. The characteristics of the effluents depend, of course, on the type of manufacture, but also on the specificities of each plant. The primary treatment of these effluents, before discharge into a municipal sewer network or upstream of a biological treatment, is very often carried out by flotation because these effluents contain, in a large part of the cases, greases and proteins which coagulate and float very well and which, at the same time, ferment very quickly in anoxic conditions. It is therefore better to avoid sedimentation, even if the TSS can be settled, which in not common.

The variety of production in the food sector is immense and it is impossible to examine each case even briefly. The few sectors discussed below are probably the most representative and frequent. Each of these sectors may have small specificities even if, on the whole, the treatment methods remain similar.

8.2.1 Dairies, Cheese Factories

There is a lot of data on the volume and composition of effluents from different milk-based productions. However, it is difficult to summarise them into a sizing guide because the values vary over a wide range—sometimes by a factor of 1 to 2, but very often by a factor of 1 to 10 or more. This is not surprising, given the huge number of products and manufacturing technologies.

The effluents are mainly formed by:

- Dairy product discharges generated during the manufacturing process such as whey, buttermilk or simple milk losses. In general, whey and buttermilk are recovered during the manufacturing process, but small volumes of accidental discharges may occur.
- Wash water from equipment and tanks. This wash water poses several problems from the point of view of its treatment.
  - Most of the volume often arrives at the end of the day when the production lines are stopped.
  - Washing is done often with soda or acid, usually both, one after the other. As a result, the pH of these effluents can vary from 2–3 to 10–12.

These variations in wastewater volume and quality require a well sized and well managed buffer tank. Because, as has already been mentioned several times, to ensure that the treatment of these effluents, whatever they may be, can work properly, it is important to have a water quality that is as constant as possible. However, the management of the buffer tank is sometimes complicated. On the one hand, it would be logical to think that a large buffer volume would allow for proper homogenisation of the effluent and provide a stable water quality to the treatment plant. On the other hand, it should be remembered that these effluents are highly biodegradable and ferment very quickly, even if properly aerated. Experience shows that a residence time in the buffer tank of more than 4–5 h, and sometimes even less, especially in summer, leads to the onset of fermentation and the appearance of odours that are quite annoying for the neighbourhood. Therefore, it is important to closely monitor the management of the buffer tank by properly controlling the production sequences, so as to ensure as much as possible a good homogeneity of the effluent with a residence time in the buffer tank limited to 4–5 h.

There are two approaches to the treatment of these effluents. If the treated effluent is discharged into a municipal wastewater sewer, the aim of the treatment is usually to remove mainly free fats (which may clog the pipes) and possibly some of the pollutants in order to bring the level of the parameters characterising the pollution more or less in line with that of municipal wastewater. In this case, a DAF clarifier operating without chemical treatment could be sufficient. A simple pressurisation is sufficient to float the particulate fats likely to be deposited in the sewers. For a non-assisted clarification DAF clarifier a net hydraulic load of 6–8 m/h with a pressurisation rate of about 20% (always considering an efficiency of 60% of the saturator) is usually sufficient to meet the requirements of a municipal network. In other cases, more stringent requirements on the quality of the discharged water impose a chemical treatment before clarification by flotation. This chemical treatment consists of pH regulation, coagulation with an organic or mineral coagulant, usually iron-based, and flocculation with a flocculant, normally anionic. But these cases are relatively few, because a low flow effluent is not a problem for a municipal plant in many cases, even if its COD is high, provided that it is easily biodegradable, which is the case.

If the effluent is to be discharged to a sensitive environment and therefore requires biological treatment, a choice is made between two possible options:

- Installing a simple DAF clarifier with no chemical treatment, as described above, to remove just the particulate fats upstream of the buffer tank. The aim is to avoid the formation of fat balls and even fat patches in the buffer tank which are difficult to transfer to the treatment plant and remain on the surface for weeks with the odours that their fermentation generates. This is probably the most common case because, as mentioned before, dairy effluents are very biodegradable and it makes more sense to treat everything biologically, as the final product is a relatively stable biological sludge that is easy to valorise in agriculture.
- Installing a DAF clarifier with chemical treatment, the purpose of which is to coagulate and flocculate the maximum amount of polluting matter before clarification. This solution produces better quality treated water and reduces the load on the biological treatment. The removal rate of CES easily reaches 80–90%. On the other hand, the efficiency of COD removal with a "reasonable" chemical treatment is not very high (30–40% maximum in most cases). Also, the physico-chemical sludge produced is more difficult to manage, as the presence of coagulant hydroxides and polymers can pose problems for their disposal, even after a strong liming with 30% or even 40% lime.

It would probably be useful to clarify in more detail the terms "fats" or "oils and greases" that are widely used in the practice and in the specifications concerning the treatment of effluents from the food industry.

The fats contained in this wastewater come in four different forms:

- Solid fats, also known as particulate fats. These are particles of solid fats, free or often associated with all kinds of SS, which are also present in the effluent. Their condition depends on the temperature of the water and the characteristics of the grease—it concerns those that are solid at the temperature of the effluent. Their density is usually around 0.9–0.95. Therefore, they float easily on the surface of the water. Fatty particles associated with other SS have a specific weight varying between 0.9 and 1, and are easily floated with pressurised water or even by simple mechanical aeration producing bubbles of 1–2 mm in diameter. This is the competing technique to dissolved air flotation in this application. Of course, mechanical aeration is simpler and cheaper to implement than dissolved air flotation, but it is also less efficient in terms of the amount of material recovered. Nevertheless, in many cases, such as municipal wastewater treatment, the efficiency of mechanical aeration is sufficient to remove the most troublesome part of the grease.
- Liquid free fats, also specified as oils. Like particulate fats, these droplets float naturally to the surface or are at least easily floated with pressurised water or even mechanical aeration.
- Emulsified fats (or emulsified oils). These very fine droplets form stable emulsions with water and do not float naturally, even after several hours of standing in static conditions. To separate them from the water, they must first be agglomerated by coagulation and/or "acid breaking" by lowering the pH to below 2–2.5. Once the emulsion is "broken", it is easy to flocculate and separate them by flotation.

– Dissolved oils that can only be removed from the water by biological treatment (for those that are biodegradable) or by membrane filtration (rare, as it is limited to very small flows of a few m^3/h, expensive and difficult to implement).

The total amount of fat in the water can be measured by extraction with a solvent such as chloroform, hexane or trichloroethylene. The parameters obtained are chloroform-extractable substances (CES) or hexane-extractables materials (HEM) respectively. These parameters do not indicate the breakdown between the different forms of fat. In practice, it is also important to measure at least the amount of free fat by removing the naturally floating fat after the sample has been left for a few hours. Subsequently, a separation by coagulation/flocculation of the emulsified fats from the sample free of particulate fats can give an indication of the amount of dissolved fats. The accuracy of the measurement is not perfect, but it gives sufficiently clearer idea of the different forms in which fats are present in water.

This clarification is necessary because these "details" are not clearly mentioned in many specifications, which can lead to confusion about the process guarantees of fat removal. Indeed, some specifications may claim up to 90% removal of "fats" with a simple flotation, without giving any precision on the type of fats concerned by the guarantee. And some suppliers do not hesitate to give such ambiguous guarantees… Because it should be noted that eliminating 90% of particulate fats by simple flotation is feasible, eliminating 90% of particulate and emulsified fats is (very) difficult, but removing 90% of all fats material without physico-chemical treatment is normally impossible for the vast majority of food industry effluents…

8.2.2 Edible Oil and By-Product Production, Ready-to-Eat Meals

The effluents from oil mills come mainly from the refining and bottling of vegetable oils. However, in many cases these plants also include oil processing facilities such as residual fats hydrogenation, salad dressing, mayonnaise and other oil-based food products. The various manufacturing plants are sometimes equipped with local oil separators, but the operation of these facilities is often poor. It is therefore preferable to discharge these effluents as quickly as possible to the wastewater treatment plant, where their treatment can be better organised.

These effluents, which mainly come from condensates, various washings, overflows and losses, essentially contain oils in different forms depending on the type of production. The concentration of oil accidentally discharged in the effluent can sometimes be very high—up to 10–15 g/l. It is therefore advantageous to direct this effluent to a DAF clarifier located upstream of the buffer tank to recover these oils, which can amount to several hundred litres per day. The DAF clarifier will only work with pressurisation without any chemical treatment in order not to contaminate the oils. Given the low flow rates—generally less than 20–30 m^3/h in instantaneous flow, depending on the flow rates of the local pumping stations—he DAF clarifier can be of the simplest design, i.e. with non-assisted clarification to avoid clogging, which may be abundant. These effluents are rarely screened and it is imperative to pressurise with recycled water and to use an ‘unblockable’ pressure relief device, such as a diaphragm with a 10–12 mm circular orifice. This represents a significant pressurisation rate (approx. 8–10 m^3/h at 5 bar), but this is the price to pay for relative reliability of operation. It is also possible to replace the pressurisation system with a self-aspirating submerged aerator producing large bubbles of 400–800 μm. The result is quite satisfactory, but the installation of the aerator requires some modifications inside the flotation tank. For the collection of floated oils it is recommended to use surface scrapers rather than spiral scoops, which clog up on the inside and are more difficult to clean. The recovered floating oils have a concentration of around 10 to 20%. They can be directed to one or more heated vats, in which the oil is liquefied and separated from the water and part of the SS carried along with it. These oils can then be recovered as by-products for the production of soap or other products.

The effluent, cleaned of particulate oil, is collected in a buffer tank with a volume of 12–24 h of discharged effluent. It is not necessary to aerate this effluent—a floating pump, which sucks the water from the surface and returns it to the depth of the tank, is sufficient to prevent the formation of a floating crust and at the same time to aerate the effluent. If the effluent is discharged into the municipal sewage system, it is generally necessary to carry out a physico-chemical pre-treatment of the effluent to remove the remaining particulate oils and, as far as possible, emulsified oils. This also reduces the COD, which can often exceed 10 g/l. The choice of the chemical treatment before flotation clarification is very important. An iron-based coagulant should be preferred and the optimum pH for coagulation should be determined, because although coagulation at more or less neutral pH works well, there may be cases where coagulation at pH 4–4.5 may be more advantageous, although it may be necessary to implement acidification followed by neutralisation of the clarified water to bring the pH to a value suitable for discharge into the municipal network (generally pH 6 to 9) or to biological treatment (pH 6.5–7 to 8.5). It may turn out that coagulation at pH 4.5 gives a better purification yield and requires much less coagulant, while producing a more compact and less abundant sludge than at neutral pH. Therefore, the reduction in treatment costs more than covers the cost of the pH reduction and final neutralisation. The purification efficiency of such a physico-chemical treatment can be in the range of 50–60% for COD and up to more than 90% for HEM.

If the effluent requires biological treatment, then physico-chemical pre-treatment will not be strictly compulsory, although these effluents containing long molecular chain fats can sometimes be more difficult to digest by an aerobic biological treatment. Of course, physico-chemical pre-treatment as described above will still be beneficial for the proper operation of the biological treatment and will almost halve its size. However, it will still produce physico-chemical sludge that is more difficult to manage than a single biological sludge. The choice depends on many factors, but in any case the treatment and management of the sludge, once produced remains, as in many cases, a major issue.

8.2.3 Slaughterhouses

Slaughterhouse effluents mainly come from various washings related to the cleaning of slaughter areas and the various production workshops. Depending on the type of animal (poultry, pigs, sheep, cattle), production workshops after slaughter may discharge effluents containing blood, visceral matter, fats that are more or less emulsified depending on the temperature of the water used and the possible use of different cleaning products. Poultry slaughterhouse effluents also contain pieces of feathers. Pig, sheep and cattle slaughterhouse effluent contains bristles and hair. It is very important to screen these effluents properly before any treatment to remove these feathers, bristles and hairs, as they are very clogging and can get everywhere.

The quantity and composition of the effluent is very variable not only in relation to the slaughtered animals, but also according to the production technology within each type of slaughterhouse. The data available on the different parameters of the effluents discharged (TSS, COD, BOD5, etc.) are, once again, quite variable, since the pollution parameters emitted per kilogram of carcass can vary by a factor of 1 to 4, and sometimes even from 1 to more than 10, so that they are difficult to use for practical forecasting. It is therefore strongly recommended to base any sizing on actual measurements carried out on site or at least collected on very similar sites.

Regardless of the destination of the effluent (municipal sewer or biological treatment), it is important to remove at least the particulate fats upstream of the buffer tank, as animal fats mostly set at ambient temperature and form thick crusts on the surface of the buffer tanks. In addition, these fats with very long molecular chains are particularly indigestible for aerobic biological treatment. A non-assisted DAF clarifier located between the sieves and the buffer tank, designed for a maximum net hydraulic load of 5–8 m/h with a pressurisation of about 20–25% (poultry slaughterhouse) and 30–35% (pig, cattle, sheep slaughterhouse), would enable these fats to be collected and avoid any formation of floating crusts in the buffer tank. Once again, it is strongly recommended to use non-clogging pressure relief devices to ensure reliable operation of the DAF clarifier.

The volume of fat collected by the DAF clarifier can sometimes be quite significant and its management—difficult. One treatment option is to hydrolyse this fat and 'pre-digest' it in a small aerobic biological reactor. The aim is not to biologically digest these fats, but simply to "break" their long molecular chains into shorter fragments to make them easier to digest by the aerobic biological treatment with the rest of the effluent in the buffer tank.

A second DAF clarifier can be installed as a physical–chemical pre-treatment after the buffer tank. A coagulation of the range of 2–3 min with $FeCl_3$ or another iron-based coagulant, followed by in-line flocculation with an anionic flocculant, results in a COD removal efficiency of around 55–65% (cattle, sheep, pig slaughterhouses) and up to 70–80% (poultry slaughterhouses). This particularly high efficiency is due to the fact that the proteins in blood, which is often the main pollutant, are easy to coagulate and eliminate. Such a physico-chemical treatment, combined with clarification by flotation, is also very effective upstream of a biological treatment and enables the volume of the aeration tanks and the energy cost of aeration to be reduced significantly. But it also produces a significant amount of physico-chemical sludge which can be difficult to manage in many cases. Indeed, this sludge is not very structured and its dewatering requires quite a lot of liming—up to more than 40%! This is why, as mentioned in the previous paragraph, the choice is often made for direct biological treatment of the effluent after the buffer tank, because on the one hand, these effluents are easily biodegradable, and on the other hand, the biological sludge produced is easier to manage and possibly to use in agriculture. If the treatment includes a DAF clarifier with physico-chemical treatment, followed by an aerobic biological treatment, then it would be advantageous to discharge the excess sludge from the biological treatment into the coagulation tank of the DAF clarifier to be finally mixed with the physico-chemical sludge and removed in the DAF clarifier. Sometimes it is more acceptable to send mixed sludge of this type for land disposal after liming and dewatering than pure physico-chemical sludge.

8.3 Oil Industry

The oil industry involves two distinct activities: the production or, rather, the extraction of the oil and its processing in refineries.

8.3.1 Oil Extraction

To better define the place of dissolved air flotation in this field, it would probably be useful to give a broader description of the overall context of this application and the main issues that engineers have to deal with.

In the early oil era producers started by exploiting the most accessible and profitable oil wells that produced virtually pure oil. This was simply put into barrels after a short journey through a storage tank which essentially acted as a buffer tank. The few percent of water that might be contained in the oil was also separated there. This small volume of water, called produced water, was stored in evaporation ponds (if climatic conditions were favourable) or simply dumped discreetly into the wild without any particular treatment. With the development of oil extraction, producers went further and further into the ground to find the black gold and became increasingly interested in oil wells from which they pumped oil containing more and more water. But until the middle of the twentieth century, the volume of produced water was often just a problem of the profitability of the fields, so much so that in the Soviet Union, according to old professionals in the field, wells giving more than 50% of produced water were simply abandoned.

Nowadays the situation has greatly changed. In the early 2000s, humanity had already extracted about 1200 billion barrels of oil (source: International Energy Agency, 2009) out of the 5500–6700 billion barrels contained in various forms in the earth's soil (estimate by the same source). Today there are countless wells producing less than 50% oil. In many cases wells producing less than 10–15% oil are still profitable, given the price of crude. In other words, in many cases much more produced water is extracted than oil. This poses two major problems, among others.

The first problem is purely environmental. Simple gravity separation of the oil in the tanks provided for this purpose does not allow sufficient quality of the water to be achieved for direct discharge into the natural environment, especially as oil losses with this water are frequent (when the oil/water interface in the separation tanks drops too low to the level of the subnageant discharge).

The produced water at the outlet of the first separation tanks generally contains 100–400 mg/l of hydrocarbons (in HEM). In addition, in many cases, these waters are very rich in dissolved salts. For example, chloride concentrations can often reach several tens of grams per litre, or even more than 200 g/l in some rare cases, which makes it a real poison for all vegetation and aquatic life. Not to mention heavy metals, such as manganese, lead and zinc, as well as a large number of toxic products whose characteristics and quantities vary greatly depending on the fields…

The second problem is hydraulic. By withdrawing a large volume of water, the pressure in the reservoir is reduced more quickly, because the water table often cannot compensate for the volume pumped quickly enough. This further reduces the production of the wells.

It is obvious that the composition of the produced water is very variable from one oilfield to another. It can also change over time during the exploitation of the same field. It is very common for field operators to add chemicals to improve the separation of oil from water (demulsifiers or "emulsion breakers"), to reduce deposits in pipes (antiscalants), to reduce corrosion in installations (corrosion inhibitors), etc. It is very difficult to know the characteristics of these products (manufacturing secrecy …) and to estimate, as far as possible, their effects on the treatability of the water.

In view of these issues, the produced water treatment can take several forms. On offshore platforms it is discharged into the sea, after treatment which generally includes coalescence filters and/or cyclones to separate the bulk of the free oil, followed by mechanically dispersed gas flotation cells. These flotation cells have different names depending on the gas dispersion technology—GDF (Gas Diffused Flotation) or CFU (Cavitation Flotation Unit), or IGF (Induced Gas Flotation). These installations use one or, more often, several successive flotation stages. In some cases, mechanical bubble diffusers are replaced by Dissolved Gas Flotation (DGF) cells, which allow for multiple stages of microbubble flotation and, of course, give better results. The hydraulic load of these specific flotation cells is very high—typically 25–35 m/h for each stage, or much higher. At these loads the efficiency of each stage is certainly insufficient, but the multiplication of stages allows, in the best cases, to remove even oil droplets smaller than a few tens of microns and to reduce the HEM content often below 30–40 mg/l, even below 10–15 mg/l in some cases.

The mechanism of flotation of these waters containing mainly oil droplets is also somewhat specific and different from the mechanism of bubble/particle aggregates formation, commonly accepted for solid particles flotation. According to this mechanism the bubble/particle bonds are created mainly by electrostatic and surface tension forces at the contact interface between the liquid (water and oil) and gas phases. Collisions between oil droplets of microbubble-like sizes and microbubbles can also cause the water film surrounding the droplets to break and the oil comes into direct contact with the air, causing the droplet to instantly surround the entire air bubble like a film (Gas attachment of oil droplets for gas flotation for oily wastewater cleanup—Roshni Moosai, Richard A Dawe, 2003). The implementation of this phenomenon requires, on the one hand, a reduction in surface tension between the three phases (water, gas and oil), obtained by adding various chemical products (surfactants, emulsion breakers) and, on the other hand, a maximum of frontal collisions between the bubbles and droplets, which occurs quite rarely given the difference in ascensional velocities between them. Hence the multiplication of successive flotation stages and also the use of large quantities of air, the ultimate aim being to increase the chances of producing such collisions. Sometimes these flotation cells use polymers to further improve performance, but the very turbulent hydraulic conditions are not suitable for the use of coagulants that form flocs that are far too fragile.

Almost all of these different types of flotation cells are developed by oil production equipment manufacturers and remain specific to this field, without having found applications outside the oil industry. Indeed, such flotation cells are sometimes installed by similarity (and by mistake) on applications requiring real dissolved air flotation, just because they have the same name and because oil professionals are familiar with them and can more or less live with their performance, which in many cases is far below what is possible.

Onshore facilities offer more options for treating these waters.

The first approach is to treat and discharge the water into the environment. This is possible when the oilfield is shallow and the produced water is relatively low in salt content. In this case, it is possible to set up clarification by flotation with or without physico-chemical treatment, followed by biological treatment, then possibly sand filtration and, finally, even filtration through activated carbon. Such a treatment is quite expensive, but normally allows to meet the standards for discharge into the natural environment. For the flotation pre-treatment part that interests us, two solutions are possible.

The first solution is to use flotation cells specially developed for oil applications, such as those described above (GDF, IGF, CFU), which usually operate without chemical treatment. In this case, the separated oil is directly recoverable, but the clarification yield may be insufficient and too much emulsified oil may be passed on to the next treatment stage.

The second solution is to use a DAF clarifier with a physicochemical treatment. In this case, the separated oils will not be directly recoverable, but coagulation will allow the stable emulsions formed by the finest droplets, whose diameter is less than 10-20μ, to be broken and the larger droplets to be better trapped in the flocs produced by the coagulation of other materials present in the water. As a result, the clarified water will be of better quality. The performance of this physico-chemical pre-treatment and flotation clarification depends, of course, on the composition of the water, which is highly variable. But in most cases a 1–2 min coagulation with an organic coagulant, sometimes followed by rapid in-line flocculation with an anionic flocculant, will give a good result—the HEM content is reduced to below 10–15 mg/l, even in the most difficult cases, with average values around 5–8 mg/l. The choice of coagulants must be made very carefully and, if possible, piloted on site. On the one hand, it is necessary to find the coagulant that gives the best result in terms of HEM reduction. On the other hand, a coagulant must be chosen that does not cause precipitation and scaling. This is because these waters often have a very high hardness, and a wrong coagulant can lead to the formation of several millimetres of deposits in just a few weeks.

The second approach, which solves both the problem of discharging the water and the problem of maintaining the pressure in the formation, is to re-inject the produced water back into the oilfield. The injection is done under pressure through surrounding non-operated wells so that the water injected into these wells seeps into the operated wells. This solution is simple and logical, but its implementation must meet a few requirements. The first are geological and concern the permeability of the subsoil in which the water is injected, the communications between them, etc. The second are related to the quality of the water and are essentially two.

The first requirement concerns the content of oil and suspended matter, because, depending on the characteristics of the soil, it is very important that the clogging capacity of the water is low enough so that it does not clog the injection wells. However, it is difficult to make estimates on this subject, especially if the permeability of the soil at the injection points is relatively low and the flow rate to be injected into the well is high. Of course, it is possible to carry out injection tests and to record the pressure curves necessary for the injection of a given flow rate, but this presupposes the availability of large volumes of produced water of different qualities, which is difficult to implement in practice. It is therefore preferable not to take too many risks and to send water of the best quality reasonably achievable into the ground. In the vast majority of cases a three-stage treatment line is sufficient to obtain water with less than 4–5 mg/l HEM, which seems to be a "universal" satisfactory threshold. These stages are as follows:

– Cyclones or coalescing filters to remove the majority of large oil drops.
– Flotation with or without coagulation/flocculation to reduce the oil content to less than 10–15 mg/l.
– Filtration on nutshell filters. Compared to sand filters, granules of different types of shells have the advantage of capturing oil droplets not only by mechanical retention, but also by adsorption on the surface of the grains. These nutshell filters are also devices developed especially for the oil industry. There are several types, which differ mainly in the washing technology of the filter media.

The second requirement relates to the presence of oxygen in the injected water—it is imperative that it does not contain oxygen. This is because the water is rich in organic matter which, in the presence of oxygen, can promote the development of biomass which will inevitably clog the well around the injection point. There are two ways to remove oxygen from water. The first involves chemical reduction of dissolved oxygen in the water with an excess dosage of a product such as sodium sulphite (Na_2SO_3) or ammonium bisulphite (NH_4HSO_3). This method is quite expensive and is suitable for small flows. The second method consists of avoiding any contact of the produced water with oxygen (originally it does not contain any oxygen, of course). This implies carrying out the entire treatment line in closed tanks under a layer of a gas other than air, most often methane or nitrogen. The same applies to the flotation plant—it is imperative to pressurise with either nitrogen or methane, depending on availability on site. In this case it is important to consider the amount of the gas used for pressurisation in the raw water. If the produced water is not saturated with pressurisation gas, some of the gas in the pressurised water will go directly to saturate the raw water first, before the rest of the gas can form microbubbles once the saturation point is reached. This may require a considerable increase in the pressurisation flow rate or pressure, or both, to provide the missing amount of gas to add to the volume of gas needed for flotation.

Pressurising with a gas other than air requires a gas tight cover over the flotation surface and a gas recovery system, which is usually common to all tanks in the process line. The containment of the pressurisation gas, combined with hydrocarbon vapours, also creates safety constraints—all equipment must be built according to ATEX (Explosive Atmosphere) standards. While the use of nitrogen is relatively straightforward and the installation of equipment meeting ATEX Zone 2 standards is usually sufficient, the use of methane can be more difficult and costly to implement. Apart from all electrical and electro-mechanical accessories, ATEX regulatory requirements may also apply to the mechanical components of the DAF clarifier such as the materials of construction and design of the chains, the glands for the drive motor shafts through the cover etc.

DAF clarifiers, sometimes called microbubble DAF clarifiers by those in the profession, more often use gas dissolving pumps than true saturators. Although the dissolution efficiency provided by the pumps is lower, the high presence of surfactants in the water allows for good quality microbubbles in terms of size and stability. In addition, dissolving pumps allow a relatively simpler reuse of the gas layer (nitrogen, methane or other) from pressurised DAF clarifiers as it can be drawn through injectors without treatment, whereas a conventional saturator would require pressurised gas, which should be treated before compression by dedicated compressors.

Microbubble flotation systems developed by oil production equipment manufacturers are essentially of three types: vertical, open horizontal and pressurised horizontal.

Vertical units have one, two, three and, in some cases, up to four successive separation stages, providing a residence time of only a few tens of seconds per stage. They are often equipped with water orientation devices creating a spiral rotation that prolongs the contact time and leads to a cyclonic separation effect. The performance of these devices is still quite sensitive to the specific characteristics of the water. They often involve the use of organic flocculants to improve separation.

Horizontal, open or pressurised flotation cells are arranged in rectangular or, more often, cylindrical tanks (for reasons of ease and cost of construction). They are separated into several successive compartments. The first compartment is often a simple gravity separator in which free oils of low density (of the range 0.85–0.88), easily floating on the surface without the assistance of gas microbubbles, are removed. The three or four successive compartments are each supplied with an appropriate flow of pressurised water containing microbubbles. The quality of the clarified water improves progressively after each compartment. Floating oil is discharged by mechanical means such as paddle wheels or by simple overflow onto adjustable weirs that allow the volume of overflow to be adjusted as much as possible to the volume of oil captured by the corresponding compartment. The water level is regulated by a weir or by an automatic valve controlled by a pressure sensor. Each compartment also has a drain to remove eventually bottom sludge if any. A conceptual diagram of such a flotation cell is shown in Fig. 8.2. In this example pressurisation is done with air through an air dissolving pump and the vessel is opened via the vent (16), but it is quite possible to use another gas for pressurisation such as nitrogen or methane. In this case the vessel will be pressurised and equipped with a system for circulating, maintaining the pressure and, eventually, treating the gas. The flow rate of pressurised water in each flotation stage is regulated by pressure relief valves (11) as required. The floated oil from each stage is collected in a common collector (12) from which it is recycled for reprocessing. The residence time of the water in each successive compartment is usually in the range of 2–4 min, but can vary within wider limits depending on the specific characteristics of the water, the temperature and the use or not of chemicals that favour the separation and agglomeration of oil droplets.

Many installations also use more ‘conventional’ flotation systems developed by water treatment equipment manufacturers. In this case flotation is accomplished in a single stage with chemical treatment by coagulation/flocculation. The hydraulic load and residence time depend on the type of DAF clarifier, but remain within the classical values of a “traditional” application. Indeed, a good coagulation of at least 30–40 s with a lively agitation ($G > 300\ s^{-1}$) followed by an in-line flocculation of the same duration are sufficient to obtain excellent results. In this case, the selection of the coagulant is of primary importance, because in order to obtain less than 5–10 mg/l of oil in the clarified water, it is necessary to coagulate almost all of the microdroplets in emulsion. Moreover, these micro-droplets of a few microns (1–5 μ) are often impossible to separate by simple flotation without chemical treatment.

While clarification of produced water remains the main application of dissolved air flotation in oil extraction, some onshore water treatment plants also include a second DAF clarifier in the treatment line for nutshell filters wash water and final sludge dewatering filtrates. The nutshell filter wash water can contain up to several g/l of oil and also hydroxides from the coagulants used in the main line DAF clarifiers. Thus, the purpose of this DAF clarifiers is to concentrate the sludge from the various filtrates and the non-recoverable sludge. The flow rate of this water is low—about 5–10% of the flow rate of the produced water. And it can be treated under aerobic conditions, as normally the clarified water is not intended to be re-injected into the formation. Depending on its destination (e.g. discharge into the natural environment after biological treatment or transfer to a refinery effluent treatment plant) this DAF clarifier can operate with or without coagulation/flocculation. The type of coagulant and flocculant can sometimes be identical to those used in the main treatment line.

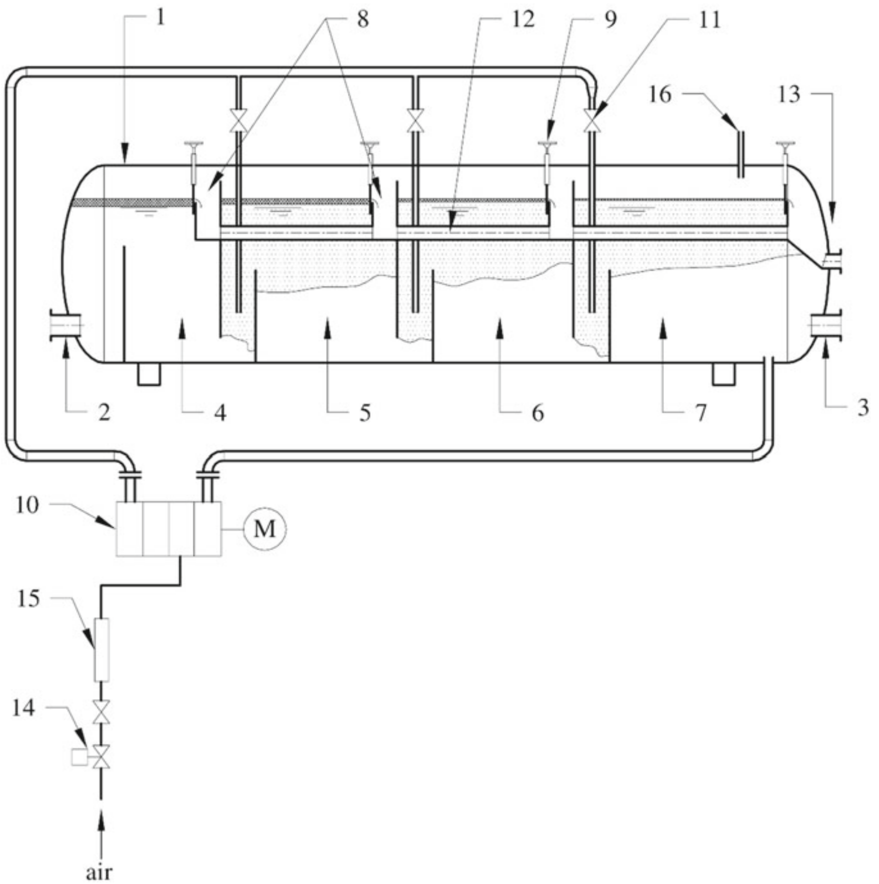

Fig. 8.2 Horizontal flotation cell. 1—cylindrical tank, 2—raw water inlet, 3—clarified water outlet, 4—gravity separation compartment, 5—first stage flotation, 6—second stage flotation, 7—third stage flotation, 8—oil channel, 9—adjustable weir, 10—air dissolving pump, 11—pressure relief valves, 12—oil collector, 13—oui outlet, 14—solenoid valve, 15—air flow meter, 16—vent

In conclusion, it seems necessary to emphasise that for this application of dissolved air (or other gas) flotation the techniques used can vary considerably from one site to another. It can happen that a unit that is satisfactory in one case is not very efficient in another case, even though it is very similar at first sight. This is why it is recommended that a pilot test campaign be carried out to confirm the choice of equipment and, possibly, the chemical treatment to be used.

Finally, it would be useful to say a few words about the construction materials of the equipment. One of the specificities of the produced water is its salt content, especially chlorides, which is often very high. Chloride concentrations of 10–20–30 g/l are common and values of over 100 g/l are not so exceptional. This is why, where possible, manufacturers opt for a mild steel construction with a high-strength epoxy coating. These coatings are quite thick, expensive to implement and often fragile. The elements need special care during transport and assembly to avoid cracks in the corners and splinters. However, some DAF clarifiers and saturators, due to their design, are difficult to paint, if at all. In this case the only solution is stainless steel. It is clear that such concentrations should exclude stainless steel with a PREN of less than 40. Unfortunately, the use of these stainless steels makes the units very expensive to build and uncompetitive with coated mild steel construction. However, for some reason, which is difficult to explain even to the stainless steel manufacturers, 316 TI stainless steel is, at least in some cases, perfectly resistant (known to last more than 15 years without significant corrosion traces) to a chloride concentration of around 20–28 g/l and a temperature of more than 30 °C, which is theoretically impossible according to the manufacturers' data, who only guarantee it for 1 g/l of chlorides at 20 °C and around 800 mg/l at 30 °C. It can be assumed that some of the oils and other products present in the water strongly reduce the aggressiveness of the chlorides, but this is only an assumption by the author. In any case it is worth trying, as it is easy to test for corrosion resistance by immersing samples of different stainless steels in water for a period of a few months and then comparing the degradation of surface appearance and weight loss. It is also important to provide good cathodic protection to avoid any risk of electrocorrosion, which is particularly dangerous in salty water.

8.3.2 Refineries

Effluents from refineries and other petrochemical complexes are composed of a wide variety of sources. The first comprehensive descriptions of the origin and composition of these effluents is provided by Milton R. Beychok in his book Aqueous Wastes from Petroleum and Petrochemical Plants first published in 1967. Despite the age of the book and the technical developments of recent decades, much information can be found in it that is still relevant today.

These effluents can be grouped into three categories in view of their treatment:

1. *Production effluents* from the various oil refining processes (simple refineries) and possibly from the production of derived products (petrochemical complexes). These effluents arrive at relatively constant flow rates and may contain from a few hundred to a few thousand mg/l of oil. They are treated almost systematically by gravity separators of the API (American Petroleum Institute) or CPI (Corrugated Plate Interseptor) type or, more rarely, by coalescence filters. These oil separators generally work without chemicals and allow the separation, in most cases, of free oils and fine droplets larger than a few tens of microns. This reduces the oil concentration in the treated water to a value of between 80 and 150 mg/l in most cases. The floating oils are pushed by a four-shaft scraper towards a slotted skimmer which allows them to be recovered periodically for re-use. The bottom sludge, which inevitably forms, is pushed by the same scraper on the return path to a sump on the inlet side of the tank, to be periodically purged.

The “de-oiled” effluent is then sent to a mixed buffer tank. Its main purpose is to allow sufficient homogenisation to ensure the most stable quality possible of the water at the entrance to the next treatment stage which is, in most cases, coagulation/flocculation followed by dissolved air flotation. The stability of the water characteristics guarantees the reliability of the chemical treatment and allows not only to maintain a good coagulation/flocculation, but also to optimise the consumption of coagulant and flocculant, which can be considerable, given the importance of the flow rates. The more the water quality varies at the outlet of the buffer tank, the more the operator will tend to overdose the chemicals to ensure that the treatment is effective “no matter what”.

Coagulation of these effluents is relatively easy. Alumina-based mineral coagulants seem to give better results, but iron-based coagulants are also used at some sites. It is difficult to make recommendations on coagulant type and dosage, which vary according to the characteristics of the water and local availability of the products. The coagulant dose should be determined on site. For flocculation, 1 to 2 mg/ of anionic flocculant may normally be sufficient. Coagulation and flocculation times are relatively short—a quick mix of one to two minutes for coagulation and two minutes for flocculation is sufficient in most cases.

Concerning the type of DAF clarifier, it is possible to use almost any of them successfully, as the flocs are relatively solid and flotation—rather easy. The oil content in the clarified water can easily reach 5–10 mg/l, which is quite acceptable for biological treatment downstream of flotation. COD reduction ranges from 50 to 80%. The pressurisation rates recommended in some tender specifications are quite high—up to 50%, which is excessive. If the saturator provides 60% saturation (in clean water) then, depending on the type of DAF clarifier and the pressure relief device, a pressurisation rate of 20–25% will most likely be sufficient.

2. *Rainwater* from areas likely to be contaminated by pollutants, such as retention tanks, unloading areas, etc. After screening, this water is collected in a buffer tank, also known as a storm water tank. In general, it is not very polluted and it is preferable to treat it separately, at a constant low flow rate, in a small installation consisting of an API or CPI type static de-oiler, a coagulation/flocculation facility followed by flotation and possibly filtration, before discharging or reusing it, as it contains little dissolved salts. The sizing of the installation’s capacity is done according to the volume of the storm water tank and the available treatment time between two representative rainfalls.

Again, the purpose of the storm tank is to ensure not only a sufficient buffer volume for the storage of these waters, but also a good homogenisation so as to allow a stable and reliable performance of the chemical treatment. The latter should be checked and possibly adjusted after each rainfall, as the composition of the water could vary according to the flow rate and the current pollution of each of the areas connected to this network.

The flotation plant and the coagulation/flocculation equipment remain quite similar to those of the production effluent treatment line. The collected sludge (floated sludge and bottom sludge) is mostly sent to the production effluent sludge treatment plant.

3. *Ballast water from oil ports.* This comes from the bilges and tank cleaning of oil tankers or oil transport cisterns, if the refinery is not on the seashore. In oil ports there are often treatment facilities for ballast water from ships. They are relatively small and treat only a few tens of m^3/h at most. These installations consist of an oil separator, a DAF clarifier with coagulation/flocculation and one or two sand filters. The chemical treatment is quite conventional—an alumina-based mineral coagulant and an anionic flocculant.

Depending on its salinity, ballast water recovered in refineries is either treated with process water or (more often) with storm water. In general, there is no dedicated facility as is often the case in oil ports.

Finally, apart from the treatment facilities for the three groups of effluents mentioned above, it is common to find flotation systems, installed in local treatment on specific points of the production lines, to directly recover certain products or pre-treat certain effluents before mixing them with the production effluents. These applications are linked to the specificities of each petrochemical complex and must be studied on a case by case basis.

8.4 Municipal Effluents

Dissolved air flotation has found several applications in municipal effluent treatment. From the 1970s–1980s onwards, the accumulated experience in this field was gradually transferred also to the biological treatment of industrial effluents. Nowadays, the following main applications can be identified:

– Primary treatment of municipal effluents.
– Biological sludge clarification.
– Biological sludge thickening.
– Tertiary treatment and phosphorus removal.

Each of these applications has its own specificities and deserves a more detailed description proposed below.

8.4.1 Primary Treatment of Municipal Effluents

If the municipal effluent treatment plant includes primary clarification (which is not always the case), then primary clarification is almost always achieved by sedimentation in primary settlers. This is undoubtedly the best solution for at least two reasons. Firstly, sedimentation allows sufficient quality of clarified water to be obtained upstream of the biological treatment without any chemical treatment and at a modest energy cost. Secondly, the primary sludge thickens easily to 4–5% dry matter, which is sufficient for digestion in digesters. Clarification by flotation would achieve more or less the same results but at a prohibitive energy cost, which excludes this technology from this application.

There is, however, one particular case in which flotation may be of interest. This is the case for small effluent treatment plants in holiday resorts, ski resorts and other municipalities which, at the arrival of the touristic season, see their population increase several times in a few days. The question then arises as to the size of the waste water treatment plant—should it be sized for the maximum population with all the consequences that this entails or should other solutions be sought? Such a situation is difficult to manage for the effluent treatment plant, because, even if it was sized for the maximum load (which is a heavy investment for only two or three months in a year), it would not be able to scale up quickly enough to cope with a 3 or 4 -fold increase in the volume of water to be treated. Even if it has additional biological treatment equipment in reserve, the biomass available in the plant will be insufficient, as it takes time to grow the amount of biomass needed for biological treatment. Not to mention the inconvenience and difficulty of operating a large plant that is running at a low motion for most of the year. This is where the use of a flotation plant in primary clarification can be useful. With chemical treatment, including coagulation with ferric chloride or other iron-based coagulant plus flocculation with anionic polymer (or cationic polymer in specific cases—to be tested), the DAF clarifier will allow a reduction in COD and BOD of around 50–60%. The DAF clarifier will not solve the problem of hydraulic overload, but it will considerably reduce the organic pollution load going to the biological treatment and thus allow it to ensure a decent treatment from, especially if the plant has been "prepared" correctly with a prior accumulation of biomass in the aeration tanks during the weeks before the beginning of the season. The DAF clarifier will be relatively small and take up little space. In addition, during the off-season it will not be useless, as it can be used to thicken excess sludge prior to dewatering.

The floated sludge produced by this pre-treatment is certainly not first class and its treatment can cause some difficulties, but it is a manageable compromise that allows the plant to get through this difficult time in providing an up to standard discharge.

8.4.2 Biological Sludge Clarification

Biological treatment techniques have evolved considerably since the 1970s-1980s. Fixed cultures and various biofiltration techniques have become more and more popular next to the "classical" free biomass treatment not only in the treatment of municipal effluents, but also in the biological treatment of many industrial effluents. In this sense, several types of aerobic biological treatment methods can be identified:

– Aeration tank with free biomass at a concentration of 3–4 g/l.
– Aeration tank with free biomass at a concentration of 8–10 g/l.
– MBBR (Moving Bed Biofilm Reactor)—fixed biomass on a moving support.
– MBBR combined with free biomass in the same aeration tank.

– Biofiltration on a fixed support consisting of gravel, slag, pozzolan, loose plastic elements or packed blocks of profiled plates.

Each of these techniques has its own specificities in relation to the use of dissolved air flotation as a means of clarification. Therefore, it would be necessary to examine them one by one.

8.4.2.1 Aeration Tank with Free Biomass at a Concentration of 3–4 g/l

In "classical" biological treatment plants, i.e. aeration tanks operating with free biomass at a concentration of 3–4 g/l, secondary clarification is almost exclusively done by sedimentation. There are several reasons for this. Firstly, clarification by flotation of a mixed liquor at such a concentration requires a significant pressurisation flow rate, which results in a high energy cost that is difficult to justify compared to the negligible energy cost of sedimentation. Secondly, the biomass in free culture has a specificity linked to the very process of liquid/solid separation in this water. This separation occurs in two stages. In a first step, even the finest microparticles of the biomass dispersed in the water have to agglomerate into flocs. Clarification only takes place fully in a second stage when these flocs are well formed and sufficiently strong to resist the microturbulence caused by their movement in the water. However, these flocs can only form under strictly laminar flow conditions, as these biomass particles have almost no electrostatic charge and agglomerate mainly by mechanical clinging. Thus, the flocs break up at the slightest agitation and become a homogeneous mass that only partially settles, leaving poor quality clarified water still containing too much TSS. It is obvious that these conditions of very low turbulence, favouring the flocs formation, require low flow velocities and a long residence time in the clarifier. They are much easier to meet in a settler, providing a residence time of 1.5 or 2 h, than in a flotation tank which will necessarily be much smaller in terms of volume and therefore more turbulent. On the other hand, a properly sized DAF clarifier would take up much less space than a settler and would produce a much more concentrated floated sludge, which would allow the volume of the aeration tank to be reduced slightly and would also make it possible to dispense with the need for a thickener for excess sludge. But, under all other conditions equal, it will produce lower quality clarified water, which is not acceptable.

In order to achieve the full benefits of a DAF clarifier, the problem of biomass floc formation would have to be overcome by adding cationicity, i.e. by adding a cationic flocculant. But this adds extra operating costs.

Conclusion: except in special cases, e.g. severe lack of space, flotation has no place in this application. The advantages of flotation do not outweigh the disadvantages.

8.4.2.2 Aeration Tank with Free Biomass at a Concentration of 8–10 g/l

What is the difference between an aeration tank with free biomass operating at 8–10 g/l and the same tank operating at 3–4 g/l? Moreover, why are the aeration tanks operated at 3–4 g/l of biomass and not at 8–10 g/l or even 15 g/l? If the pollution treatment capacity depends on the amount of biomass in the aeration tank, then why not use smaller aeration tanks with more concentrated biomass? The reason for this is the settleability of the biomass, usually characterised by the Sludge Volume Index (SVI), called sometimes simply Sludge Index (SI). This is the volume (in ml) containing one gram of sludge (in dry matter) after 30 min of settling in a one litre Imhoff cone. This parameter indicates (in ml/g) the capacity of the sludge to concentrate during settling. The smaller the volume occupied by one gram of dry matter, the better the sludge's settleability. A SVI of less than 100 ml/g characterizes a biological sludge that settles and concentrates well. It is usually relatively aged and highly mineralised. Conversely, an SVI of more than 250–300 ml/g is typical for highly loaded and poorly mineralised biological sludge. It may also indicate the presence of filamentous sludge. A well-functioning biological plant produces sludge with a SVI typically between 120 and 160–180 ml/g.

What is the practical meaning of this parameter? It is that if one gram of sludge occupies 250 ml (SVI = 250 ml/g) and if the water contains 4 g/l of sludge then one will need a volume of $4 \times 250 = 1000$ ml to contain it. In other words, there is no more settling possible in the Imhoff cone which is 1000 ml. Therefore, by sizing the concentration in the aeration tank to 4 g/l, one estimates that the SVI will never exceed 250 ml/g. And if one wants to operate at 10 g/l in the aeration tank, one must bet on a SVI of less than 100 ml/g, which is rather daring for a continuously operating plant. If the sludge is not sufficiently settleable in relation to its concentration, the settler will balance out by losing the extra sludge in the clarified water. Hence the "reasonable" upper limit of 4–4.5 g/l sludge concentration in an aeration tank followed by a settler.

Going back to the aeration tank operating at 8–10 g/l biomass concentration, one can say that in reality this is not an insurmountable constraint—one just has to get rid of the secondary settling problem. There are two solutions:

- Use microfiltration membranes instead of settling (Membrane Bioreactor). The quality of the clarified water is certainly excellent (better than that obtained by sedimentation), but the membranes are expensive and remain sensitive and delicate to operate, whatever one says.
- Use a DAF clarifier instead of a settler. It will be much less sensitive, if at all, to sludge compactibility.

This second solution is finding more and more applications and gives good results, if it is implemented properly. Indeed, like any specific technology, it only develops its full benefits if it is used in the right context. What are its advantages and disadvantages?

Advantages

– Allows the volume of the aeration tank with free biomass to be reduced by a factor of 2–2.5. This reduction in tank volume should not be confused with the aeration system. The aeration capacity should always remain the same, as it is mainly related to the amount of biomass and much less to the volume of the tank.
– The DAF clarifier is much smaller than a settler. The SS load of a non-assisted clarification DAF clarifier will be in the range of 6–8 kg/m^2·h, compared to about 2 kg/m^2·h for a sedimentation tank. This can rise to over 50 kg/m^2·h in a vertical DAF clarifier with "U"shaped elements. The space saving can therefore be very significant, not to mention the possibility of installing the DAF clarifier above the aeration tank. In some cases where space is at a premium this can be a decisive factor.
– The DAF clarifier will give a much more concentrated floated sludge than a settler—typically around 3% compared to 0.8–1% for a settler. The sludge recirculation rate will therefore be 3–4 times lower than with a settler.
– The DAF clarifier will be much less sensitive to the quality of the biological sludge than a settler. In this respect the operation of the DAF clarifier will be much easier.

Disadvantages

– Energy cost of pressurization. If the sludge concentration is 10 g/l, the pressurisation rate will easily exceed 100% and could even reach 150% of the incoming flow for some difficult industrial sludges. As an indication, for a pressurisation pump of 100 m^3/h at 5.5 bar this represents an energy consumption of around 0.18–0.25 kWh/m^3 of treated water.
– To ensure maximum quality of the clarified water the DAF clarifier will need flocculant—usually 0.5–1.2 kg (up to more than 2 kg for some particularly difficult industrial effluents) of cationic polymer per tonne of dry sludge. This is equivalent to 10–20 g/m^3 of treated water at 10g/l concentration. This is significant... This is perhaps a good time to point out that continuous dosing of cationic polymer recycled in the aeration tank does not pose any particular problems, as its longevity is relatively short—in the range of 24–48 h maximum.

An analysis of the above-mentioned advantages and disadvantages regarding the application of this clarification technology from a practical point of view leads to the following conclusions:

1. In a municipal wastewater treatment plant the flow rates are generally quite high in relation to the pollution load. The COD of these effluents rarely exceeds 800 mg/l and therefore the volume of the aeration tank is not very large. Reducing its volume is always advantageous, but it is not enough to tip the balance. On the other hand, pressurisation and flocculation of large volumes of water would be quite expensive. Therefore, the use of an 8–10 g/l aeration tank followed by a DAF clarifier for secondary clarification in a plant treating an effluent containing only a few hundred of mg/l of COD is not justified as the advantages offered by the concept do not outweigh its disadvantages in such an application. This is

particularly the case for municipal effluents with a high flow rate and relatively low pollution—on average 600–700 mg/l COD.

2. On the other hand, the situation is very different for many industrial effluents that are highly polluted but have low flow rates. This is the case, for example, for a large proportion of the effluents from the food industry. Their average flow rates are usually between 4–5 and 40–50 m^3/h at most. However, they are highly polluted and their COD is several thousand mg/l, sometimes even more than 10 000 mg/l. For large flows with such a high COD, an anaerobic treatment may logically be considered, as it requires less energy than an aerobic treatment. However, a plant with an anaerobic digester is always more complex and more difficult to operate, especially as the anaerobic digester alone will not achieve a COD of less than 600–800 mg/l, which is not sufficient for discharge into the natural environment. It would almost necessarily have to be followed by a second aerobic "polishing" stage. Thus, many industrialists prefer to opt for a plant that is above all reliable and simple to operate, even if it means compromising on a fraction of the plant's energy consumption. This is where the concept of an 8–10 g/l aeration tank with clarification by flotation becomes very interesting because its advantages become particularly attractive. A COD of several thousand mg/l involves a large aeration tank to the extent that it becomes the main structure of the plant. Reducing its volume 2.5 times and clarifying on a small DAF clarifier that can be placed almost anywhere means reducing the plant surface and the civil works by almost half. In industrial areas or in companies, which have gradually merged with residential areas, available space is becoming increasingly difficult to find and space saving is often an important factor. In addition, this concept, if well thought out and implemented, allows the entire operating area to be concentrated within a small building, which is not only more comfortable for the operating personnel, but also for containment and odour treatment. The operating costs for pressurisation and flocculation are higher per m^3 of water treated, but one has to look closely at what this actually means. Because the costs are mainly linked to the flow rate, which is very low. As an example, for a plant treating a flow of 10 m^3/h (240 m^3/d), the daily electricity consumption related to the pressurisation would be of the range of 80 kWh per day and that of the flocculant—of the range of 2.5–4 kg per day. In total, this represents (in 2023) an amount of only 70–80 €/day, which is quite acceptable considering the operating comfort and the reduced construction cost. These figures are, of course, quite approximate and the corresponding costs may vary significantly from one country to another, but they give an order of magnitude. And this is without considering the savings in electricity and flocculant for the thickening of the excess sludge, which in this case leaves the circuit well flocculated and at a concentration of about 3%, i.e. ready to be dewatered directly.

Finally, why limit the biomass concentration in the aeration tank to 8–10 g/l? In reality, these values keep a small safety margin, as these plants can operate without problems at concentrations up to 12 g/l. In fact, it is recommended to size the DAF clarifier for this maximum concentration of 12 g/l (without forgetting to take into account the recirculation flow which is added to the incoming flow). Above 12 g/l it is considered that the risk of oxygen transfer problems in the aeration tank becomes too high, and above 15 g/l of biomass aeration with pure oxygen becomes necessary, which is only done in exceptional cases.

8.4.2.3 MBBR (Moving Bed Biofilm Reactor)—Fixed Biomass on a Moving Support

This technology uses plastic elements, called carrier, with a very large developed surface area, which are designed to provide a fixed biomass growth medium. It is used in the biological treatment of municipal and some industrial effluents. The effluent after the biological reactor generally contains only a few hundred mg/l of TSS, consisting mainly of excess sludge particles detached from the carrier. They are quite similar to the excess sludge in the biofilters. Clarification after the biological reactor can be done by sedimentation, flotation or microfiltration (more rarely). Flotation is well suited to the clarification of these effluents, as their TSS concentration is low. The consumption of (cationic) flocculant is relatively modest and exceeds 2 mg/l only in rare cases. For a well-designed DAF clarifier the pressurisation rate would be only slightly higher than in drinking water treatment—in the range of 15% (assuming, as always, that the efficiency of the saturator is around 60%). In this case, the floated sludge is sent to dewatering, which requires little flocculant as the sludge already contains some. Some operators even consider that the flocculant dosed for clarification is almost entirely recovered during dewatering, which then requires less product.

Although all types of DAF clarifiers can be used in this application, compact assisted clarification DAF clarifiers are particularly well suited due to the low SS loading.

8.4.2.4 MBBR Combined with Free Biomass in the Same Aeration Tank

The difference with the previous application is that the floated sludge is partially recycled to the aeration tank in order to maintain a free biomass concentration of about 1.5–2 g/l, which would logically "help" the fixed biomass and therefore increase the oxidation capacity of the aeration tank without increasing its volume. This configuration is very well suited to secondary clarification by flotation and the value of 1.5–2 g/l is not chosen by chance. It is considered that a TSS concentration of up to 1.5–2 g/l is optimal for flotation in this application and does not require oversizing of the DAF clarifier compared to the concentration of a few hundred mg/l generated by the excess sludge from the carrier alone. In other words, a DAF clarifier sized for MBBR cases would also work in this case. In the worst case, the pressurisation flow rate would have to be increased slightly to 20% of the inflow, but the corresponding energy consumption would be at least largely compensated by the almost free increase in the oxidation capacity of the aeration tank, as the free biomass will be aerated free of charge by the (relatively generous) air flow rate required to keep the carrier in motion.

8.4.2.5 Biofiltration on a Fixed Support Consisting of Gravel, Slag, Pozzolan, Loose Plastic Elements or Packed Blocks of Profiled Plates

These biofilters were quite successful in the 1950s–1970s because of their low energy consumption. This is because the water is aerated as it flows over the biomass support, whatever it may be. The support is not submerged and the air circulates freely inside. There is therefore no energy consumption for biomass aeration. Nevertheless, this technology appears to be less and less used in recent decades for the treatment of large flows of wastewater because of its disadvantages in terms of maintenance, especially the risk of clogging.

Excess sludge from this type of bio-filter is quite similar to that from MBBRs and clarification by flotation can be achieved in the same way.

8.4.3 Biological Sludge Thickening

This is probably the most common application of dissolved air flotation in the biological treatment of municipal and industrial effluents. In practice, the thickening of these sludges is most often achieved by one of the following technologies:

- by settling in static thickeners.
- by mechanical means (dewatering tables and other mechanical devices).
- by dissolved air flotation.

Static thickeners work well for primary sludge thickening and consume little energy, but for excess sludge thickening from extended aeration or excess sludge from plants with primary settling they have some disadvantages:

- They are much more voluminous compared to other thickening technologies. They are designed for a SS loading of only 1–1.3 kg/m^2·h, which is about 5–6 times lower than that used for non-assisted clarification DAF clarifiers.
- The concentration of thickened sludge rarely exceeds 2%, which is often insufficient.
- The residence time is too long (12–24 hours), which favours fermentation, resulting in odours and deterioration of sludge quality.

These disadvantages may limit somewhat their use for thickening excess biological sludge.

Dewatering tables and other mechanical devices work well on excess biological sludge and give good results in terms of thickening (usually 6–8%) and filtrate quality.

However, they require good flocculation with a flocculant consumption of about 3 to 8–10 kg/t of dry matter. These devices are particularly useful upstream of a belt press, whose operation is greatly improved with such a high concentration of sludge at the feed. Indeed, dewatering tables are often integrated with belt presses. However, the high concentration they achieve is not suitable to dewatering by centrifugation or filter press, as the 6 or 8% sludge is very viscous, difficult to transport and to re-flocculate properly upstream of these devices. This technology is compact and well suited to small and medium-sized treatment plants (up to 15–20,000 equivalent inhabitants).

It should be mentioned that it is also possible to eliminate the thickening stage before dewatering by processing the excess sludge directly through a centrifuge. This technology can be used to dewater sludge directly from the secondary clarifier, but also simply to thicken the sludge significantly (to 5–6%) for anaerobic digestion. Centrifugal thickening is very advantageous in terms of space because the installations are very compact. On the other hand, centrifuges, compared to other thickening techniques, are more delicate in terms of operation (they are sensitive to concentration variations and tuning) and maintenance (high speed rotating machines). Energy consumption is also quite high—more or less double that of dissolved air flotation, while producing a poor quality centrate. Flocculant consumption is 3–8 kg/t.

Dissolved air flotation is widely used in large plants for the thickening of biological sludge from plants with primary settling or extended aeration. This can be done in view of their digestion or in view of their dewatering.

If the sludge from the plant is directed to an anaerobic digester where it is advantageous to have the sludge at a concentration of at least 4–4.5%, then there are several possibilities. If the plant operates with extended aeration, then there is no choice but to thicken the excess sludge to the maximum. If the plant has a primary clarifier, then it is possible to send the excess biological sludge to the primary clarifiers and obtain a sludge mixture that is then thickened in a static thickener. This solution, widely used in the past, is chosen less and less often, because this sludge mixture does not thicken well in thickeners. Finally, it is also possible to thicken the biological sludge alone to 4–4.5% and then mix it (upstream of the digester) with the primary sludge thickened separately in a static thickener to 6–8%. The concentration of the resulting sludge mixture will certainly be higher than 4.5–5%, which is generally acceptable.

Whether the plant is operated with primary sedimentation or extended aeration, dissolved air flotation is widely used for thickening excess biological sludge prior to dewatering. It combines several particularly valuable advantages:

- Relatively compact installation compared to sedimentation.
- Floated sludge concentration usually 3–4%, which is perfectly suited to filter press or centrifuge dewatering. It is, of course, possible to obtain more concentrated floated sludge—4.5–5%, but this is not really necessary and may even be counterproductive in some cases. The optimum range for centrifugation would be in the range of 2.5–3%, as the sludge is already sufficiently concentrated and at the same time still liquid enough to be relatively easy to mix and flocculate. For filter presses, feeding too much concentrated sludge (more than 4.5–5%) can

cause problems with the homogeneity of the filling of the trays and the discharge of the filtrate.
- Air keeps the sludge aerated and prevents, at least partially, anoxia. This preserves the quality of the sludge and prevents or at least reduces odours. In addition, it prevents the release of phosphorus fixed by the biomass and allows biological dephosphatation to be carried out (the phosphorus remains in the dewatered sludge which is discharged and does not pass into the filtrate which is recycled at the plant inlet).
- The clarified water is of good quality—it contains only a few tens of mg/l of SS.
- Thickening can be done without flocculant or with a low dosage of about 0.6–1 kg/t. In some cases the flocculant dosage can be as high as 3–3.5 kg/t, but these are exceptional cases and will be discussed later.

Flotation can be implemented in several ways. It can be operated with direct pressurisation of the sludge or pressurisation with recycled clarified water. One can also operate without flocculant or with flocculant. All four cases exist in practice, as each has its advantages and disadvantages. There is therefore no “best” solution, only the best compromise for each case, depending on the constraints of location, operating costs and equipment operation.

The pressurisation mode is a strategic choice that is made at the design stage of the installation and determines the sizing and certain details of the equipment. Changing the pressurisation mode during operation would require some significant modifications. On the other hand, it is always possible to decide whether or not to use flocculant in any installation. The flocculant is always cationic. The dosage is done in line, usually without post-dilution. For municipal sludge, a dosage of 0.6–1.2 kg/t can be considered a good compromise to obtain, at a reasonable cost, a sufficiently concentrated sludge for dewatering (generally 3–3.5%) and good quality clarified water (TSS less than 100 mg/l). In some cases of biological sludge from industrial effluent treatment, the flocculant dosage required to achieve a good result can increase significantly—up to 2.5–3 kg/t, which adds to the operating costs. A high overdose of flocculant in municipal sludge can also allow a significant increase of the SS loading of the DAF unit, but this remains an exceptional regime for troubleshooting rather than normal operation due to the high cost of the chemical.

At the same time, it should be noted that, according to the opinions collected from some plant operators treating mainly municipal effluents who took the time to study different operating modes of their flotation systems with indirect pressurisation, a significant part of the flocculant dosed on the flotation system is deducted from the flocculant dosage necessary for dewatering. For example, in a first configuration they ran the DAF clarifier without flocculant and the dosing to the centrifuge was in the range of 8 kg/t. In a second configuration, they dosed 1.5 kg/t of flocculant on the DAF clarifier. In this case, to obtain the same dryness of the dewatered sludge, the consumption on the centrifuge was only about 6.5–7 kg/t. Of course, other factors come into play, such as the time and storage conditions of the thickened sludge before dewatering. The shorter the time the better, as the cationic polymer has a relatively short shelf life. Also, the more the sludge is mixed during storage, the lower the residual efficiency of the flocculant. Also, the quality of the sludge may vary slightly during the test periods. These are just a few real-life examples that do not allow general conclusions to be drawn, but they at least show a trend. Moreover, according to the same operators, the polymer consumption on the centrifuge can increase with the increase in the concentration of the thickened sludge that feeds them, whereas one would tend to think the opposite, since thicker sludge means a lower hydraulic load on the machine, which can only be logically beneficial. The explanation for this probably lies in the fact that it is harder to mix the flocculant intimately with more (too?) concentrated sludge. It would seem that from this point of view the optimum concentration of sludge at the centrifuge inlet would be in the range of 2.5–3%, but this empirical estimate is based on only a few cases from the author's personal experience, which is insufficient to make it a reference.

8.4.3.1 Direct Sludge Pressurisation

It consists of pressurising all the excess sludge in the saturator and making the pressure relief at the floatation inlet. In this case it is not necessary to have a contact zone, but rather a well adapted pressure relief space to avoid excessive coalescence and to ensure an optimal transition to the flotation zone. For this pressurisation mode it is more advantageous to take the sludge directly from the aeration tank where its concentration is of the range of 3–4 g/l and not from the outlet of the settler where its concentration exceeds 6–8 g/l. This is because the amount of air dissolved in the water will remain about the same and will even tend to decrease with increasing TSS content. Therefore, the more diluted the sludge is, the higher the Air to Solids (As) ratio will be, which can only be beneficial for thickening. For example, if the saturation level of the saturator is around 60% and the pressure—5 bar, then at 16 °C there will be approximately 0.06 Nm^3 (0.072 kg) of air per m^3 of pressurised water. If the concentration of the sludge is 4 kg/m^3, then As will be 0.018 kg/kg. This is close to the "classical" recommendation of 0.02 kg/kg for this application. But if the sludge concentration is 8 kg/m^3, then this ratio will be 0.09 kg/kg, which would probably be a bit low. Of course, these are only parameters and indicative values that do not characterise all aspects of the process (air adherence to flocs and agglomerate stability, coalescence, sludge specificities etc.), but in any case such an As would be insufficient or at least give a fragile result.

What are the advantages and disadvantages of direct sludge pressurisation? A few can be listed, but they have to be considered in the context of each case.

Advantages

– According to the Degrémont's Memento Technique de l'Eau (internet version on www.suezwaterhandbook.com available on line), direct pressurisation allows to obtain a better concentration of floated sludge (+5 to +10 g/l) compared to indirect pressurisation with recycled water. One could try to explain this by the fact that during pressure relief the sludge is completely destructured into very fine particles which are easier to compact afterwards. Conversely, pressurisation with recycled water would better preserve the structure of the biological floc, which would necessarily be more voluminous. But this is only a personal hypothesis of the author.

- According to the same source, this pressurisation mode allows operation without flocculant, whatever the quality of the sludge, especially whatever the Sludge Volume Index (SVI). The explanation for this lower sensitivity probably lies in the same phenomenon of sludge destructuration at the time of pressure relief, as the capacity of sludge to compact is strongly influenced by the structure of the biological floc, which is more or less compact.
- This mode also reduces the amount of bottom sludge.

Disadvantages

- The concept itself limits the amount of available air. If the sludge is not very concentrated, dissolved air is sufficient in most cases. However, if the SS concentration exceeds 5–6 g/l this limitation can become problematic. In this case dilution is a possuble option.
- The flow rate of the pressurised sludge must be relatively constant because of the adjustment of the pressure relief devices. Any significant change in flow rate requires intervention to change this setting. Unless several pressurisation pumps are installed, each with a saturator (or at least an injector in a common saturator) and a number of pressure relief devices. This would allow the removal rate of excess sludge to be varied, but would complicate the installation.
- The management of excess sludge removal needs to be done relatively regularly during the day to avoid prolonged periods of shutdown of the DAF clarifier and the risk of anoxia. One solution would be to provide a feed of treated water to the pressurisation system from the plant outlet so that the DAF clarifier can be 'aerated' without extracting sludge if necessary.
- The sludge may contain particles (yarn and hear,...) that can cause clogging of the pressure relief devices, especially in extended aeration without primary settling.

Table 8.1 Estimated concentration of thickened biological sludge in direct pressurisation without flocculant

Sludge type	SS load $kg/m^2{\cdot}h$	Sludge Volume Index ml/g	Floated sludge concentration, %
Extended aeration without primery settling	4–6	<150	4.5–5.5
		150–250	4–4.5
		>250	3.5–4
Biological sludge with primary settling	3.5–4.5	<100	4–4.5
		100–200	3.5–4
		200–300	3–3.5
		>300	<3

Source Memento Technique de l'Eau

This implies the installation of automatically flushing pressure relief valves and possibly filters to protect the pressurisation pumps.

– The quality of the clarified water is not as good as with indirect pressurisation, especially when operating without polymer. However, it is still acceptable for recycling a head of the plant.

The sizing of direct pressurisation DAF clarifiers, proposed by the *Memento Technique de l'Eau* in operation without flocculant, is based on a SS load of 4–6 kg/m^2·h. The floated sludge concentration is estimated according to the SVI—see Table 8.1.

8.4.3.2 Pressurisation with Recycled Water

This technique is relatively easier to implement. In this case the DAF clarifier can be fed either from the aeration tank or from the sludge recirculation circuit, with a slight preference for the second solution, as the pumps and piping are smaller. In both cases the sizing criterion will be the SS load and not the hydraulic load. Compared to direct pressurisation it involves a slightly different operation mode which also has its advantages and disadvantages.

Advantages

– Allows as much air to be supplied as required. There are two possible concepts here. The first is to size the pressurisation system for the maximum load and accept the extra energy consumption during periods of lower load operation. This is probably the most common operation mode, as it is particularly convenient from an operational point of view. Sludge extraction can be started, reduced or stopped at any time without worrying about the DAF clarifier—it will always be available to do its best work. The second one is simply to vary the flow rate of the pressurisation as required. However, the saturator and pressure relief device must allow such a variation in flow rate to be made quickly and easily by the operator. The energy saving is not optimally achieved if the same pressurisation pump is always used, but a substantial reduction in power consumption can still be achieved by reducing the flow rate.
– The DAF clarifier is always aerated even with a low pressurisation rate, which eliminates the risk of anoxia, especially if the floated sludge blanket is removed before a prolonged stop of the feed.
– Better clarified water quality compared to direct pressurisation.
– Less risk of clogging, which is due to the use of clarified water for pressurisation.

Disadvantages

– Higher energy consumption, especially if a constant pressurisation flow rate is chosen and sized for the maximum load (which is mostly the case) and if the DAF clarifier is running at full capacity for much longer than the actual sludge extraction time (which is also, unfortunately, often the case). The problem is mainly the time the DAF clarifier is running compared to the actual time it is fed with sludge. There is no real energy overconsumption during feeding, which is quite similar to the energy consumption in direct pressurisation, since in the end more or less the same amount of air is supplied.

– In the continuous feeding regime the floated sludge concentration may be slightly lower compared to direct pressurisation. However, this is somewhat relative, as feeding is often intermittent (on time basis or on level), whereas pressurisation is continuous. As a result, when the feed is stopped, the floated sludge concentration increases, due to the air that continues to accumulate under the sludge blanket.

In addition to the main design parameters such as SS loading, sludge index and pressurisation rate (amount of air supplied), the dryness of the floated sludge also depends on the thickness of the sludge blanket. This parameter is often ignored, as the thickness of the sludge blanket is rarely visible and hardly ever measured. However, it is easy to equip DAF clarifiers with a window for observing the sludge blanket thickness (this is more difficult for DAF clarifiers with a cover). More microbubbles accumulated under the blanket, combined with a thicker floated sludge blanket, allows air to push upwards more strongly causing compaction and sometimes even a slight ‘draining’ of the upper part of the blanket (the piezometric line of the water passes below the surface of the sludge). And this is precisely the part extracted in priority by the spiral scoop or by the surface scrapers. The role of the thickness of the sludge blanket is to keep the air microbubbles in a structure that prevents coalescence. If the layer is thin, and therefore fragile, and the air underneath is abundant, it will quickly agglomerate into large bubbles that will pierce the blanket and form an useless layer of foam on the surface.

A method of sizing DAF clarifiers with indirect pressurisation with recycled water is proposed by a study carried out by the author in 1992 on several biological sludge thickening plants, the aim of which was to determine the influence of the Sludge Index and the use of flocculant on the floated sludge concentration. The data were obtained from five plants without primary settling. The design of the pressurisation system and the type of DAF equipment was always the same, i.e. circular DAF clarifier with spiral scoop, water depth 3 m. Unfortunately, the facilities did not allow the pressurisation rate (the amount of air) to be modified significantly during the tests at different SS loads. The amount of air supplied by the pressurisation was fixed and sized in relation to the flotation area—approximately 0.06 $Nm^3/h \cdot m^2$ of flotation area. As an indication, for a SS load of 6 $kg/m^2 \cdot h$ this means an Air/Solid (As) ratio of about 0.012 kg/kg. Respectively for 4 $kg/m^2 \cdot h$ the As is 0.018 kg/kg, i.e. close to 0.02 kg/kg, which is the “classical” value recommended for this application. The thickness of the floated sludge blanket was kept between 30 and 50 cm. Some DAF clarifiers were equipped with automatic measurement and control of the sludge blanket thickness. Others just had a window to allow the operator to regulate the thickness manually. The results with flocculant corresponded to a dosage of about 1–1.2 kg/t of dry matter. The summary of the results is shown in Fig. 8.3.

This sizing method has its advantages and disadvantages. It is, of course, simple to use because it is based on a correlation between the SI, the target floated

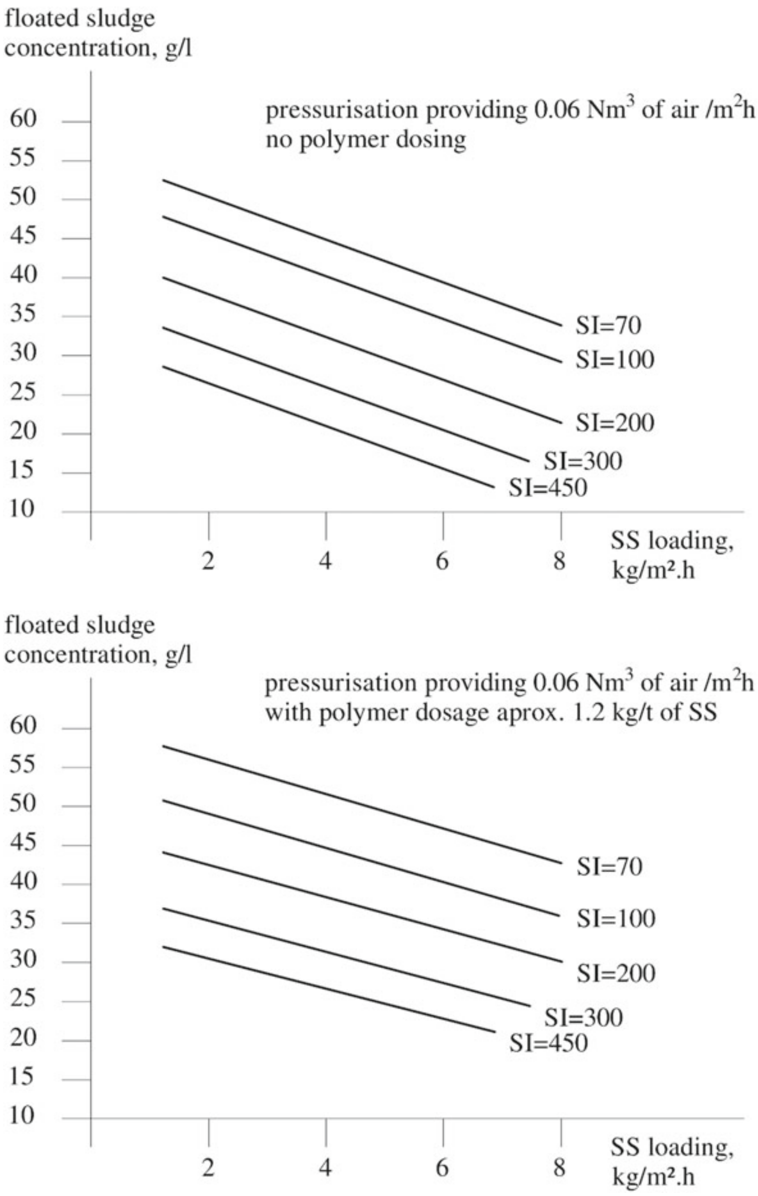

Fig. 8.3 Floated sludge concentration depending on the SS loading and the Sludge Index—pressurisation with recycled water

sludge concentration and the SS loading to be applied to achieve this concentration. However, it does not take into account three other parameters that can influence the process.

The first is the amount of air, which in this case is set at 0.06 $Nm^3/h.m^2$ of flotation surface. It could be intuitively assumed that a progressive increase of the air quantity, in parallel with the increase of the SS load in order to maintain a constant As, could allow to improve the concentration of the floated sludge at high SS load and even to keep it constant. But this improvement would probably not be very significant because, even if a certain amount of air is necessary to provide a sufficient microbubble concentration in the water (in order to ensure maximum contact between them and the particles), in reality only a fraction of these microbubbles clings to the surface of the flocs or, better still, gets trapped in their structure. The majority of the remaining microbubbles agglomerate around these flocs and, through coalescence, form larger bubbles that eventually rise to the surface and form a foam that is not beneficial to thickening.

The second parameter is the compaction time of the sludge on the surface. The concentration of the sludge depends on its capacity to be compacted (characterized by the SI), but, as in sedimentation, it also tends to increase with time. Thus, an increase in SS loading, even at a constant As, results in a decrease in sludge concentration, as the sludge has less time to compact on the surface. The thickness of the accumulated sludge blanket could, of course, be increased, but in the author's experience, an increase beyond 60–80 cm has little effect on the dryness of the sludge at the surface. On the other hand, the extension of the thickening time remains beneficial for a long time, since the sludge continues to concentrate even after the installation is stopped, i.e. without air supply. In fact, after one night's shutdown, it is common to find the floated sludge so concentrated the next day that it no longer flows. One can even stick a coin in it vertically. Of course, there is no point in aiming for such concentrations, as the thickened sludge becomes very difficult to handle. And such a concentration has no advantage for dewatering even on a belt press, as it is almost impossible to mix it effectively with the flocculant to allow the remaining water to be squeezed out.

The third parameter is the capacity of the sludge to fix the air, in other words the attraction between the microbubbles and the flocs. This is quite variable depending on the specific characteristics of each sludge. It sometimes happens that highly mineralised biological sludge with a very low SI retains air poorly. In addition, coalescence can be quite rapid, probably due to the low concentration of organic matter that can favour the "holding" of microbubbles. Therefore, the result without the use of flocculant can sometimes be disappointing despite the low SI. The use of a cationic flocculant may then be necessary to solve the problem.

It is important to note here that the "classical" SS loading design values of 4 to 6 $kg/m^2{\cdot}h$ are valid for DAF clarifiers with non-assisted clarification (mostly circular). On the other hand, some sources report SS loads with the use of flocculant of up to 12 $kg/m^2{\cdot}h$ and even up to 30 $kg/m^2{\cdot}h$ in some extreme cases. This may be quite possible. However, to achieve this, the required flocculant dosage per tonne of dry matter would have to increase significantly and, if necessary, approach that of a dewatering table, which would considerably increase the operating costs and reduce the interest in flotation. But the SS loading, related to the flotation surface, can be much higher for some types of assisted clarification DAF clarifiers. For example, the SS loading on a vertical DAF clarifiers with "U"-shaped elements can be as high as 80 kg/m^2·h related to the surface area of the floated sludge collection chamber. At the same time the air flow rate relative to the same surface area is 0.8 to 1 Nm^3/m^2·h. Furthermore, these values change with the size of the unit, even though the Air-to-Solid ratio (As) remains constant—0.012–0.015 kg/kg. On the other hand, these DAF clarifiers almost always work with flocculant to compensate for the relatively short sludge thickening time. It is therefore clear that these parameters can only be considered relevant in a well defined context.

These examples again show that the main design parameters, mentioned above, can hardly be considered independently of each other. They form a set that attempts to frame the performance of the flotation, but does not offer a complete, single and unambiguous description of the process. There are several possible combinations to achieve the same result. Only experience and, above all, a thorough analysis of the situation on site can help to find the best solution for each case. For example, in order to achieve a certain floated sludge concentration, the SS loading or possibly the pressurisation flow rate (if it is proven to be beneficial in the specific case), or the flocculant dosage can be varied. The SS loading influences the investment and the space occupied, the pressurisation influences the energy consumption and the flocculant dosage—the operating costs and eventually the possibilities of agricultural use of the dewatered sludge.

Another application of sludge thickening by dissolver air flotation concerns the washing water of bio-filters with filter media such as Biofor (Degrémont), Biostyr or Biocarbone (Veolia). Unlike non-submerged media bio-filters, the various types of submerged media bio-filters have developed significantly over the last few decades. Among other things, they have the advantage of treating carbon and nitrogen pollution and filtering the treated water at the same time, which avoids the need for secondary clarification. Excess sludge is periodically removed by washing sequences similar to those used for sand filter washing (which served as the basis of inspiration for the development of this technology). This wash water is large in volume and relatively low in sludge concentration—typically the TSS content is a few hundred mg/l. Dissolved air flotation is particularly well suited to the concentration of this type of sludge, prior to dewatering or digestion with primary sludge, and many references exist. The low volume of the DAF units, their reliability of operation and the high concentration of the produced floated sludge (4% minimum) are particularly valuable in this application.

Almost any type of DAF clarifiers can be used, although contractors tent to prefer those with assited clarification because of their small footprint. However, experience suggests that the larger circular DAF clarifiers would use slightly less flocculant and produce a slightly more concentrated floated sludge due to the thicker sludge blanket that is built up. However, they are still much larger and require a slightly higher pressurisation rate.

Due to the sludge characteristics, DAF clarifiers are often equipped with odour control covers with extraction and treatment of the exhaust air in the deodorisation facility of the plant. In this sense, the covers of rectangular flotation units are relatively simpler and less expensive, especially when compared to the rotating covers of the circular spiral scoop DAF clarifiers.

8.4.4 Tertiary Treatment and Phosphorus Removal

Tertiary wastewater treatment is necessary when the effluent leaving the biological treatment still contains pollution above the discharge standards. The most concerned parameters are:

- Phosphorus.
- COD, much of which is hard COD (non-biodegradable).
- TSS.
- Colour (especially for industrial effluents).

In some cases, simple filtration of the effluent may be sufficient. It allows the elimination of part of the SS (larger than a few tens of microns in the best cases) and the pollution they contain (COD and phosphorus). In general, this makes it possible to meet the discharge standards for TSS. Probably the most common filtration devices used in this application are disc filters, which have the advantage of being very compact and reliable. Sand filters can also be used, but their installation directly after secondary clarifiers is rare, as they are more sensitive to accidental clogging. However, the pollutants contained in the finest fraction of TSS and especially in colloidal matter can only be removed by coagulation with a mineral coagulant. In this case, the use of direct filtration after coagulation becomes more problematic, as the coagulant produces more very fine and clogging TSS. The use of a flocculant does not really improve the situation, as the flocculant itself is a clogging agent for fine filter media. Therefore, chemical treatment upstream of disc filters or sand filters makes their operation more sensitive, which may limit their use.

In cases where coagulation/flocculation treatment is required, flotation clarification, possibly followed by filtration, is one of the most commonly used techniques for improving water quality after biological treatment. The most commonly used coagulants are aluminium-based (aluminium sulphate $Al_2(SO_4)_3$) or iron-based (ferric sulphate $Fe_2(SO4)_3$ or ferric chloride ($FeCl_3$)).

Liquid aluminium sulphate (in aqueous solution), which is more widely used, contains up to 48% dry alum. In this case the solution has a density of 1.2 kg/l and contains 3.9% Al by weight. There are other commercial products with different concentrations—see the relevant suppliers' product sheets.

Ferric sulphate is available in different commercial solutions up to 60% dry product. In this case the density is 1.62 kg/l and the product contains 12% Fe by weight.

Ferric chloride is available in commercial solutions, the concentration of which is around 40–41%. At this concentration the density of the solution is 1.4 kg/l and the iron concentration is 14% by weight.

Phosphorus removal is done as aluminium phosphate $AlPO_4$ (with a minimum solubility at pH 6 equal to 0.01 mg/l of residual P) or, respectively, iron phosphate $FePO_4$ (with a minimum solubility at pH 5 equal to 0.06 mg/l of residual P). This information on coagulants is summarised in Table 8.2.

For phosphorus precipitation with an Fe-based coagulant, the stoichiometric amount needed is 1 mol of Fe for 1 mol of P, i.e. 1.8 g of Fe to precipitate 1 g of P producing 4.87 g of $FePO_4$ sludge. In practice the amount of Fe required is higher than the theoretical value, as some Fe^{3+} is precipitated simultaneously as iron hydroxide $Fe(OH)_3$. Another part of the Fe also reacts with the organic matter in the water and helps to reduce the COD by forming flocs that are easy to separate together with the hydroxide and phosphate flocs. In reality, the dose required to precipitate 1 g of P can represent up to 4 times the molar ratio of Fe supplied to P eliminated (source: Cemagref, 2007). The situation is the same with alumina—the actual dose required can be several times the 'theoretical' dose. The difference between the initial and final phosphorus concentration, the conditions under which the reaction is carried out, and the specific characteristics of the water are among the most influential factors.

In most countries the discharge standards for total phosphorus concentration impose a maximum value of 2 mg/l for small plants and 1 mg/l for medium and large plants. However, in some particular cases (specific industrial effluents or particularly sensitive environment) the standards may impose values lower than 1 mg/l of Pt. In this case, coagulation/flocculation, followed by flotation, may be sufficient to

Table 8.2 Main characteristics of the most commonly used coagulants in phosphate removal

Coagulant	Al^{3+} or Fe^{3+} content g/kg pure product	Concentration of the commercial solution % dry product	Density of the commercial solution kg/l	Al^{3+} or Fe^{3+} content content g/kg of solution	Al^{3+} or Fe^{3+} content g/l of solution	Residual soluble P equivalent* mg/l
$Al_2(SO_4)_3$	158	48	1.2	90	108	0.01 à pH 6
$Fe_2(SO_4)_3$	367	60	1.62	120	194	0.06 à pH 5
$FeCl_3$	344	41	1.4	140	196	0.06 à pH 5

1 mg/l of Al is equivalent to 11 mg/l of $Al_2(SO_4)_3 \cdot 14\ H_2O$ in terms of provision of Al

1 mg/l of Fe is equivalent of 3.39 mg/l of $Fe_2(SO_4)_3$ anhydrous in terms of provision of Fe, i.e. 5.03 mg/l of $Fe_2(SO_4)_3 \cdot 9\ H_2O$

1 mg/l of Fe is equivalent of 2.91 mg/l of $FeCl_3$ anhydrous in terms of provision of Fe, i.e. 4.83 mg/l of $FeCl_3 \cdot 6\ H_2O$

*A small part of the phosphate produced remains in solution. This value corresponds to the equivalent quantity of residual dissolved P contained in this soluble part achieve 1 mg/l of P in the discharge. Sometimes it is even possible to achieve a slightly lower concentration, but such performance is fragile and not always safe. To reliably achieve a maximum concentration of less than 0.6–0.8 mg/l the best solution is to use a DAF clarifier with a in-built sand filter, as the filtration allows the finer particles to be retained and the maximum amount of phosphorus and precipitated organic matter to be removed. In this application, DAF clarifiers with in-built sand filters are usually designed for relatively low hydraulic loads of the filter bed—7–9 m/h for the peak flow or about 6 m/h for the average daily flow. This rather generous sizing allows the system to operate with as low a flocculant dosage as possible, to avoid the risk of excessive sand clogging and the formation of mud balls. The washing system is sized for a filtration cycle duration of 8 to 12 h in the most unfavourable conditions, but in practice one can observe a filtration cycle duration closer to 18–20 h and even up to 24 h when the water at the inlet of the installation contains little TSS.

The removal of a large part of the hard COD is achieved with the same coagulants and at the same time as the precipitation of phosphorus, as already mentioned above. It is considered that for the coagulation of 1 g of hard COD, 0.1–0.2 g of Fe is required, i.e. approx. 0.75–1.5 g of ferric chloride (0.54–1.08 ml of 41% solution). In all cases, the quality of the coagulation/flocculation is of great importance and special care should be taken. For this reason, it is recommended that a pilot test or at least a laboratory test be carried out before the installation is built to determine the type of coagulant and the doses to be used, the coagulation and flocculation times required, and the quantity of sludge produced.

8.5 Drinking Water

Drinking water clarification is probably the application of dissolved air flotation that has seen the most significant development in recent decades. It works particularly well for the removal of pollutants of organic origin that form light and fragile flocs, often difficult to remove by sedimentation (unlike contaminants of mineral origin that form more compact flocs that settle better).

The pollutants present in natural waters are extremely varied. They can be divided into two categories—TSS comprising solid particles, micro-organisms (algae, bacteria and other detritus from aquatic life) and dissolved matter grouped under the name Natural Organic Matter (NOM). Quantitatively, all these materials are characterised by the following parameters:

- TSS, forming the bulk of turbidity. Surface waters often have a high turbidity that varies according to the season. In contrast, groundwater turbidity is generally low and more stable.
- Particulate Organic Carbon (POC), expressing the organic pollution contained in the TSS. The POC of groundwater is generally low.
- Dissolved Organic Carbon (DOC), expressing the organic pollution contained in the NOM.

– Total Organic Carbon (TOC), which is the sum of POC and DOC. This is the parameter that appears in the regulations governing the characteristics of treated water, although it is formed overwhelmingly by DOC, as POC is practically totally eliminated in the filtration stage.

8.5.1 Coagulation

The first treatment step is coagulation. In this application, it is of particular importance and its proper implementation greatly influences the quality of the clarified water.

It should be remembered that in drinking water treatment, optimal coagulation must meet several requirements:

– It must enable the electrostatic charges of the solid particles to be neutralised as much as possible so that they can agglomerate into flocs.
– It must allow the coagulation of a maximum of NOM that are in a more or less dissolved form in the water.
– It must be carried out with as little coagulant as possible to reduce the cost of the treatment as much as possible.
– It should be carried out in such a way as to produce as little sludge as possible.
– It must leave the minimum residual coagulant dissolved in the treated water.

In order to satisfy all these requirements at the same time, it is essential to take into account not only the specific characteristics of the organic pollutants to be removed, but also the mineral characteristics of the water and the chemical properties of the chosen coagulant. A brief summary of the most important practical information on the main participants in coagulation and the interactions between them is given below.

The main coagulants used for drinking water coagulation and the characteristics of the most common commercial solutions are shown in Table 8.2. For drinking water, the various types of Poly Aluminum Chlorides (PAC) available on the market can also be added, which have the advantage of being less acidic, consuming less alkalinity and causing less of a drop in pH for the same dose of coagulant.

The pH of all these coagulants is very low. When mixed with water, they behave like acids by releasing H+ which reduces the pH. They instantly form aluminium hydroxides $Al(OH)_3$ and iron hydroxides $Fe(OH)_3$ respectively, which are the soluble form of aluminium and iron respectively. These hydroxides are the main coagulating agent, allowing the neutralisation of the electrostatic charges of the particles and the NOM and the formation of complexes with the coagulated materials. The solubility of these hydroxides depends on pH and temperature. Hydroxides in solution are not available for the formation of complexes with the materials, whose electrostatic charges have been neutralised. Therefore it is advantageous to keep these hydroxides in the solid state as much as possible. For alumina the minimum solubility is around pH 6.3 at 20 °C and 6.7–6.8 at 10 °C. For iron this minimum solubility point corresponds to a pH in the range of pH 7–8, but their solubility remains very low over a much wider pH range compared to aluminium hydroxides—from pH 5 to pH 8 at 20 °C.

The best results in terms of coagulation and floc formation are generally obtained when coagulation and subsequent flocculation are carried out at the lowest solubility pH. In this sense, iron has a double advantage over aluminium:

– It allows coagulation in a wider pH range and the formation of flocs is, therefore, less sensitive to pH variations.
– The amount of residual iron dissolved in the water is much lower than that of aluminium. This is one of the reasons why more and more operators prefer to coagulate with an Fe-based coagulant, especially when the TOC is high. Indeed, a high dosage of aluminium-based coagulant requires a strict and permanent monitoring of the residual aluminium in the water, usually limited to 0.2 mg/l, whereas with Fe the maintenance of the same 0.2 mg/l dose limit is much easier and less sensitive to possible coagulant overdosage.

The water characteristics influencing coagulation are as follows:

- *pH*

The dosage of a mineral coagulant must, above all, satisfy the cationic demand of the pollutants present in the water. With regard to the influence of the coagulant on the pH, three configurations are possible:

– The coagulant dosage corresponding to the cationic demand is insufficient to reduce the pH sufficiently to the point of lowest solubility of the coagulant used. In this case there are two solutions:

  (a) If the lack of acidity is small, then it is possible to supplement it with a small overdose of coagulant. This will result in a slight increase in hydroxide sludge production, but the simplicity of the solution easily justifies this choice.
  (b) If the lack of acidity is important (high alkalinity and hardness of the water), then the only solution is to add an acid*.

– The coagulant dosage is sufficient to bring the pH into the lowest solubility range.
– The coagulant dosage is high and causes the pH to fall too much. This occurs especially with fresh waters of low alkalinity and high TOC. In this case two solutions are possible:

  (a) If the excess acidity brought by the mineral coagulant is important, then there is no other choice than to adjust the pH with Na(OH) soda.
  (b) If the excess acidity is moderate, it is possible to compensate for part of the mineral coagulant with a small dose of cationic flocculant in the range of 1 mg/l. In this case the dosage of cationic flocculant remains constant and one adjusts by varying the dosage of mineral coagulant. This technique works well with aluminium-based coagulants, but can also be applied with Fe-based coagulants.

*Note: If an acid is required, a strong acid can be used, such as H_2SO_4 sulphuric acid or HCl hydrochloric acid. However, the pH correction is most often done with CO_2 which has several advantages over strong acids:

– It is a weak, non-toxic and non-corrosive acid.
– It is inexpensive, simple and easy to control.
– Even when overdosed, the pH does not fall below 5.5, which is a significant safety factor.

- *Alkalinity*

This is a measure of the capacity of water to neutralise acids and its ability to resist changes in pH. It is most often expressed by the Full Alkalinity Titer and characterises the concentration of carbonates, bicarbonates and hydroxides present in the water. Alkalinity is measured in terms of equivalent in calcium carbonate $CaCO_3$. It is considered low if it is around 50–60 mg/l of $CaCO_3$ (5–6° French), medium if it is 50–60 to 120–140 mg/l of $CaCO_3$ (12–14° French) and high if it is above that.

- *Buffer intensity*

It expresses the resistance of water to pH change or more precisely the amount of strong acid needed to change the pH by one unit. The higher the alkalinity, the greater the buffering intensity of the water. As a result, the pH tends to become more and more stable and less sensitive to the addition of the same amount of acid. This is particularly important when a mineral coagulant that is acidic is added. If the alkalinity is low, a small amount of coagulant could lower the pH and ideally bring it to the optimum point of minimum solubility of the hydroxide formed. If the alkalinity is high, then the mineral coagulant required for coagulation is unlikely to be sufficient and the pH will have to be adjusted by the addition of extra acid.

- *Hardness*

Hardness includes alkalinity and all salts dissolved in the water. The harder the water, the more the electrostatic charges of the particles decrease, which is due to the presence of salts. Therefore, hard water is easier to coagulate than soft water, because the particles are easier to destabilise.

- *Temperature*

It influences the physical properties of water, especially its density and viscosity, which increase with decreasing temperature. The colder the water, the slower the mixing of chemical reagents, and the more difficult and slower the contacts between the different particles and materials in the water. This is why cold water requires more energy for flash mixing and more time for flocculation. They also influence the solubility of the hydroxides formed by the coagulants.

Table 8.3 Recommendation for coagulant dose per mg TOC

Coagulant	Coagulation pH	Coagulant dose for 1 mg of TOC
$Al_2(SO_4)_3$	5.5	0.5 mg of Al
	6–7	0.6–0.65 mg of Al
	7–7.5	1 mg of Al
PAC	6–7	0.4–0.6 mg of Al
	7–7.5	0.7–1 mg of Al
	>7	>1 mg of Al
$Fe_2(SO_4)_3$ and $FeCl_3$	5–6	1.3–1.8 mg of Fe
	6–7	2–3 mg of F
	7–7.5	3–4 mg of Fe

1 mg/l of Al is equivalent of 11 mg/l of $Al_2(SO_4)_3 \cdot 14\ H_2O$ in terms of provision of Al
1 mg/l of Fe is equivalent of 3.39 mg/l of $Fe_2(SO_4)_3$ anhydrous in terms of provision of Fe, i.e. 5.03 mg/l of $Fe_2(SO_4)_3 \cdot 9\ H_2O$
1 mg/l of Fe is equivalent of 2.91 mg/l of $FeCl_3$ anhydrous in terms of provision of Fe, i.e. 4.83 mg/l of $FeCl_3 \cdot 6\ H_2O$

For more information the reader can refer to the book *Dissolved Air Flotation for water clarification* by James K. Edzwald and Johannes Haarhoff, where he will find a much more complete and detailed description of the water chemistry, the characteristics and the behaviour of the different coagulants. In the same book the authors give some recommendations concerning the dosage of coagulant per mg of TOC. A summary of these recommendations are given in Table 8.3.

8.5.2 Floculation

Flocculation is usually carried out with a low dose of different types of non-ionic or anionic flocculants—usually 0.1–0.2 mg/l maximum is more than sufficient. The flocculant has two functions in this case.

The first is to allow the agglomeration of small flocs, produced by coagulation, into larger (millimetre-sized) flocs while at the same time providing some structural strength to these flocs. This helps to ensure the resistance of these flocs to turbulence in the flocculation tank and especially in the contact zone into which the white water is injected. This resistance will also be appreciable when the floated sludge is removed, whether by a surface scraper or even by hydraulic overflow. Experience often shows that the turbidity of the clarified water increases slightly during the floated sludge removal phase. These small floc detachments are more important in the case of surface scrapers, but can occur, to a lesser extent, even with hydraulic overflow of the sludge.

The second function of the flocculant is to improve the adhesion of the air microbubbles to the flocs by its low electrostatic charge. This is all the more beneficial when the hydraulic load of the DAF clarifier is high.

8.5.3 Coagulation and Flocculation Implementation

The process of neutralising the electrostatic charges of the particles and the NOM is quite fast, provided that the coagulant is perfectly mixed with the water. Two techniques can be used to achieve this:

The first is to use violent mechanical mixing (flash mixing), carried out in a small volume, to provide maximum shearing force. The values of the velocity gradient G are in the range of 400–1000 s^{-1}. The residence time in flash mixing is in the range of 30–40 s. In some cases the volume of the coagulation tank is a little larger (residence time in the range of 60 s) and the velocity gradient G is lower—in the range of 280–400 s^{-1}. In this case it is important to inject the coagulant in the axis of the mixer just above the propeller to ensure rapid and efficient dispersion of the product. In both cases, the optimal shape of the tank is close to the cube, as in all cases of using mechanical propeller mixers.

The second technique is to use a static mixer installed in a channel or pipe. This technique is often preferred, especially for large flows, as it is less expensive in terms of equipment and consumes little energy. If the supply is by pumping, then the only energy consumption is that corresponding to the pressure losses in the static mixer, which vary from a few centimetres to a few tens of cm (30–40 cm) of water column at most.

The Coagulation/flocculation process is carried out in two stages: a flash mixing tank, mentioned above, in which the residence time is some tens of seconds, and one, or more often two, successive flocculation tanks. The flocculation tank is often separated into two equal parts. The first part is mixed more intensively with a velocity gradient G in the range of 80–100 s^{-1}. In this part, the main aim is to create contacts to initiate the floc formation and to capture all the coagulated matter as best as possible, hence the need for more sustained mixing. In the second part, these small flocs are agglomerated in larger flocs, which are more fragile and more sensitive to turbulence, hence the choice of a more moderate mixing—velocity gradient G in the range of 40–60 s^{-1}. However, these values sometimes vary from $\pm$ 15 to $\pm$ 20% depending on the recommendations of the mixer manufacturers and the experience of the designers. This concept is probably the most common. In this case it would be very useful to carry out the injection of the flocculant with particular care. It is very important to mix it perfectly with the water before it enters the flocculation tank. Indeed, the mixing in this tank will be far too weak to ensure a homogeneous distribution of the product in the whole volume. This can be done either with a perforated flocculant dispersion ramp (with a dilution station to ensure sufficient flow) above a weir, or by feeding the flocculation tank through a compartment equipped with a static mixer.

A second concept is to install a small flocculant mixing tank with a residence time of 1–2 min, equipped with a mechanical mixer. The water then passes into a static around-the-end hydraulic flocculator, where floc formation is completed. This concept has the advantage of having little electromechanical equipment and consuming very little energy. However, it does not allow for variation of the mixing force and thus the floc formation conditions in the static flocculator.

A third concept is to provide, after flash mixing, a coagulation tank with rather sustained mixing (G in the range of 200–250 s^{-1}, or even more) without adding flocculant. The residence time can be up to 10–15 min, as this concept is used for the coagulation of rather soft and especially very cold waters, i.e. waters that are difficult to coagulate. The flocculant is only added in a second flocculation tank, this time mixed like a normal flocculation tank ($G = 60–100\ s^{-1}$), in which the floc formation is completed for a residence time of about 5 min. For example, the Krasnokamsk plant in the Urals, Russia, can be cited. The plant treats river water that flows through ponds and contains a lot of humic matter, tannins and lignins coming from the ponds. In winter this water has a strong colour—up to more than 250° Pt–Co units. In summer it contains a lot of phytoplankton and algae. The water temperature in winter is only a few °C. Trials with iron-based coagulants have not been successful. The best results are obtained with PAC, which works equally well in winter and summer. Extended coagulation (15 min), without the addition of flocculant, is particularly necessary in winter. After flash mixing, a slow and gradual increase in turbidity (microflocs formation) can be observed over several minutes. The flocculant is added downstream in a second compartment sized for 5 min residence time, but in reality 2–3 min would have been more than enough, as flocculation is quite rapid. Tests with the floculant addition in the first tank, located just after the flash mixing of the coagulant, were disappointing despite a total flocculation time of 20 min. On-site observations suggest that if the flocculant is added at the outlet of the coagulant flash mixing, it will flocculate the coagulant hydroxides too quickly, without allowing them time to react and fully complete the coagulation. It can also be assumed that other secondary reactions will occur between the particles after their neutralisation by the coagulant. In contrast, during the summer season, this first coagulation tank, which provides a residence time of 15 min without adding flocculant, is bypassed. Flocculation is carried out in the second 5-min tank, which is fed directly from the flash mixing tank. A similar scheme is used in a plant in Neman, Kaliningrad region, Russia. In both cases clarification is made by DAF clarifiers with in-build sand filters.

8.5.4 Clarification

Rectangular DAF clarifiers with concrete tanks are the most commonly used for drinking water clarification. Since the 1990s these units have been progressively improved to reach hydraulic loads of 30 and even up to 40 m/h in some special (and exceptional) cases. These clarifiers are described in detail in Chap. 7.

After setting the design parameters for the equipment in the coagulation/flocculation part, there are some strategic choices to be made regarding the design of the flotation unit. The first two are the pressurisation rate (usually between 10 and 12% of the inflow) and the hydraulic load, which can usually vary between 20 and 30 m/h. The exact values will be chosen either after a pilot campaign on site (which is the best solution) or by analogy with other similar cases. The third strategic choice is the floated sludge extraction method, which can be by surface scraper or by hydraulic overflow. This choice determines the shape of the flotation tank, which also influences the design of flocculation and even coagulation tanks. A scraper flotation tank will have a flotation area close to the square or slightly elongated in the water flow direction. Its width will be limited by the mechanical constraints of the scraper, which is no wider than 8–10 m. In contrast, the flotation area of a hydraulic sludge overflow flotation unit will be rather short and wide in relation to the direction of water flow. As discussed in Chap. 6, the choice depends on several factors:

– The amount of floated sludge to be discharged, thus the concentration of TSS at the inlet to the DAF clarifier.
– The treatment of the floated sludge.
– The size of the plant and the number of DAF clarifiers.
– The layout constraints.

The issue of TSS concentration was discussed in Chap. 7. It is obvious that if the TSS concentration (after coagulation/flocculation) is low (say less than 10 mg/l), hydraulic floated sludge overflow would be more beneficial. Conversely, if it is high (say higher than 30 mg/l), then hydraulic overflows will be too frequent and water losses too high. A surface scraper, allowing to obtain a floated sludge more or less 10 times more concentrated, would then be preferable. But what to choose between these two values? And what to choose if the TSS concentration has strong regular or exceptional seasonal variations—for example, low variation most of the year and high in case of algae bloom?

The way in which the floated sludge is treated can help in this choice. If it is discharged directly somewhere (to a municipal sewage treatment plant, lagoon or similar) and if the water losses from the low concentration of discharged sludge (0.2–0.3% at most) are acceptable, then the balance may be in favour of hydraulic overflow. If, on the other hand, the sludge has to be dewatered on site, then surface scrapers giving a sludge concentration of 2.5–3.5% might be more attractive.

If the plant size is large (several thousand m^3/h) and the number of DAF clarifiers is significant, there is also a third option, which is to select DAFs with hydraulic sludge overflow, collect the overflowed sludge together with the filters' washwater and install a small DAF with a surface scraper to concentrate this mixture of floated sludge and washwater. The floated sludge from this flotation unit will be dewatered and the quality of the clarified water will be good enough to be discharged into the environment. Depending on the characteristics of the mixture, a small addition of coagulant and flocculant may be useful to optimise the quality of the clarified water and the floated sludge concentration. Although this solution will lead to an increase in the volume of the wash water storage tank and the size of the additional DAF clarifier to be installed, it will have two advantages:

– It will eliminate the need for surface scrapers which, for large DAF clarifiers, and especially for large seawater DAF clarifiers, are quite expensive in terms of investment and maintenance.
– It will combine the floated sludge with the filters' wash water which, in any case, must be treated.

8.6 Sea Water

Water pre-treatment for seawater desalination plants is probably the latest important development in the use of dissolved air flotation. This technology has been proven since the early 2000s with a considerable and growing number of large installations, mostly in warm seas and oceans and areas with high organic pollution and seasonal algal bloom risks, especially for protection against red tide.

The function and operation of seawater flotation plants is, on the whole, quite similar to that of freshwater treatment plants, despite the many small differences between the chemistry of seawater and freshwater, and between the behaviour of coagulants in freshwater and seawater. It consists of the best possible separation of TSS and organic matter upstream of the filtration stage using coagulation/flocculation and dissolved air flotation clarification.

However, there are several differences, the most important of which are the following:

The first is related to the very design of any desalination plant that uses reverse osmosis (RO). More specifically, the particularity lies in the extremely high requirements regarding the quality of the RO feed water. The porosity of the membranes is extremely fine, which makes them very sensitive to all kinds of fouling. They can be easily clogged by solid particles in the water or even by organic material from the cell fluid of cells burst by osmotic pressure. This requires a very thorough filtration pathway upstream of the RO. Most RO membrane suppliers recommend an inlet water turbidity of less than 0.2–0.5 NTU, sometimes as low as 0.1 NTU.

Two concepts are used to achieve this level of turbidity in the clarified water leaving the pre-treatment. The first is to filter the clarified water from the DAF clarifiers through dual-media filters—anthracite/sand or pumice/sand. This can be done either with separate dual-media filters or with DAF clarifiers with in-built dual-media granular filters. The filtration rate is around 10–12 m/h, max 14 m/h in n-1 regime. The second concept uses microfiltration (MF) membranes or, more often, ultrafiltration (UF) membranes. In general, UF membranes provide a slightly better quality of filtered water than dual-media filters, as the filtration threshold is lower. The installation is also more compact. On the other hand, they can sometimes be more delicate in operation, as they are more sensitive to clogging compared to dual-media filters.

In both cases, regardless of the filtration technique (dual-media filters or UF), cartridge filters are usually installed behind them for ultimate protection of the RO membranes.

Turbidity is not the only parameter characterising the quality of RO feed water. The filterability of the water, characterised by the Silt Density Index (SDI), is of great importance. This parameter characterises its clogging capacity. This measurement, described by the ASTM 4189-07 standard, consists of filtering water through a standardised filter with a diameter of 47 mm and a porosity of 0.45 μm, under a fixed pressure of 2 bar by measuring, at the beginning of the measurement and after a certain period of time (typically 3, 5, 10 or 15 min depending on the %PF), the time required to filter 500 ml of water. The SDI is calculated as follows:

$$\mathrm{SDI_T} = \frac{\%\mathrm{PF}}{\mathrm{T}} = \frac{\left(1 - \frac{t_i}{t_T}\right) \cdot 100}{\mathrm{T}}$$

t_i—initial filtration time (to collect 500 ml of water), min
t_T—second filtration time, min.
T—total filtration time.
%PF—percent of clogging factor. Must not exceed 75%, otherwise T must be reduced.

The higher the clogging capacity of the water, the shorter the filtration time T. Thus the SDI of raw water is often measured over 3 or 5 min (SDI3 or SDI5). The SDI of the water upstream of the RO is measured over 15 min (SDI15). As a guide, the SDI15 of the water, feeding the cartridge filters upstream of the RO, should be less than 5 for 100% of the time and normally less than 4 at least 90% of the time. There is no correlation between the SDI measurements for the different filtration times T.

The second difference concerns the type of coagulant. Given the very low porosity of RO membranes, the use of alumina-based coagulants poses a problem because, whatever the pH at which coagulation is carried out, the quantity of residual dissolved aluminium remains high, which results in fouling of the membrane surface with hydroxides and alumina silicates. Alumina-based coagulants are therefore formally prohibited in favour of iron-based coagulants, especially $FeCl_3$, as iron is much less soluble than aluminium and, in addition, allows coagulation without risk between pH 6 and pH 8. As an indication, even at the pH of lower solubility, the dissolved residual aluminium will ideally be in the range of 0.05–0.1 mg/l depending on the temperature, whereas under the same conditions the dissolved residual iron will be of the order of 0.1 μg/l. It would appear that in practice the aim is to keep the total iron at the head of the RO below 0.01 mg/l.

A similar problem arises with nonionic and anionic flocculants which are more viscous and clogging than cationic flocculants. They can be used on dual-media filters, if really necessary, but at very low doses and with care to avoid overdosing, which can lead to the flocculant reaching the RO membranes. On the other hand, some low molecular weight, high cationicity cationic flocculants and Poly-DADMAC type products can be used in combination with $FeCl_3$, regardless of the filtration technique upstream of the RO.

The third difference concerns pressurisation. The solubility of air in seawater decreases with increasing salinity and temperature. Therefore, pressurised water produced under the same conditions (same saturator, same pressure), in a temperature range of 15–35 °C and a salinity range of 30–40 g/l will contain about 20–30% less air with seawater than with fresh water. This should therefore be taken into account when sizing the pressurisation system. To achieve equivalence in the volume of air injected into the contact zone, the dissolving pressure in the saturator can be increased by the corresponding proportion, or the pressurisation rate can be increased by the same proportion. The first approach (increasing the pressure in the saturator) is more advantageous from a hydraulic point of view, as it does not increase the hydraulic load on the DAF clarifier. On the other hand, it is possible that this configuration consumes a little more electricity because of the change in the efficiency of the pressurisation pumps depending on the diameter of the impeller and the operating point. This is to be seen on a case by case basis with the curves of the chosen pump, but in any case the difference in terms of power consumption between the two concepts will probably not be more than a few %. Of course, it is also possible to combine the two methods and achieve the same final result in terms of volume of air injected.

The fourth particularity concerns the construction materials of the equipment. Seawater is particularly corrosive, especially at high temperatures (over 25–30 °C), and "classic" stainless steels, such as 304L, 316L or 316Ti, are unusable, even for components that are not permanently immersed, but which may occasionally be wetted by water splashes or drops. Even the air above the flotation zone in the immediate vicinity of the water is corrosive because it is highly saline. The best solution is to use non-metallic materials as much as possible—mainly various plastics and polyester (FRP or GRP). Otherwise, stainless steels with a PREN > 40 should be used, which are quite expensive. However, it is quite possible to dispense with stainless steels altogether for elements that are submerged or exposed to seawater splashes, as some of the more advanced seawater DAF clarifiers manufacturers have developed solutions to do so. In all cases, grounding and cathodic protection of all metallic components is essential.

The density of sea water is slightly higher than that of fresh water. However, this difference is small and has very little influence on the rising velocity of the microbubbles and the clarification process. It is negligible from a practical point of view.

Chapter 9
Conclusions

What are the conclusions to be drawn from the previous chapters and the important points to which particular attention should be paid when analysing the feasibility, selection and sizing of equipment and the implementation of a dissolved air flotation plant? What are the main criteria and parameters to be considered first? What are the possible ways of optimising the operation of a plant? The following few pages attempt to offer some advice on these subjects.

9.1 The Reasons for Choosing This Technology Over Another

Like each of the technologies for separating suspended solids, dissolved air flotation has its 'conquered' areas of application and also its limitations. In clarification, there are essentially two competing techniques: sedimentation and filtration. Compared with these two technologies, flotation has certain advantages, but also certain disadvantages, which can be summarised as follows:

Compared with its main competitor, sedimentation, flotation has the following advantages:

- In general, it gives better results when it comes to removing fine particles composed mainly of organic matter, which tend to float naturally or settle at a very slow velocity—let's say less than 0.5–0.8 m/h. Its advantage is even greater in cases where the aim is to remove not only TSS but also colloidal matter using a chemical coagulation/flocculation treatment, as the flocs formed are fairly light and fragile in the vast majority of cases. In addition, the electrostatic charges provided by this chemical treatment are particularly favourable to flotation, as they reinforce the adhesion of the microbubbles to the flocs formed.

R. Kaltchev, *Dissolved Air Flotation*, Springer Water,
https://doi.org/10.1007/978-3-031-51869-0_9

- Overall, flotation performance is more stable in the event of variations in the quality of the treated water.
- The sludge produced is more concentrated than that obtained by sedimentation. It can be dewatered directly without pre-thickening.
- The aeration of the effluent and the short residence time in the clarifier prevent fermentation.
- The installations are much more compact and take up less space.

However, there are two disadvantages:

- Energy consumption related to pressurisation (pressurisation pump + air compressor).
- Some additional maintenance costs associated with the pressurisation pump and air compressor, as these are high-speed rotating machines.

In some applications involving water with low suspended solids content, filtration may be more appropriate than flotation, especially where chemical treatment is not required. If the effluent does not present significant risk of clogging, filtration through woven filter fabrics can very well separate a few tens of mg/l of TSS. For example, compared with disc filters, flotation has the following advantages:

- It is not sensitive to accidental increases in TSS concentration (if such a risk exists) or to clogging by fatty matter or other deposits that may form on the filter fabric.
- No consumable parts (filter panels have a limited lifespan).

But it has the same disadvantage as above—the power consumption related to pressurisation. Disc filters can also, in many cases, form even more compact installations than flotation.

Finally, competition between flotation and sand filters (or other granular filter media) is relatively rare, since it only applies to water with a very low TSS content—no more than a few mg/l. If the water contains no clogging products or other special cases, sand filters will give a better quality of filtered water at a lower energy cost. However, they do produce a certain volume of wash water that normally requires treatment.

In biological sludge thickening, the techniques competing with flotation are static thickeners (sedimentation), various filtration devices (mainly drums, screens and dewatering tables) and centrifugation.

Sedimentation thickeners enable a relatively low concentration of biological sludge to be obtained (around 1.5% DM) and require a very long thickening time (up to 24 h). On the other hand, they operate without flocculants and consume very little energy.

Compared with flotation, filtration equipment achieves better sludge concentration (5–8% DM) while consuming less energy. On the other hand, they require a high dosage of cationic flocculant (in the range of 6–9 kg/tonne DM) or, in some cases, FeCl3 and lime. By comparison, flotation produces sludge thickened to 3–4% DM without the use of flocculant, or with flocculant dosed at 1–1.5 kg/tonne DM for the most difficult cases.

As for the centrifuges, they can simply be used to avoid the thickening stage before dewatering. It is possible to feed them directly with excess sludge at a concentration of just a few g/l and obtain dewatered sludge at 20–22% DM at the outlet. However, this solution has some serious drawbacks:

- Flocculant consumption of up to 10–12 kg/tonne DM
- Very high power consumption—more than double that of a centrifuge fed with sludge thickened to 3–4%.
- High investment and maintenance costs (heavy machines running at very high speed)
- Requires very rigorous operation management in these conditions

So how do to choose? Unfortunately, there are no precise rules, and there are cases where one can hesitate. The choice belongs to the water treatment specialists, who will make the decision on the basis of an overall analysis of the entire treatment plant in the specific context of each project.

9.2 The Chemical Treatment to Be Used

For dissolved air flotation applications, the chemical treatment (if one is required) must meet a few specific criteria. It is important to bear these in mind.

While, in sedimentation, one ideally seeks to form rather large and compact flocs that settle well, this is not the case in flotation. The size of the flocs is relatively unimportant. On the other hand, their electrostatic charge is of great importance, as it is this charge that largely ensures the adhesion between the flocs and the microbubbles.

There are usually two possible scenarios:

- simple flocculation with a flocculant
- coagulation followed by flocculation.

In the first case, a cationic flocculant is almost always used. In settling, it is usually added upstream of a mixed flocculation tank or a pipe flocculator (for low flow rates), the purpose of which is to allow the flocculant to neutralise the few weak electrostatic charges, trap the particles and cause the agglomerates to grow until they form solid, compact flocs that settle well.

The approach is very different in flotation. In this case, in-line flocculation is generally preferred. The cationic flocculant will typically be added just before the injection of the white water so that it ensures rapid flash mixing which will gradually slow down in the contact zone of the clarifier. The aim here is not so much to make the flocs grow but to form them in the presence of the microbubbles so that some of them become trapped inside the flocs as they form. So, even small flocs float very well. What's more, small flocs have a larger developed surface area than large ones, so they are able to retain more microbubbles on their surface.

In the case of coagulation followed by flocculation, the two techniques may also require different approaches. In sedimentation, it is often possible to supplement the action of the coagulant (a very strongly cationic product) with a cationic flocculant to agglomerate the flocs formed by the coagulant. Correct flocs can thus be obtained which settle well, even if the sum of the cationicity provided by the two products remains insufficient to neutralise all the negative charges present. This lack of cationicity can nevertheless pose a few problems for flotation, particularly for the adhesion between the flocs and the microbubbles. And an overdose of cationic flocculant will not always improve this adhesion. In this case, it is preferable to increase the dosage of coagulant to slightly exceed the neutrality point and flocculate with an anionic or nonionic flocculant. In this way, negatively charged microbubbles will adhere more easily to positively charged flocs.

Chemical treatment can be more complex for drinking water clarification. Sometimes it is possible, thanks to a well-adjusted chemical treatment, to obtain good adhesion of the microbubbles to the small flocs without using flocculant. If the floc capture rate is sufficient under these conditions, this method of operation avoids introducing residual flocculant into the sand filters and can lengthen the filtration cycle.

It's even trickier in seawater treatment, where there are additional requirements. Here, the slightest error can cause deposits on the UF membranes (if such membranes are used). In this application, daily monitoring by a specialist is essential.

It is therefore clear that using a simple jartest (used normally for sedimentation tests) is not enough. Tests for verifying chemical treatment must be carried out in combination with flotation. On site, a small amount of pressurised water can be taken downstream of the saturator—normally there is always a small valve somewhere on the installation for this purpose. In the laboratory, pressurised water can be produced using specially designed equipment (a flotatest) or a simple garden sprayer half-filled with treated water, pressurised to the limit of its safety valve (usually 3 bar) and shaken vigorously for about thirty seconds. This may not sound very professional, but it works well enough for tests aimed mainly at comparing different chemical treatments and product dosages.

Of course, these recommendations are not rules that apply in all cases. Normally, microbubbles have a negative charge, but there may be exceptions with certain industrial effluents. There are cases where, for reasons that are sometimes difficult to explain, the best result is obtained with a chemical treatment that is quite different from what might be expected. The existence of such exceptions could be a good reason to check the chemical treatment regularly, and even have it checked or validated periodically by a water chemistry specialist, whenever there is a significant change in the quality of the treated water. This recommendation is addressed above all to the operators of small industrial effluent treatment plants, who do not always have the necessary skills in-house. They should not hesitate to call on their chemical suppliers or an outside specialist as often as necessary. It's important to remember that, with the right chemical treatment, a poorly sized or mediocre flotation plant could give better results than an excellent plant where the chemical treatment is not up to scratch.

9.3 Equipment Selection

The choice of equipment is, of course, of great importance in the design of a flotation installation. As discussed in previous chapters, there are several types of saturators and flotation clarifiers on the market, sold by different manufacturers, each with their own marketing arguments. Some of the advantages and disadvantages of the main concepts are discussed, in a non-exhaustive way, throughout the previous chapters so that the reader can form a more well-argued opinion on the subject.

Generally speaking, it should be underlined that most of the equipment described in this book can give satisfaction in most applications if implemented properly. However, some equipment should be avoided for certain applications because, apart from the risk of poor performance, it may pose more operating and maintenance problems.

The following recommendations and warnings should be considered as indicative only, as they are based on the author's personal experience, which is, of course, limited.

9.3.1 Selecting Saturators

Packed saturators are reserved for drinking water or, more generally, water containing very little organic matter and nutrients. Any significant development of biomass on the packing can lead to clogging, preferential water paths and, consequently, a drop in efficiency. In such case, packing replacement can be necessary every few months.

Saturators with assisted regulation of the air flow rate, usually by detection of the water/air interface, are also intended primarily for drinking water. They can, of course, be used in waste water treatment, but in this case the type of level sensor and its installation should be carefully selected to avoid any deposits or clogging likely to interfere with detection.

Some large saturators (residence time greater than 60 s) may be sensitive to internal fouling. Industrial effluents containing a lot of organic matter, starch, glues (paper industry), fats (food industry) or filings (hair in municipal effluents) can form deposits in nooks and crannies where water velocity is low and insufficient to provide a self-cleaning effect. It would be better to prefer "compact" saturators in which the water circulates everywhere at high speed and in which there are as few as possible clinging elements and surfaces not swept by the water at sufficient velocity. Their efficiency may be slightly lower than that of a saturator designed for a 60 or 90 s residence time, but it is still sufficient for most of them.

Generally speaking, as long as we are dealing with small installations pressurising less than 15–20 m^3/h, the energy impact of the saturation rate of the saturator is relatively low in absolute value. In this case, giving priority to operating ease and reliability may seem justified. For these low flow rates, it is almost possible to save more energy by judicious selection of the pressurisation pump. In fact, it should be remembered that the efficiency of small pumps at 5–6 bar is generally low and can easily vary between 30 and 50% from one pump to another, which is a lot in proportion. (For comparison, the efficiency of a 200 m^3/h pump at the same pressure varies between 73 and 80% from one pump to another).

As the pressurisation flow rate increases, the impact of the saturation rate on energy consumption increases in absolute terms and may justify the choice of a more efficient saturator if the clarifier manufacturer can offer one.

9.3.2 Selecting Pressure Relief Devices

Installing a high-performance saturator doesn't make much sense if it's followed by an inappropriate pressure relief device. The end result is likely to be disappointing. As previously discussed, it is perfectly possible to expand pressurised water in such a way as to produce only micro-bubbles or, conversely, to produce lots of large bubbles and very few micro-bubbles. It all depends on the pressure relief device and the conditions under which the white water is mixed with the raw water.

The two main 'enemies' are coalescence and clogging. Large pressure relief orifices do not clog, but they do favour coalescence and can cause a lot of air to be lost. Small orifices produce excellent micro-bubbles, but are susceptible to progressive clogging and plugging, even when treating fairly 'clean' water. So how to manage these two constraints? Of course, pressure relief devices need to be adapted not only to the flotation clarifier, but also to the application and to the specific characteristics of the water being treated. But it's hard to find a simple and reliable solution that works everywhere.

It is difficult to propose solutions on a case-by-case basis, but as a general rule, it would be recommended to avoid the following if possible:

- Carrying white water (after pressure relief) in long pipes, especially if it is only slightly diluted with raw water, as this can cause a lot of air to be lost through coalescence. And, except in special cases, the "cleaner" the water, the greater the risk of coalescence causing damage.
- High points in the pipes after the injection of the white water. These high points fill with air and promote the loss of microbubbles and coalescence.
- Use a single large-diameter pressure relief valve if the installation allows the use of several smaller ones. The same applies to calibrated orifices.
- Install pressure relief devices above the water level in the clarifier.
- Relieve pressure through orifices that are too small and liable to be plugged by large particles.
- Install pressure relief devices in inaccessible places (such as at the bottom of the clarifier's contact zone) if these devices are not self-cleaning (periodic flushing) or can be easily removed for cleaning without having to stop the installation or, even worse, drain the clarifier.

9.4 Sizing the Main Equipment

9.4.1 Sizing Saturators

To date, there is no universal method for sizing saturators. The main concepts available on the market are all based on prototypes that have been tested and improved with experience. Their main characteristic, the saturation rate, varies essentially according to two parameters: the contact area and the contact time between the water and the air. Each manufacturer has its own design and range of standard saturators designed for a certain range of flow rates between a maximum flow rate and a minimum flow rate.

However, it would be interesting to know the variation in saturation rate as a function of feed rate within this range of flow rates. This could enable a more refined choice of saturator size, especially when we are at the limit between two sizes. For example, if we know that at the maximum flow rate of one size of saturator the saturation rate is a little lower than that which could be obtained at the minimum flow rate, then, to supply a given quantity of air, we can use more pressurised water with a smaller saturator or a little less pressurised water by using a saturator of the size above.

This approach is logical and easy to use. But it only makes sense if one knows exactly how much air one needs to provide. And therein lies the main problem of sizing the pressurisation system. We know how to size a saturator to deliver a precise quantity of air, but we never know exactly how much air we really need. It must be sufficient, but not excessive. It should be the sum of:

- The volume of air in the form of microbubbles "firmly" associated with the flocs,
- The volume of air in the form of free microbubbles ensuring sufficient concentration of said microbubbles in the water. In fact, as they rise, some flocs lose microbubbles attached more weakly to their surface and, at the same time, attach others in the event of a collision. This cloud of free microbubbles also entrains the flocs in its overall ascent and often makes a significant contribution to the quality of the clarification,
- The volume of air that will be lost in coalescence if the pressure relief conditions are not perfect (which is often the case).

Of course, these volumes depend on the characteristics of the water to be treated, but also on the performance of the chemical treatment if one is used.

As already discussed, experience accumulated in this area is essentially expressed in terms of two parameters:

- The Air-to-Solids ratio—the necessary amount of air is related to the TSS amount to be treated
- The volume of air to be supplied per m^3 of treated water—the necessary amount of air is related to the water volume to be treated

Each of these parameters is relatively reliable within a more or less restricted range of characteristics of the water to be treated and of TSS concentration. Using them outside their 'range of reliability' can be misleading.

A good example would be the biological sludge thickening. The recommended Air-to-Solids ratio varies between 0.012–0.015 and 0.02 kg/kg. In this application, the parameter is relatively reliable, but the sludge concentration is usually between 5 and 8 g/l. If the same sludge were diluted 10 times, there would be a risk of running out of air if the same values were used, as this would result in a volume of air of less than 2 l/m^3 of treated water.

The volume of air per volume of treated water (values usually retained between 5–6 and 8 l/m^3) seems to be a relatively more universal parameter because it ensures a volume of air in the clarifier regardless of the TSS concentration. It can be widely applied for TSS concentrations ranging from a few mg/l (drinking water) to several hundred mg/l of TSS. But it also has its limits. Applied to a case of biological sludge thickening such as the example given above, it could still give relative satisfaction for a concentration of sludge to be thickened in the range of 0.7–0.8 g/l, but certainly not for a concentration of 5 g/l, because in this case the Air/Solid ratio would be less than 0.0015 kg/kg, i.e. 10 times less than the recommended value.

It is therefore difficult, with the knowledge and methods available to us today, to estimate precisely the importance of each of the parameters influencing the quantity of air that is really needed for the installation to work properly. So we can only make estimates based on our own experience, or that of others. On the other hand, once the installation has been completed and commissioned, it would be perfectly possible to adjust the settings if the equipment allowed. Unfortunately, this rarely happens, for two reasons. The first is that not all the equipment involved is adjustable. The second is that fine-tuning the operation of the installation in this way takes time.

In conclusion, it can be said that in many cases pressurisation is oversized, sometimes significantly oversized, especially in small installations. There are many reasons for this.

Firstly, there is always a tendency (quite rightly!) to take reserves, to ensure that things work well in all circumstances and to avoid unpleasant surprises. After all, it works well and the customer is happy. But rare are the cases where a technician spends time on the installation gradually reducing the pressurisation flow rate (and power consumption) to find out, once commissioning has been completed, what pressurisation flow rate is really needed. This approach could lead to the accumulation of valuable know-how.

Secondly, in the vast majority of cases the saturator, and sometimes the pressure relief devices, are designed to operate at a fixed flow rate. Varying the pressurisation flow rate without affecting the saturation rate under these conditions is not straightforward.

Thirdly, a small electrical over-consumption of small installations (a few tens of m^3/h) is considered acceptable in relation to operating comfort. With the inevitable rise in energy costs (reference 2023, the year of writing), this could perhaps change in the future.

9.4.2 Clarifiers Sizing

For flotation clarifiers sizing, the recommended values are usually based on the mass load (kg/m^2· h) and the hydraulic load (m^3/m^2· h or simply m/h). As implied in the previous paragraph, the mass load begins to influence the sizing of the pressurisation system and, consequently, also the flotation unit, for TSS concentrations exceeding 1000–1500 to 2000 mg/l. Below these values, it is considered that, in most cases, hydraulic sizing is determinant.

The hydraulic loads shown in most manufacturers' marketing brochures are relatively similar. For flotation units with non-assisted clarification, they usually vary between 6 and 8 m/h, with a maximum of 10 m/h for some particular units. For assisted clarification flotation units (lamellar flotation units and flotation units with "U" shaped profiles) the hydraulic load is expressed per water mirror area and is around 30 m/h for the horizontal versions of the units. In both cases, it is rarely specified whether these values relate to the inflow alone or to the sum of the inflow and the pressurisation flow.

Normally, it would be more logical to consider the sum of the two flow rates, as the pressurisation flow rate can often vary by as much as double, or even more.... These values are, admittedly, close to the actual capacity of the flotation devices in many cases, but sometimes they are too often referred to in the design phase without taking the time to carry out a flotation test (when this is possible) and refine the sizing. A simple measurement, even an approximate one, of the flotation velocity in a 1 l test tube, would sometimes make it possible to avoid oversizing. There are cases where it is possible to operate the flotation clarifier at loads well in excess of the standard values. There are, of course, also cases where it would be preferable to reduce the hydraulic load so as not to have to make up for it with excessive flocculant doses.

So what would be the ideal approach? It consists of:

- Testing whenever possible. For existing effluents, it is always possible to collect a representative sample to test the chemical treatment to be used and measure the flotation velocity before making the final choice. This is more difficult for new installations. But even in these cases, it would always be useful to carry out a measurement campaign (within the limits of the possibilities offered by the installation in terms of variations in flow and treatment capacity) after commissioning. Even if the plant is operating satisfactorily, this would allow experience to be accumulated that could prove very useful for future similar plants and avoid repeating the same mistakes several times.
- If it seems useful, one should not hesitate to adapt the various elements of the clarifier to each specific case. These are usually small modifications to the inlet and outlet devices, water level regulation, the floated sludge collection and extraction device, etc., which can bring appreciable improvements in terms of performance and operating comfort.

9.5 What Can Be Improved?

The first thing that could be improved is the on-line measurement of water characteristics, so that chemical treatment can be continuously adapted. The instruments we currently have do not allow reliable measurement of certain parameters which we feel are the most representative of water properties, such as zeta potential or cationic demand, or the electrostatic charges of particles, or the formation of specific chemical components, etc... A set of instrumentation and control algorithms that can be used in both clear and waste water would be a major step forward in improving the operation of water treatment plants in general.

Apart from chemical treatment (if such treatment is used), the most sensitive element of a flotation installation is the pressurisation system. It is the main consumer of energy, which is one of the major disadvantages of dissolved air flotation compared with its competitor techniques. It would therefore be logical to try to make it as flexible as possible, so that it can be adjusted as closely as possible to the real needs of the installation. In most cases, it's quite the opposite—once installed and commissioned, it operates at a fixed flow rate, since at least one of its components does not allow for variations.

What would be the perfect pressurisation circuit design? Well, it's one that offers the possibility of varying the pressurisation flow rate over a wide range (say $\pm$ 30%) while maintaining the maximum saturation level of the saturator and providing perfect pressure relief conditions, i.e. without creating any large bubbles after the pressure-relief device. And, of course, without any unnecessary waste of energy by the pressurisation pump, such as the use of valves to regulate flow or pressure.

Let's start with the pressure relief devices. As already discussed, pressure relief devices are either fixed flow (pressure relief nozzles and other calibrated orifices) or variable flow (manually adjustable valves or pre-set automatic valves with periodic flushing). Those with small fixed orifices provide good aeration quality, but can only be used for drinking water because of the risk of clogging. And it is virtually impossible to vary the flow rate within a significant range, even if the water pressure is varied considerably, which would cause problems for the saturator and additional energy consumption. It is only possible to vary the flow rate if one has a certain number of them, mounted on parallel diffusion ramps that can simply be isolated individually without deteriorating the quality of the mixture of white water and raw water. So, if one has three ramps, and if the design of the saturator allows it, one can vary the pressurisation flow rate to 33, 66 or 100%. This is what some manufacturers do in drinking water clarification. This solution is practically impossible to apply to wastewater.

The flow rate of manual valves and pre-set automatic valves with periodic flushing is easy to vary if they are installed outside the clarifier, i.e. on pipes. They are well suited to waste water, but the quality of the white water they provide is somewhat less than perfect. In this case, some of the air is lost through coalescence.

So, for drinking water, we have a concept that gives a very good white water quality, but does not allow any variation in flow, except, eventually, in large steps.

And vice versa—for waste water we have devices that allow the flow rate to be varied easily, but they offer mediocre aeration quality and cause air to be lost.

It would therefore be advantageous to use pressure relief devices that are:

- Designed to provide a pressure relief through small orifices—ideally not more than 2–3 mm
- Immersed in the clarifier's contact zone so that the white water is diffused and mixed with the raw water without passing through a pipe or even through a valve body to avoid coalescence.
- Equipped with a means for easy adjustment of the water flow rate over a wide range and from outside the clarifier.
- Fitted with a flushing facility to remove any possible clogs. This can be done periodically on a timer, or only in the event of clogging.

The perfect saturator must meet the following requirements:

- Allow the water flow rate to vary without altering the hydraulic conditions inside. Packed saturators can meet this requirement because their water distribution system causes little head loss and is usually relatively insensitive to flow rate variations. However, this type of saturator is reserved almost exclusively for drinking water. For saturators with water dispersion or recirculation, used in waste water, a significant change in water velocity could lead to a reduction in the contact surface between the water and the air and, consequently, a reduction in the saturation rate. This concerns especially saturators with submerged hydroejectors, which need sufficient drive force to suck in the air. Some saturators can be fitted with a device to regulate water dispersion. Lastly, a saturator fitted with an external recirculation pump can also be used, making it easy to vary the flow rate of pressurised water at a very modest additional energy cost (compared to other solutions). However, this requires an additional pump.
- The saturation rate should be at least 60–65%. If the saturator is used with the "perfect" pressure relief devices described above, then it would probably be advantageous to go further in terms of saturation rate. This should be achieved without increasing the mixing energy consumption. But also without excessively increasing the volume to avoid clogging in the nooks and crannies. Here too, saturators with an external recirculation pump would be the most flexible and reliable solution, but also the most expensive one in terms of investment.

Finally, one must not forget the pressurisation pump. Any change in flow rate will result in a change in water pressure, and therefore in the quantity of air dissolved in the saturator. It is essential that the pump is controlled by a regulation loop and powered by a frequency inverter that can maintain constant pressure in the saturator over a relatively wide range of flow rates (depending on the pump curve).

Such a 'perfect' pressurisation system would enable the air supply to be adjusted to a 'reasonable' minimum level for each installation. And even, if necessary, to vary it automatically according to the variations of a few chosen parameters. After all, each installation has its own particularities, even if, taken as a whole, it may resemble many other similar installations. And, given its energy and, eventually, chemical consumption costs over its long lifetime, it's worth trying to optimise it as much as possible.

In this chapter all these ambitions and dreams of improvement may, admittedly, seem a little exaggerated. After all, the current installations work well and give satisfaction. True enough. But let's not forget that the cars of the 1930s were already fulfilling the function for which they were built. Nevertheless, they've come a long way since then...

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