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Design, modelling, simulation and operating conditions for a lamellar settler in a plastic recycling company

Grado en Ingeniería Química

Trabajo Fin de Grado

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ABSTRACT

To improve the efficiency of the water treatment system, a plastic deinking company has decided to implement a lamellar decanter in its process. This work will try to design, model, simulate and test different operating conditions to try to maximize the benefits of the equipment.

The simulations will be carried out with a CFD program based on finite volume methods called Ansys, which will be combined with MATLAB in order to study the results obtained and to be able to perform a sensitivity analysis. In addition, a surrogated model will be obtained to calculate the settling efficiency without having to perform the simulations and to reach the result in a faster way.

As a complement, the Navier-Stokes equations used by the program to predict the fluid flow will be developed.

KEYWORDS

Lamellar settler; Simulation; Computational fluid dynamics (CFD); Ansys; Finite volume method; MATLAB.

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1. INTRODUCTION

Cadel Deinking is a company that has developed a process that allows to remove the ink printed on the plastic surfaces before recycling it in order to obtain a product with a quality very similar to virgin plastic.

To do this, the industrial plant has four stirred tanks in series. The first two are filled with a mixture of reagents and water and his objective is to eliminate as much of the ink from the plastic as possible. Next, the following two tanks are filled only with water and are responsible for the rinsing.

Finally, thanks to a drying system that has centrifugal separators and a thermal dryer, it is possible to eliminate almost all the persistent moisture in the plastic.

Figure 1 shows a more detailed diagram of the process.

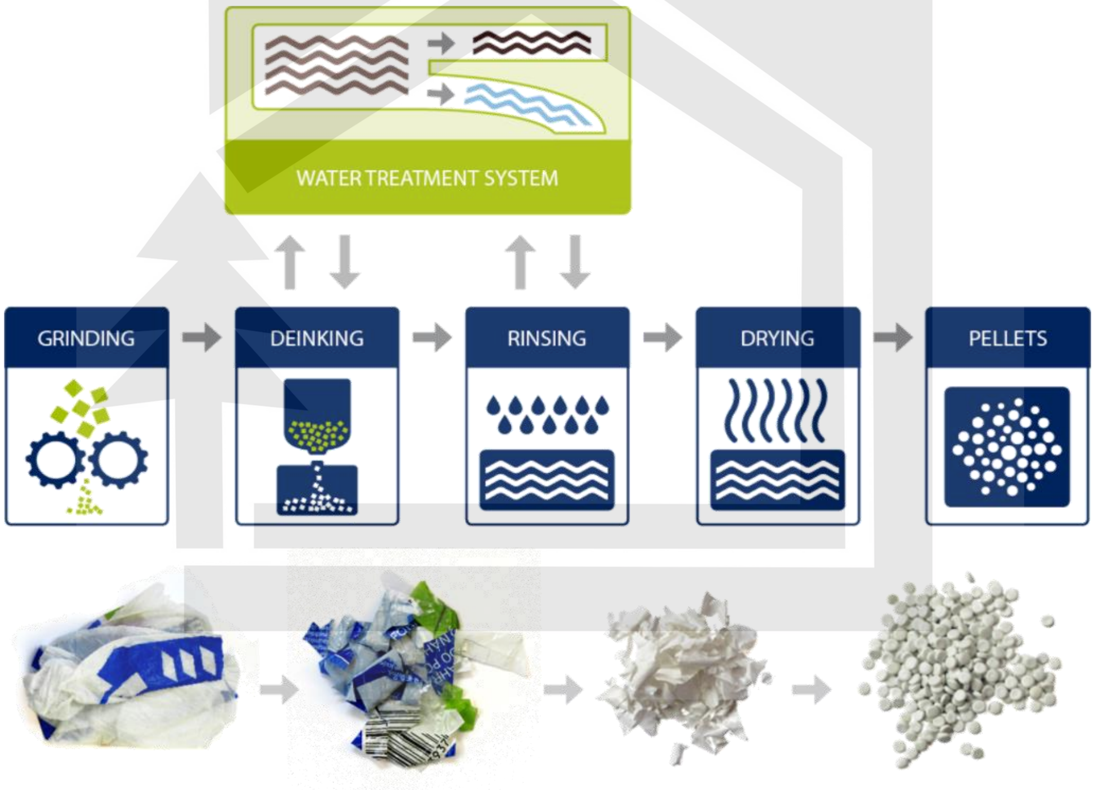


Figure 1. Cadel Deinking company process diagram.

As part of the process, the plant has a treatment system for the water leaving the tanks. This system is equipped with an evaporator, whose purpose is to separate the ink from the water that has remained after the reaction with the plastic. After this step, the clean water is condensed and is recirculated to the tanks.

However, the operational cost of the evaporator is very high due to this equipment consumes a lot of electrical energy. Therefore, it has been proposed by the company to introduce a lamellar settler to separate as much ink as possible from the water before it is sent to the evaporator in order to increase the efficiency of the water treatment system.

In the lamellar settler the ink is separated from the water by sedimentation. Sedimentation is a solid-fluid separation operation in which the solid particles of a suspension, denser than the fluid, are separated from the fluid by the action of gravity. It is an operation controlled by the transfer of the amount of motion.

The advantage of choosing a lamella decanter over traditional decanters is that, thanks to the implementation of lamellae (consisting of a series of closely spaced flat plates inclined at an angle), it is possible to reduce the distance that the particles have to travel until they settle (McKean et al., 2010).

The main benefit of implementing a lamellar decanter is that it does not have an associated operation expense (OPEX), it is only necessary to purchase the equipment and, through the force of gravity, it is possible to concentrate the dissolved and suspended ink in the water. The capital expenditure (CAPEX) of the equipment is estimated to be 25000 euros.

To calculate the total price of the water treatment system, the CAPEX of the evaporator, which is 100000 euros, should be added to the price of the decanter, but this equipment will also have an OPEX. Knowing that the power of the evaporator located in the plant is 53 kW and that it is in operation 250 days a year, working 8 hours a day and the price of electricity is approximately $0,2\,\frac{€}{kW\,h}$, the annual operating cost is 21200 euros.

As a large outlay of money must be made, the motivation of this project is to design, model and simulate the lamellar decanter in order to implement it in the water treatment system of a company so that the clarified stream that is returned to the process has the least amount of ink possible.

To meet the objective, a software based in finite volume method called Ansys will be used, which allows predicting fluid flow by solving partial differential equations (PDEs). The main advantage of using this CFD software is that a more detailed and rigorous study of what happens inside the equipment can be carried out in order to set an optimal operation mode among different possibilities. It will be sought at all times that the simulations reproduce what happens in the decanter of the plant, therefore it will be tried to reproduce as realistically as possible, through mathematical models, the physical phenomena that take place.

On the other hand, it will be used the MATLAB programming platform, where the results obtained with Ansys will be imported, in order to be able to represent, analyze and compare the results achieved.

To determine what it will be the final result of this project, it will be studied both comparative graphs extracted from MATLAB, as well as visually examine what happens inside the decanter over time using a postprocessor included in Ansys called CFD Post. ANSYS CFD-Post software delivers everything needed to visualize and analyze fluid dynamics results.

2. PROBLEM STATEMENT

In this work, the problem of designing, modeling and simulating a lamellar settler can be stated as follows:

From the geometry shown in Figure 2, it must be found a design and operating conditions that, combined, increase the amount of ink that is able to settle in the lamellar decanter for a certain period of time without discharging it, as well as to find a mathematical model to describe what happens with the mixture of ink and water inside the equipment. In addition, the geometry of the decanter will be the domain where the systems of partial derivative equations will be applied. By working with CFD software, it will be feasible to directly evaluate possible problems or defects that may impair the efficiency of the equipment, since the simulation will be carried out in a transient state.

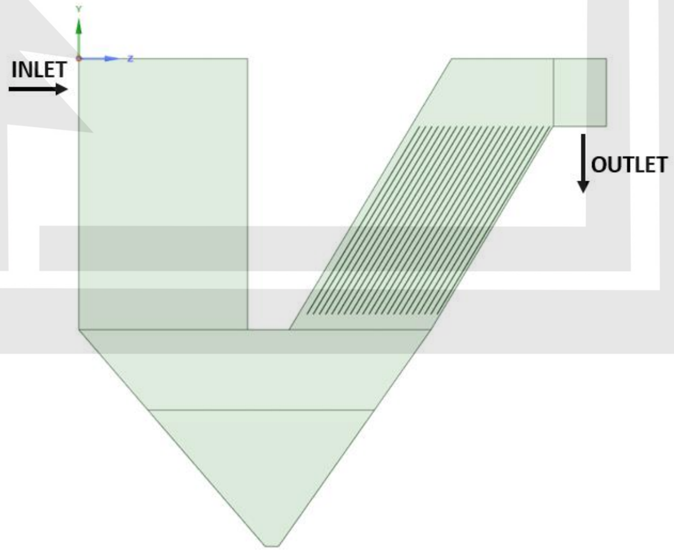


Figure 2. Initial geometry of the lamellar decanter.

The decanter, illustrated in Figure 2, will receive a stream from the tanks that are responsible of the deinking of the plastic and it will be assumed that this stream contains only water and ink.

The inlet and outlet stream are continuous and the ink that sediments will go to the lower part of the equipment. This lower part is known as the cone of the decanter.

The characteristics of the design that starts as the basis of the simulations are the following:

- Decanter volume: 1645 L
- Cone volume: 215 L
- Number of lamellae: 22
- Width of the lamellae: 2 mm
- High of the lamellae: 800 mm

Furthermore, it is assumed that other conditions are met:

- It is intended that the sludge of the decanter is discharged within two hours of operation of the equipment (what happens after this time will not be of interest). Discharge refers to the opening of the bottom of the decanter to remove sedimented ink.
- In order to speed up the simulations, these will be started with a full tank and an initial ink concentration of 20 g/L.
- The ink, both dissolved and suspended, is considered to have a constant and known particle diameter.
- The ink, both dissolved and suspended, is considered to have a constant and known density.
- The ink, both dissolved and suspended, is considered to have a constant and known viscosity. It should be noted that in the overall project the ink will be considered as a solid, however, the program needs to know the viscosities of the secondary phases in order to carry out the simulations. Therefore, viscosity values must be given even though solids do not have this property.

On the other hand, the changes that will be applied to the geometry that starts as a base will have the objective of maximizing the amount of ink in the cone, since this will be the main indicator that the separation between the ink and the water is being increased. Therefore, the process will be considered to be optimized when higher values of ink concentration are achieved in this zone.

The changes to be studied will be the following:

- ✓ Change the number of lamellae in the decanter.
- ✓ Change the angle of inclination of the lamellae with respect to the horizontal axis.
- ✓ Change the extension of the lamellae.

It is important to note that, no matter how much the geometry of the decanter is varied, the volume of the cone will always be kept constant in order to make a fair comparison of the results.

Additionally to changes in geometry, various modes of operation will also be tested. This will be done by setting different inlet volumetric flow rates, which will directly affect the residence time of the particles, in order to determine which one achieves the best results, also calculating what settling efficiency would be attained in each case.

After the study of the inlet volumetric flow rates, a surrogated model will be sought that allows to calculate what efficiency will be obtained without having to carry out the simulations and, thus, reduce the calculation time.

3. STEPS TO PREPARE THE SIMULATIONS IN ANSYS

CFD simulation consists of three stages: pre-processing, calculation and post-processing. The scheme of a problem in which it is desired to study the fluid flow inside a continuous body using the finite volume method is shown in Figure 3.

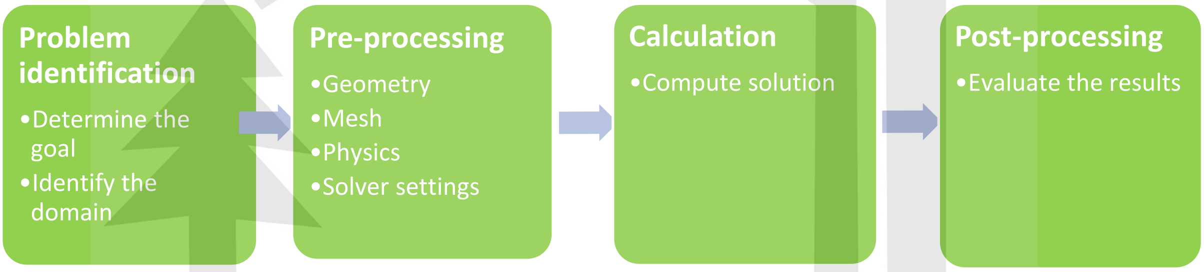


Figure 3. Diagram of the steps to be followed to study the fluid flow using finite methods.

In this section of the project, the pre-processing will be presented, which is also the most time-consuming part of the project

3.1. GEOMETRY

The first step is to design the equipment through which the fluid will flow. This can be done in two different ways:

- Importing a CAD geometry to Ansys.
- Use the Ansys SpaceClaim tool, which allows the design of 3D models.

In this project, a 3D geometry of the lamellar decanter provided by a company specialized in the design of these equipments has been imported and, with the help of Ansys SpaceClaim, it has been cut the part to obtain the 2D geometry and speed up the simulations. This cut was possible because of the symmetry of the 3D design.

An image of the decanter designed by the specialized company is attached in appendix B and the 2D cut is shown in Figure 2.

3.2. MESH SELECTION

Ansys uses the finite volume method to solve the governing equations of fluid flow (Bhaskaran, 2016). The basic idea of this numerical technique is to take a flow domain and divide it into little volumes and apply conservation to each little volume.

Meshing is the process of discretizing the continuous body into a finite number of cells (also called control volumes). It is one of the most important steps in the analysis of the finite volume method. The mesh defines the locations at which the flow solution is computed. The more the number of cells, better will be the accuracy of the results but will be more time consuming. Therefore, a balance must be found between good mesh quality and the number of cells.

In this case, a more precise meshing will be used in the inlet and outlet area of the equipment, as well as in the area of the lamellae, since these are the parts where it is of interest to obtain results with higher resolution.

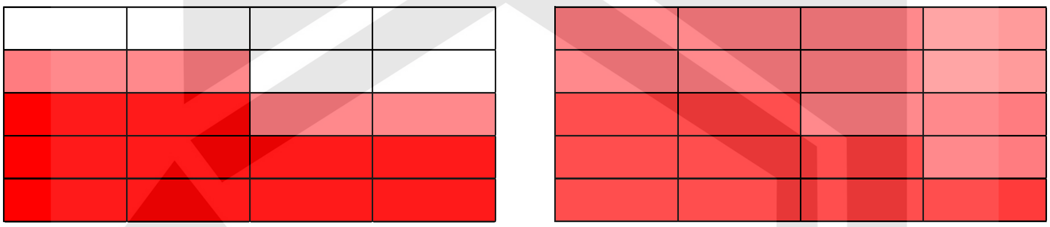
An image of the geometry after meshing is shown in appendix A.

3.3. SELECTION OF THE PHYSICAL MODEL

The selection of the mathematical model is a key step in order to make the simulation similar to what actually happens in the plant. Having a mixture formed by water and ink, it must be apply some model that considers several phases, that is, a multiphase model. Depending on the basic physical concepts used to formulate the multiphase flow, averaging procedures can be classified into three main groups, namely the Eulerian averaging, the Lagrangian averaging and the Boltzmann averaging (Manninen et al., 1996).

Ansys gives the option to work with the Eulerian model, as well as with simplifications of it, such as the mixture model or the volume of fluid (VOF) model theory. The difference between these models lies, as Wimshurts (2019) explains, in the interaction between the phases:

Eulerian multiphase models can account for dispersed-continuous phase interactions and continuous-continuous phase interactions. The difference between these types of interaction is that in dispersed-continuous phase interactions can take any value of volume-fraction between 0 and 1 whereas in continuous-continuous phase interactions are restricted to a volume-fraction of either 0 or 1 (except in the interface region). Physically means that when the volume-fraction is zero, there is no dispersed phase in the medium, while as the volume-fraction increases, it indicates that the concentration of the dispersed phase is increasing (in continuous-continuous phase interactions it is formed a discrete interface, and they are immiscible with each other). The difference between the two types of phase interactions can be seen clearly in Figures 4 and 5.



Figures 4 and 5. The figure on the left shows how there are clearly two continuous phases (which take a volume-fraction of 0 or 1 except in the interface region). The figure on the right shows a dispersed-continuous phase interaction, where the volume-fraction can take any value between 0 and 1.

In addition, Ansys allows working with simplified Eulerian models. One of them is the mixture model, that is a simplified version of the full Eulerian model for dispersed-continuous phase interactions. The other is the volume of fluid (VOF) model that is a simplified version of the full Eulerian model for continuous-continuous phase interactions.

In the mixture between ink and water, it will be considered that there is a main phase (water), which is the continuous phase, and two secondary phases (the dissolved ink will be taken into account on the one hand and the suspended ink on the other), which are dissolved in the main phase. Because of that, both the Eulerian method and the mixture model could be applied.

To study the sedimentation operation, the Ansys guide itself recommends using the mixture model, as it will reduce the number of variables to be calculated with respect to the full Eulerian model, which is recommended for more complex mixtures (ANSYS Fluent 12.0, 2009). Therefore, the physics to be used has already been determined.

3.4. BOUNDARY CONDITIONS AND SOLVER SETTINGS

Boundary conditions are essential component of a mathematical model, since these define how a solution to a differential equation behaves at the boundary of a system. Within the domain where the systems of partial differential equations will be solved, the following boundary conditions have been fixed:

- ✓ Inlet mass flow rate of each component (water, dissolved ink and suspended ink).
- ✓ Pressure at the outlet of the equipment.
- ✓ Both the lamellae and the surfaces that limit the equipment (except for the inlet and outlet area) have been fixed as "walls". The velocity in this contour is zero, so that the flow does not pass through it and there is no slip.

Figure 6 shows the boundary conditions that have been applied to the geometry in a more visual way.

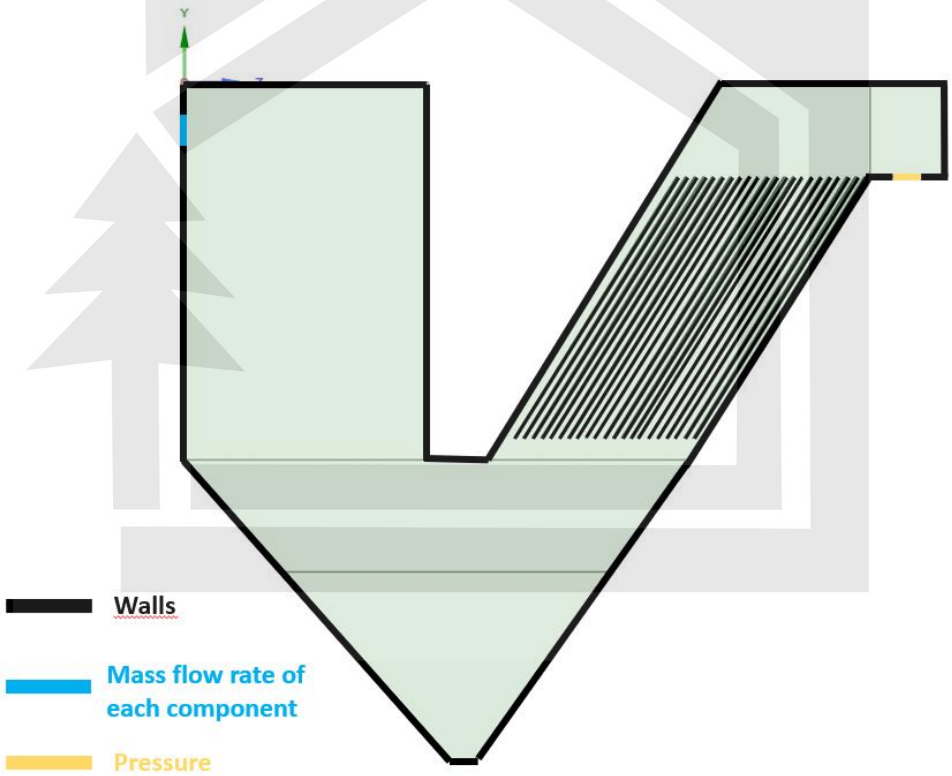


Figure 6. Boundary conditions applied to the problem.

Once the boundary conditions have been set, the equations that will be solved by the software using the previously chosen mixture model will be shown below.

The mixture model solves the continuity equation for the mixture and the momentum equation for the mixture and, in addition, the energy equation, although the latter will not be exposed since temperatures remain constant and there is no heat flow. In short, the Navier-Stokes equations are solved, which are a set of nonlinear partial derivative equations that describes the motion of a viscous fluid. The Navier-Stokes Equations are the most important in fluid dynamics because they can predict the motion of every fluid (Navier, 1838).

The first of the Navier-Stokes Equations is also know as continuity equation. The continuity equation is a mathematical expression of the principle of conservation of mass, which in fluid dynamics is explained as the mass flow rate that goes into the volume will always be the same as the mass come out from the volume plus the rate of mass increase inside the volume (Connor, 2019). The continuity equation solved by Ansys when the mixture model is set is as follows:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0 \quad (1)$$

Where $\vec{v}_m$ is the mass-averaged velocity:

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m} \quad (2)$$

Where the subscript k refers to the phase k and ρ_m is the mixture density:

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \quad (3)$$

With α_k as the volume fraction of phase k.

On the other hand, the momentum equation will also be solved. This equation is a restatement of the Newton's second law and it states that the rate of change in linear momentum of a volume moving with a fluid is equal to the surface forces and the body forces acting on a fluid (Azimi, 2021). The equation is as follows:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m(\nabla \vec{v}_m + \nabla \vec{v}_m{}^T)] + \rho_m \vec{g} + \vec{F} + \nabla \cdot (\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}) \quad (4)$$

Where n is the number of phases, $\vec{F}$ is a body force, μ_m is the viscosity of the mixture:

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \quad (5)$$

$\vec{v}_{dr,k}$ is the drift velocity for secondary phase k:

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \quad (6)$$

Once the equations that will be applied have been described, it is necessary to set a series of parameters that Ansys needs to be able to initialize the simulations and to characterize the substances with which it is working. It is only necessary to give characteristic data of the dissolved ink and the suspended ink, which are the secondary phases, because the data of the water, which is the main phase, is already included in the software. The properties to be set for the secondary phases are: particle diameters, viscosities and densities. These three parameters are the ones that appear in Stokes' Law of sedimentation, which allows determining the particle fall velocity using the following equation:

$$u = (2/9)\frac{(\rho_p - \rho_f)gr^2}{\mu} \quad (7)$$

Where:

- g is the gravitational field strength (m/s^2)
- r is the radius of the spherical particle (m)
- ρ_p is the mass density of the particle (kg/m^3)
- ρ_f is the mass density of the fluid (kg/m^3)
- μ is the dynamic viscosity (kg/m/s)

To arrive at the above equation, it must be assumed that the particles are spherical, there is no interference between them, and they are in a fluid with a laminar flow regime (Shearer & Hudson, 2008).

By studying the Stokes' Law equation in detail, it can be determined that the most influential parameter in the sedimentation velocity of a particle is its diameter, due to the fact that the radius is squared. This is why it will be essential for the simulations to correctly determine the particle diameters of both dissolved and suspended ink.

To demonstrate the importance of this parameter, the base design will be simulated, as an example, with any inlet volumetric flow rate and giving values to the particle diameters of the suspended ink and the suspended ink. For confidentiality reasons the values of the diameters to be tested will not be shown, only the fact that D1<D2<D3<D4 is given. In addition, the particle diameter of the dissolved ink will be considered to be one third of the suspended ink, i.e. if the diameter of the suspended ink is D1, the diameter of the dissolved ink will be D1/3.

The results obtained are shown in the graph in Figure 7 and the MATLAB code is attached in Appendix C.

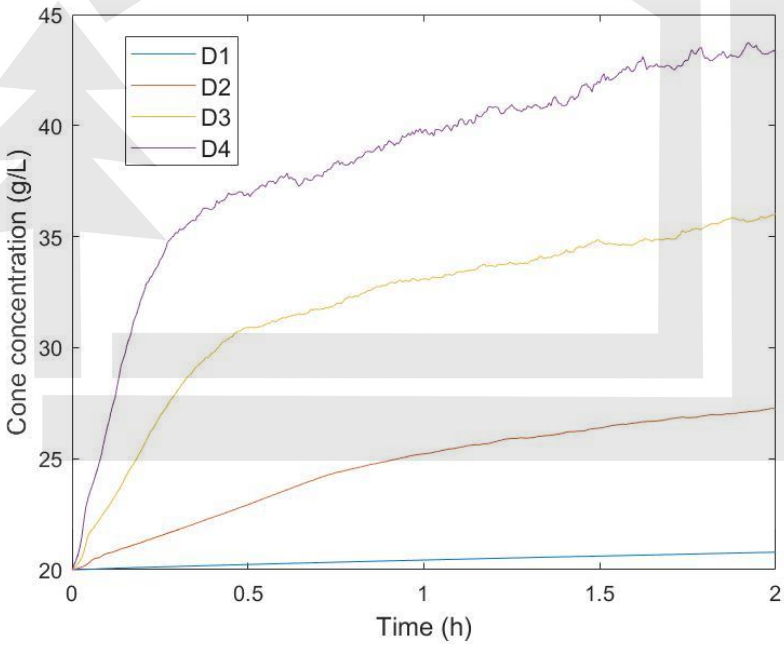


Figure 7. Results of the amount of ink concentrated in the cone for different particle diameters.

In view of the results in Figure 7, it will be possible to greatly increase the amount of ink that is concentrated in the cone when the particle diameter of the suspended ink and the dissolved ink is greater.

Because of that, it would be interesting to try to make the particle diameter as large as possible. A good idea to improve the efficiency of the decanter would be to add flocculant to try to agglomerate both the dissolved and suspended ink particles and, thus, favor decantation.

The other two parameters to be analyzed are densities and viscosities, whose values, also for reasons of confidentiality, will not be shown.

Starting with the density, it will be an important parameter because the speed of fall of the particle will be greater the more difference in densities there is between the particle and the fluid, since the difference $(\rho_p - \rho_f)$, which is in the numerator of the equation, will become greater and, in addition, a greater density will imply a greater gravitational force, which will facilitate the solid-liquid separation process. This is why the vast majority of the ink that sediments is suspended ink, because it has the greatest difference in density with respect to water. However, dissolved ink, having a density very similar to that of water, will be more difficult to separate from water.

Finally, the particle fall velocity will be inversely proportional to the viscosity of the fluid through which the particle flows. A higher viscosity will mean that there is a greater resistance to movement and, therefore, that the sedimentation process is longer, since the particle will take longer to reach the bottom of the equipment. As the main phase is water, which is a Newtonian fluid with a low viscosity, this parameter will not be a problem in the sedimentation process.

4. SENSITIVITY ANALYSIS

This section will present the design variables that have been considered most interesting in order to try to determine which combination of these gives the best value of the dependent variable of interest, which, in this project, as mentioned in the introduction, will be the concentration of ink in the cone.

The design variables that will be combined to achieve the separation of ink and water are as follows:

- Number of lamellae.
- Inlet volumetric flow rate.
- Inclination of the lamellae, as well as their extension.

The sensitivity analysis will be carried out by testing for each design variable a series of values within a realistic range for the operation of the equipment and taking into account the original geometry (see Figure 2). That is why in the present work not all the possibilities that can be given have been considered, but those that have been considered the most relevant.

4.1. NUMBER OF LAMELLAE

One parameter that can strongly influence the decanting is the number of lamellae. It is necessary to remember that the function of the lamellae is to shorten the distance that the particles must travel before settling.

Three different designs of the lamellar settler have been made, with 11 lamellae, 22 lamellae and 44 lamellae, to determine which of them is able to concentrate the most ink in the cone. The design of the geometries is shown in appendix B of this report.

As the design is in 2D, the length of the lamellae is not being considered, but only the height (800 mm) and width (2 mm) are taken into account. Therefore, the particle will have four contact surfaces, the two sides of the height and the two sides of the width.

The contact surface is calculated as follows:

$$Contact\ surface\ (m^2) = height\ of\ the\ lamella\ (m) * width\ of\ the\ lamella\ (m) * number\ of\ lamellae \quad (8)$$

Table 1 shows the contact surface data available with each design. It is a considerable variation, since the difference in contact surface between the design with 11 lamellae and the design of 22 lamellae, as well as the difference between the design with 22 lamellae and the design of 44 lamellae, is 50%, while there is 75% more surface contact when comparing the design with 11 lamellae and the design of 44 lamellae.

Table 1. Contact surface provided by the lamellae depending on the number of these in each design.

Number of lamellae	Contact surface (mm^2)
11	17600
22	35200
44	70400

To make the analysis more rigorous, the three designs were simulated at two different inlet volumetric flow rates (500 L/h and 1500 L/h) to see that the trend of the results is the same regardless of the inlet volumetric flow rate. Figure 8 shows the graphs obtained with MATLAB (the codes used to obtain the results can be found in appendix C).

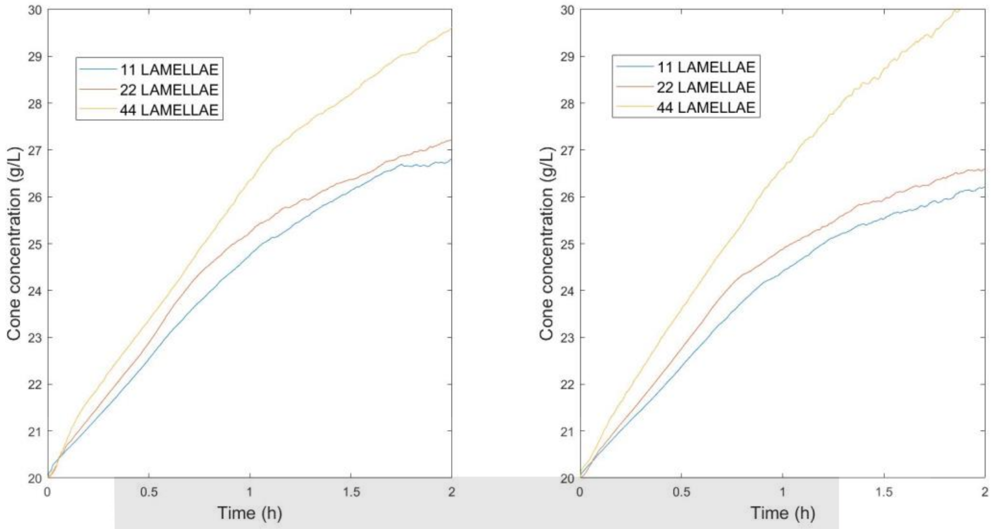


Figure 8. Results of ink concentration on the cone when testing designs with different lamella numbers.

The simulations require a computing time of 2 hours with a computer with six processor cores with the following characteristics:

- PC processor: Intel(R) Xeon(R) W-2235 CPU @3.80GHz 3.79GHz
- Available PC memory: 32.0 GB (31,7 GB usable)

Figure 8 shows that the design of the decanter with 44 lamellae is able to concentrate more ink in the cone than the decanter with 11 and 22 lamellae. In addition, once the results have been obtained, Ansys gives the option, through a post-processor called Ansys CFD-Post, to visualize and analyze the results dynamically. Figures 9, 10 and 11 show screenshots of the volume fraction of the suspended ink in the lamellar decanter for each design after 2 hours of operation. It can be seen visually how with the 11 and 22 lamella designs a similar volume fraction is achieved, while with the 44 lamella design there is a big difference in the amount of suspended ink that has sedimented in the cone.

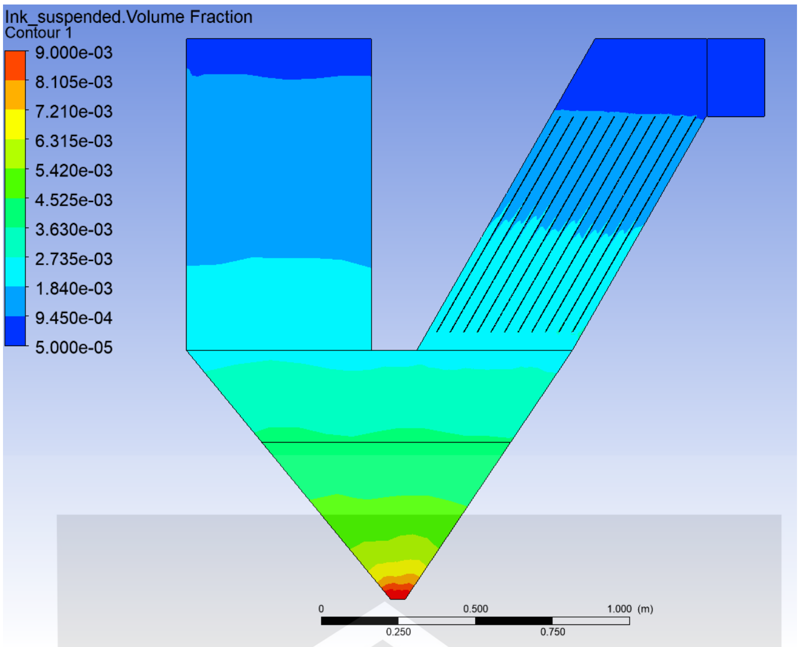


Figure 9. Volume fraction of suspended ink in the design with 11 lamellae at 2 hours of operation.

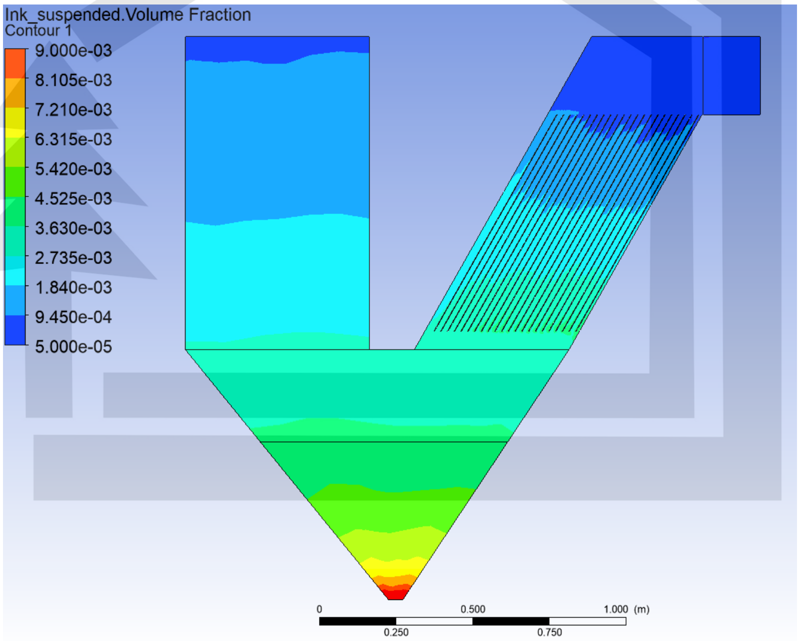


Figure 10. Volume fraction of suspended ink in the design with 22 lamellae at 2 hours of operation.

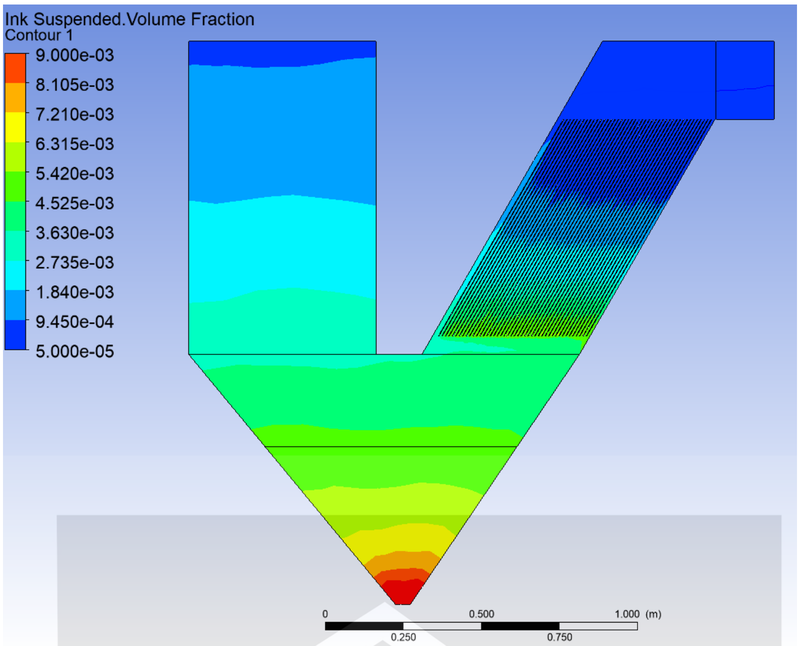


Figure 11. Volume fraction of suspended ink in the design with 44 lamellae at 2 hours of operation.

It should be noted that the results obtained do not conclude that the more lamellae the decanter has, the better, but rather that among these three designs, the one with 44 lamellae is the one that manages to settle more ink. When choosing the number of lamellae, it must be taken into account that there is a minimum recommended distance between lamellae ranging from 2 to 10 cm, with a recommended range of 3 to 5 cm (Gutiérrez & Bueno, 2003).

Therefore, from now on, in order to see how the rest of the parameters are influenced, simulations will be performed only with the design of 44 lamellas.

4.2. INLET VOLUMETRIC FLOW RATE

Another variable that can be controlled and therefore analysed is the inlet volumetric flow rate to the equipment. This parameter is very important for several reasons:

The first is that it is related to the residence time, being inversely proportional. Because of that, this study will give an idea of the average residence time of the mixture in the decanter.

The second and most important reason is that in order to achieve a good separation between the ink and the water, the flow inside the equipment must be as laminar as possible, as the sedimentation operation is highly favoured at low Reynolds (Poh, 1984).

In order to find an inlet volumetric flow rate with which to concentrate more ink in the cone, a consensus was reached with the company on the minimum and maximum feed values that could be provided to the equipment. The intention of setting the operational extremes is that the first simulations will be carried out with the minimum and maximum inlet volumetric flow rates (250 L/h and 1500 L/h) and it will be also tested two completely arbitrary intermediate values (500 L/h and 750 L/h). The objective of this first study is to narrow the range to estimate where the optimum inlet volumetric flow rate could be found.

The results obtained are shown in Figure 12, while the MATLAB code used to obtain the graph is given in appendix C.

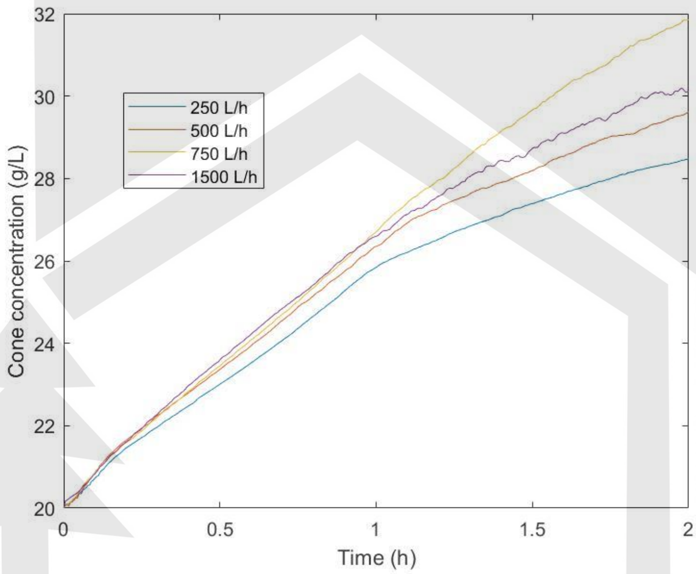


Figure 12. Concentration of ink in the cone obtained for the study of a wide range of inlet volumetric flow rates.

In view of the results, it can be determined that the optimum value of the inlet volumetric flow rate will be above 500 L/h and below 1500 L/h, due to the fact that with a flow rate of 250 L/h worse results are obtained than with a flow rate of 500 L/h and with a flow rate of 1500 L/h worse results are obtained than with a flow rate of 750 L/h. The purpose of the first study has been achieved, which was to limit the range where the optimal inlet volume flow will be found.

Now the following simulations will be carried out in order to try to further narrow what could be the optimum inlet volumetric flow rate. As it has already been confirmed that the optimum will be between 500 L/h and 1500 L/h, the following flow rates will be tested: 600 L/h, 850 L/h, 1000 L/h and 1500 L/h. The results obtained for the flow rates of 750 L/h and 1500 L/h will be plotted together and are the results are shown in Figure 13.

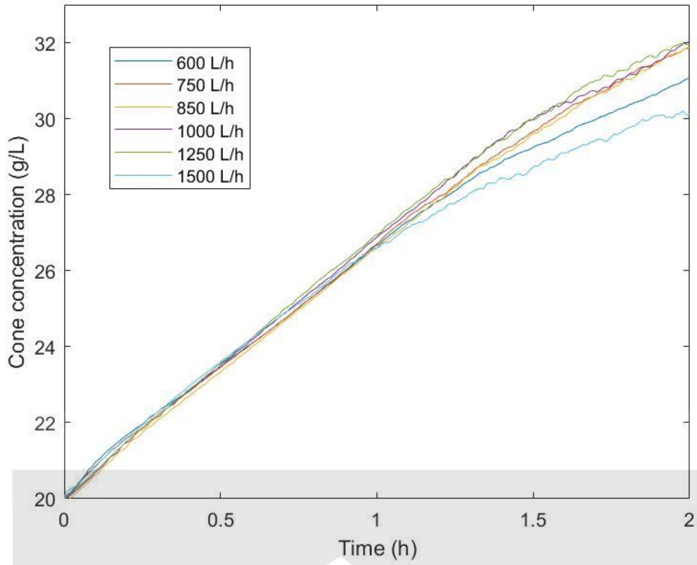


Figure 13. Concentration of ink in the cone obtained for the study of more limited inlet volumetric flow rates.

Visually it is very difficult to draw convincing conclusions from the graph shown in Figure 13. What can be seen is that when the equipment has been in operation for one hour, with practically all the values of inlet volumetric flow rates chosen within the range of study, the same amount of ink will be separated and, after this time, it is true that there are better results with certain flow rates. This is normal, since the sedimentation separation operation is a slow process. However, in order to have a more solid idea, it will be calculated how much the ink concentration in the cone is increased per hour depending on the volumetric flow rate entering the equipment. This will be done considering that the results obtained in the graph of Figure 13 are straight lines and its slope will be calculated, whose value will indicate, in g/L/h, how much the ink concentration in the cone increases per hour.

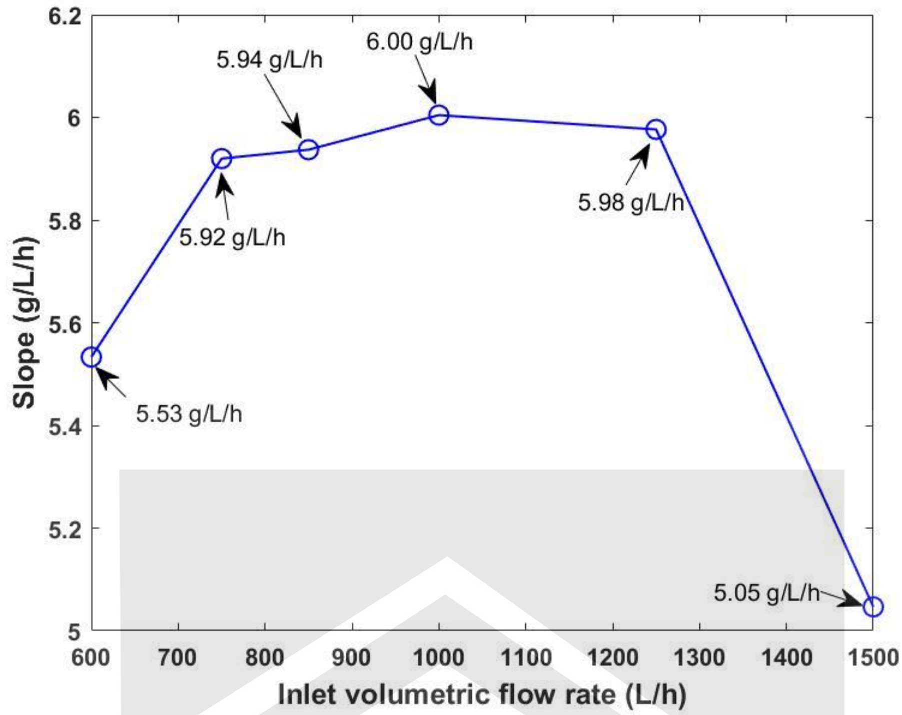


Figure 14. Increase of ink concentration in the cone per hour depending on the inlet volumetric flow rate.

The graph in Figure 14 shows that the best results are obtained with an inlet volumetric flow rate of 1000 L/h, since this is the one that achieves the greatest increase in ink concentration in the cone per hour.

Now it will be calculated what settling efficiency is achieved in the lamellar settler cone when working with the different inlet volumetric flow rates that have been tested. The equation to be used is as follows:

$$Settling\ efficiency\ (\%) = \left(1 - \frac{Initial\ concentration\ in\ the\ cone}{Concentration\ at\ two\ hours\ in\ the\ cone}\right) * 100 \qquad (9)$$

Table 2 shows the efficiency results obtained for each flow rate.

Table 2. Efficiency values obtained for each inlet volumetric flow rate.

Inlet volumetric flow rate (L/h)	Efficiency (%)
250	29,74
500	32,40
600	35,62
750	37,19
850	37,25
1000	37,52
1250	37,41
1500	33,54

In order to concentrate more ink in the cone and, therefore, to achieve a cleaner clarified stream, a volumetric flow rate of 1000 L/h should be introduced at the inlet of the equipment, among all the assumptions that have been simulated.

Finally, a surrogated model will be obtained. The idea of this is to obtain an equation that allows to calculate the efficiency that will be obtained depending on the inlet volumetric flow rate to the equipment, avoiding a simulation and arriving at the result in a more agile way. The scheme of what is sought with the surrogated model is shown in Figure 15.

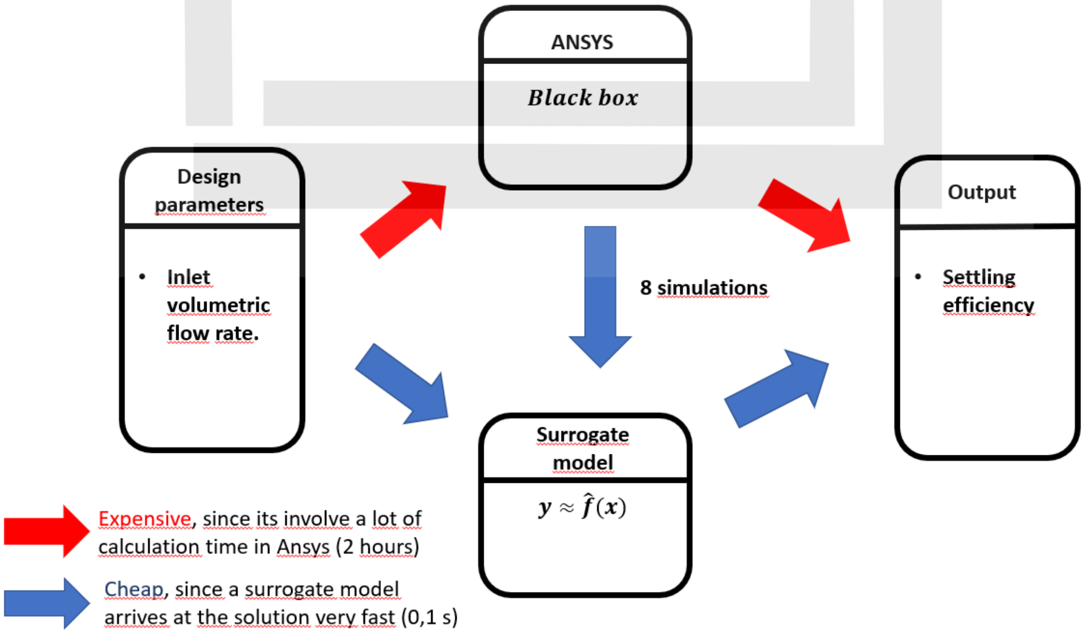


Figure 15. Outline of the benefit of using a surrogate model.

The idea shown in the scheme of Figure 15 is that from the design variables that were set, simulations were performed to obtain values of the dependent variable of interest. Well, by means of a surrogated model, it is possible to avoid these simulations and, directly with an equation, it is possible to estimate the value of the dependent variable, saving all the calculation time that Ansys needs.

This surrogated model has been obtained with the help of the MATLAB cftool function (that an explanation of how this application works is attached in appendix D), which gives the option of finding a mathematical function that reliably reproduces the data obtained from the simulations done in Ansys. The function best suited to the case study is a Gaussian one, whose equation is given below:

$$f(x) = A\, exp\left(-\left(\frac{x-B}{C}\right)^2\right) \tag{10}$$

Where: A = 37,82; B = 1005 L/h; C = 1488 L/h; f(x) in %; x is the inlet volumetric flow rate in L/h.

Figure 16 shows a graph comparing the points obtained from the simulations run in Ansys and the points that would be obtained using the surrogated model equation.

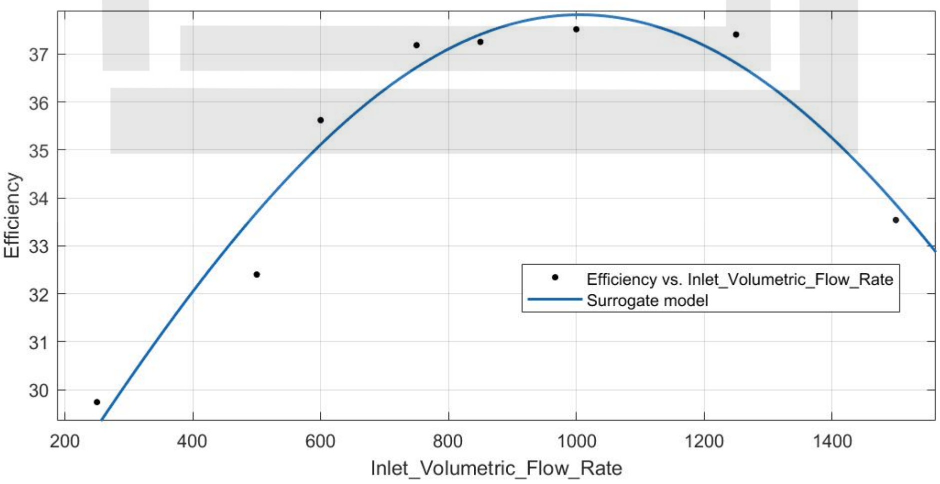


Figure 16. Comparison of the points obtained with the simulations made in Ansys and the points that would be obtained using the surrogated model.

To determine the goodness of fit of the Gaussian function chosen, a graph of the error being made if the surrogated model is used instead of the simulation is shown in Figure 17.

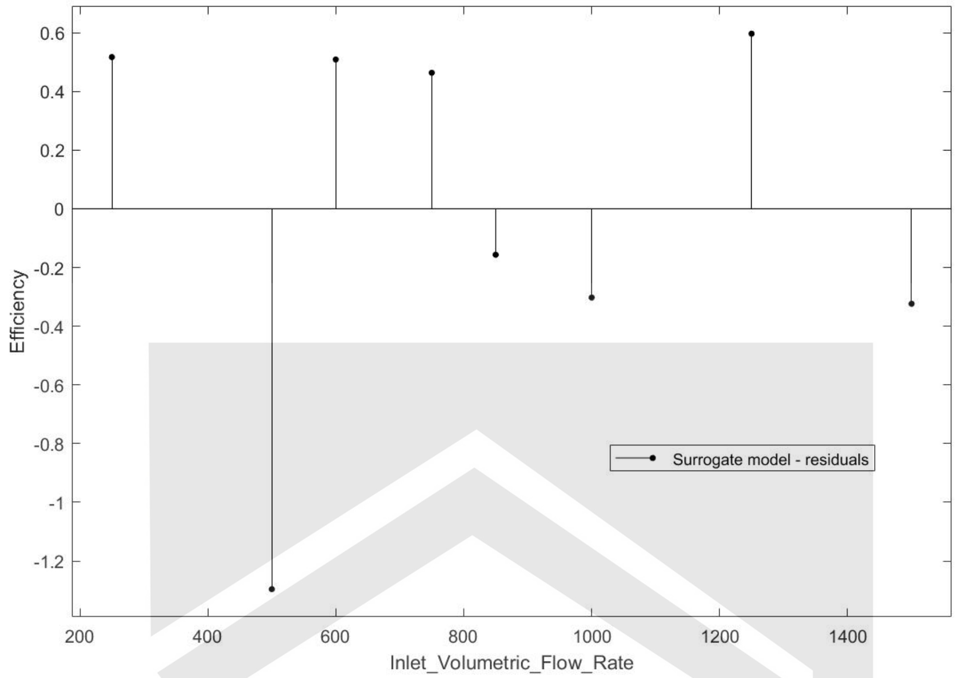


Figure 17. Scale of error committed at each point by using the surrogated model instead of performing the simulation.

4.3. INCLINATION OF THE LAMELLAE

So far, the inclination of the lamellae with respect to the horizontal axis has been 60º. However, it is interesting to study the influence of this parameter in order to determine whether it is possible to concentrate more ink at a given inclination.

Most studies recommend that the angle of the lamellas with respect to the horizontal should be between 45 and 70 degrees (Fouad et al., 2016). In addition, several researchers (Demir, 1995) reported maximum sedimentation efficiency when plates are inclined at an angle of 50º. Therefore, two new models were designed with an inclination of 50 and 70 degrees, since the 60 degrees is the one that has been working with until now. With these degrees of inclination, the flow follows the same direction as the lamellae, which is known as a pro-flow arrangement.

In addition, a new decanter has been designed with a lamella inclination of 120º in order to study the results when the plates are oriented against the flow, that is, the water stream must change its direction to flow through the lamellae. An image of how the design looks with this angle of inclination is attached as appendix B.

In both cases, whether in favour or against the flow, the decanter is working in counterstream because the water and sludge flow in opposite directions.

The results obtained are shown in the Figure 18.

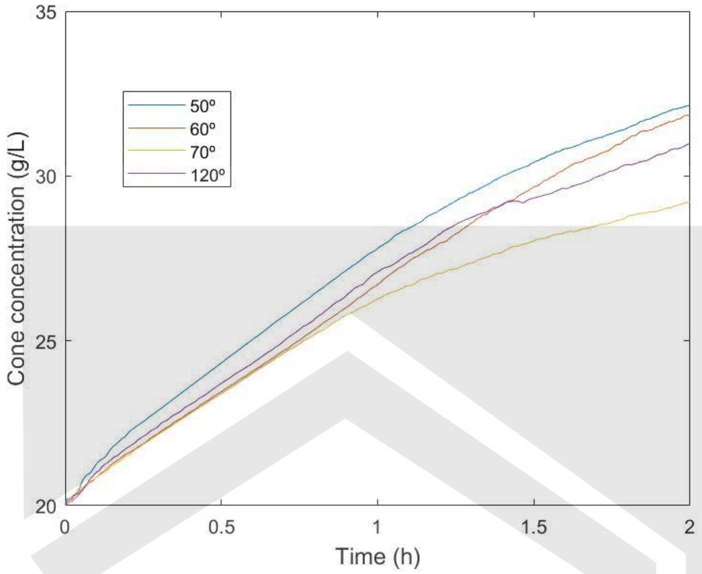


Figure 18. Results obtained for the study of lamellae inclination.

Several conclusions can be drawn from the graph shown in Figure 18.

The first of them is that of the 3 selected angles that provide an arrangement in favor of the flow, it is with the 50 degrees when it is possible to concentrate more ink in the cone. This result reinforces the veracity of the studies from which the idea of varying the inclination was drawn.

On the other hand, it would also be better to have an arrangement of the lamellae in favor of the fluid with an inclination of 50º instead of an arrangement against the fluid, because the results are better than with the 120º design.

Finally, once it was determined, among all the options that have been tested, which design and mode of operation achieved the best results, the Ansys CFD-Post post-processing tool was used to evaluate the fluid flow dynamically. In carrying out this step, it was detected that in the lower zone of the lamellae there was an increase in the velocity of the suspended ink particles, a fact that can cause some turbulence and interfere significantly in the sedimentation process. Figure 19 shows an image of the velocity of the suspended ink in the decanter after two hours of operation.

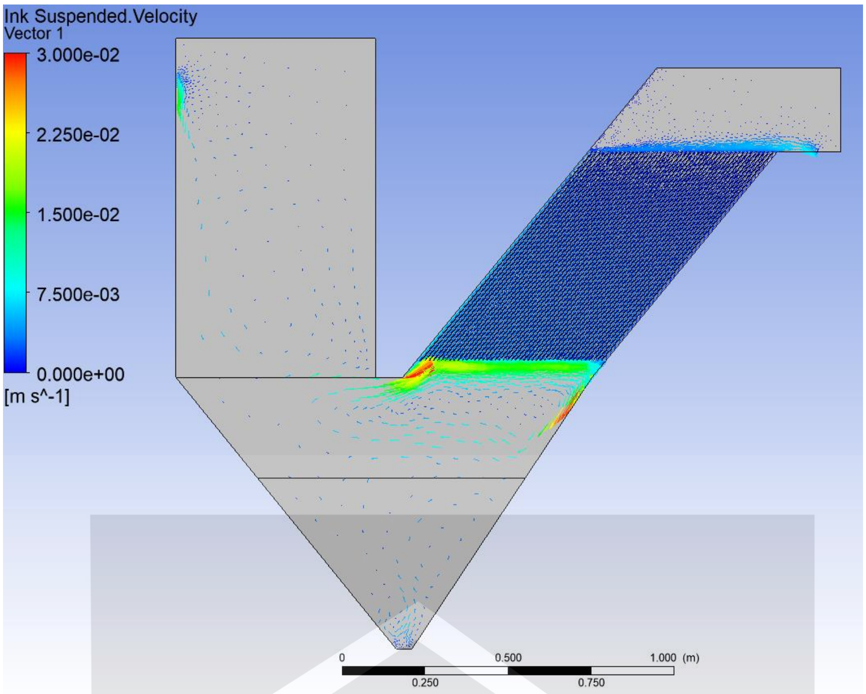


Figure 19. Suspended ink velocity when the equipment has been running for two hours with a lamella height of 800 mm.

In order to try to correct this increase in suspended ink velocity, it is considered that a solution could be to extend the lamellae by 50 mm, as this would not cause any problems when constructing the real equipment.

Once the lamellae were extended, the dynamic study was carried out again and the results obtained can be seen in the Figure 20.

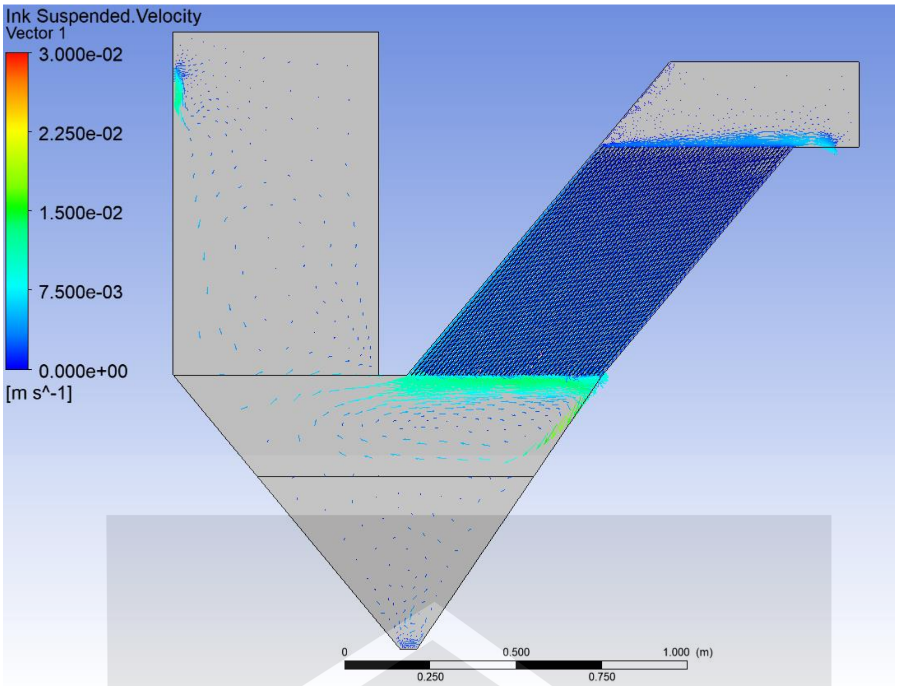


Figure 20. Suspended ink velocity after two hours of operation with extended lamella design.

It can be clearly seen how the velocity of the ink suspended in the lower part of the lamellae has been reduced, i.e., the objective sought with the new design has been achieved.

Therefore, after the sensitivity analysis carried out, the best solution found would be a lamellar settler with 44 lamellae, inclined at 50º and extended 50 mm more than the original design, with an inlet volumetric flow rate of 1000 L/h.

5. CONCLUSIONS

After studying the design and mode of operation of a lamellar decanter to be integrated into a water treatment system of a plastics recycling company, a series of conclusions can be drawn:

If computational fluid dynamics is used to perform the fluid flow analysis, the most time-consuming part is the pre-processing. This happens because, first of all, the geometry must be discretized and then the physical models to be used by the program and the boundary conditions must be set. Therefore, as the idea is that the simulations reproduce what really happens in the industrial plant, it is necessary to have as much information as possible to configure the program set up as best as possible. Once the pre-processing stage is finished, the calculations and the examination of the obtained results take place.

By exporting the results obtained in Ansys to the MATLAB program, the results of several simulations can be represented in a single graph. This has allowed a sensitivity analysis to determine that the best solution when studying the number of lamellae would be to put 44 of them, since it will be possible to concentrate more ink in the cone.

It was then shown that the inlet volumetric flow rate that gives the best results is 1000 L/h and that it achieves a settling efficiency of 37.52%. In addition, with equation 10 it is possible to estimate this settling efficiency without having to perform the simulations because a surrogated model was obtained.

In the last step, it was found that the results are improved with an orientation of the lamellae in favor of the flow, with an inclination of 50 degrees above the horizontal, and that it is recommended that the lamellae be extended by 850 mm to avoid the formation of turbulence that could affect the sedimentation process.

Finally, the study could continue if an economic analysis is carried out to see if it is profitable to add this lamellar clarifier not only to improve the quality of the water returning to the system but also to calculate how long it would take to amortize the equipment.

APPENDIXES

Appendix A. Decanter meshing.

In order to apply the finite volume method, it is necessary that the domain is discretized. For this purpose, the geometry will be divided into small control volumes (also called cells)

Meshing the geometry well is one of the most time-consuming steps of the pre-processing stage, because the mesh quality must be adequate to obtain reliable results. However, the more accurate the meshing is, the more computational time the program will need to reach a solution, so a balance must be found between mesh quality and computational time consumed by the program.

In this case, as it is of interest to have a greater detail in the area of the lamellae, as well as in the inlet and outlet of the equipment, a more precise meshing will be determined in these parts.

Figure 21 shows the result of one of the meshed geometries. In this figure it is clearly seen how, in the places where a more precise meshing has been chosen, more cells are detected.

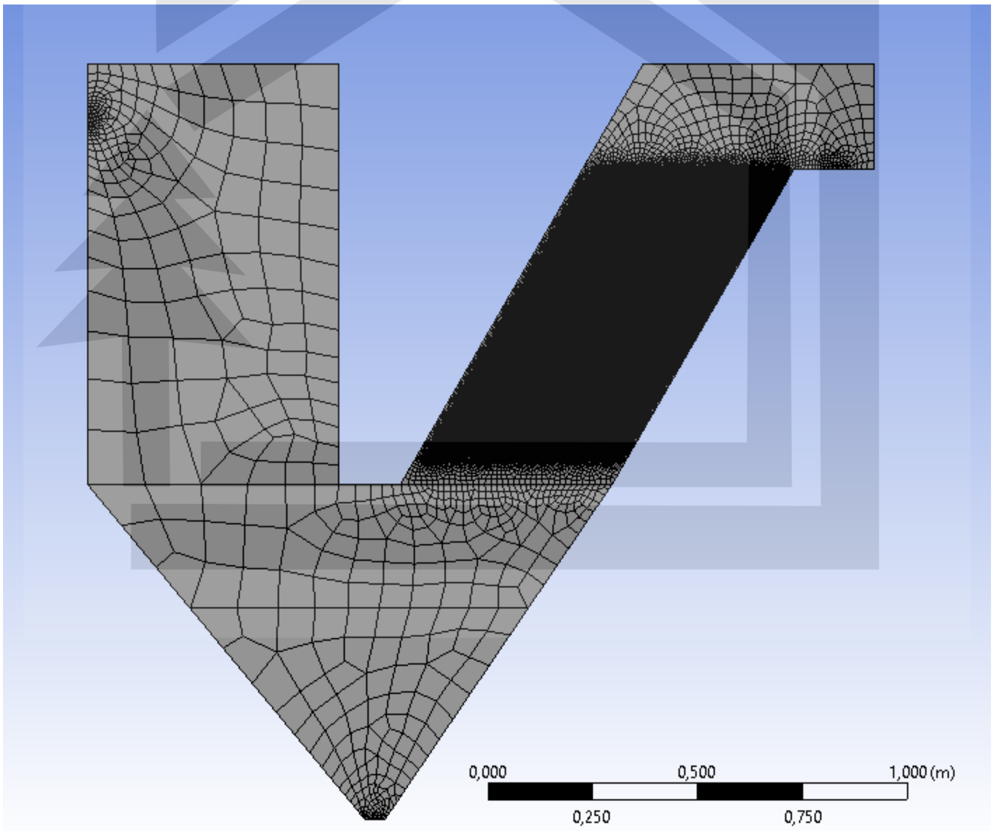


Figure 21. Result of the domain after the meshing is done.

Appendix B. Lamellar decanter designs.

This appendix shows the different designs that have been used to carry out the different analyses.

First of all, Figure 22 shows the base design in three dimensions from which a cut was made to obtain the 2D designs. This design was made by a company specialized in this type of equipment.

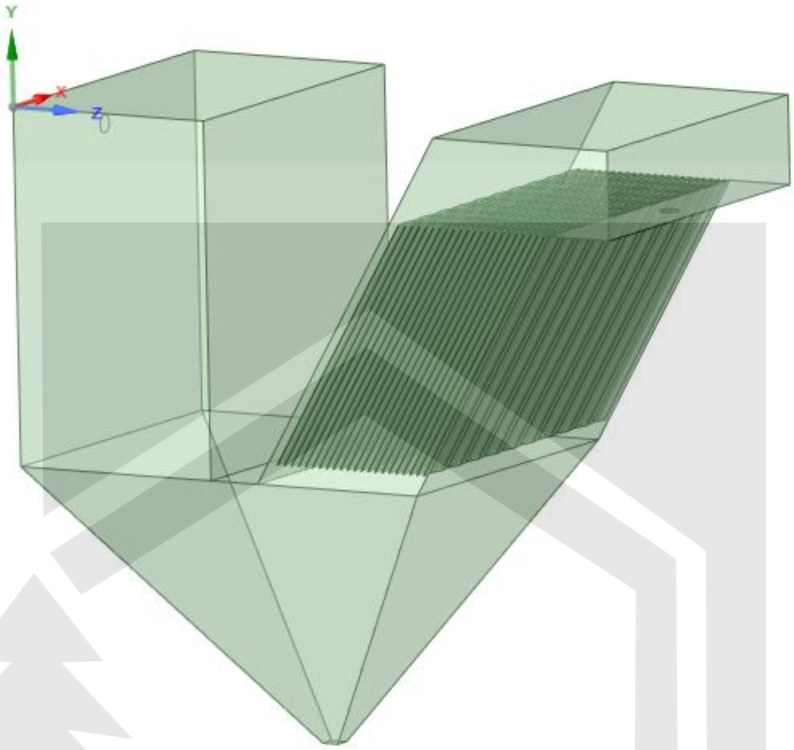


Figure 22. Design of the 3D lamellar decanter that was provided by a company specialized in this type of equipment.

Next, in the Figures 23, 24 and 25 the designs, already in two dimensions, of the lamellar decanters with different numbers of lamellae are included.

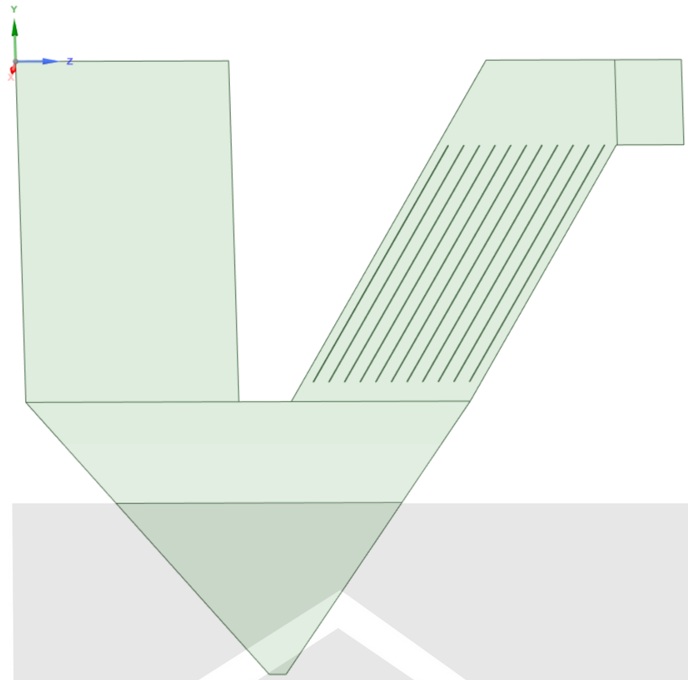


Figure 23. Decanter design with 11 lamellae.

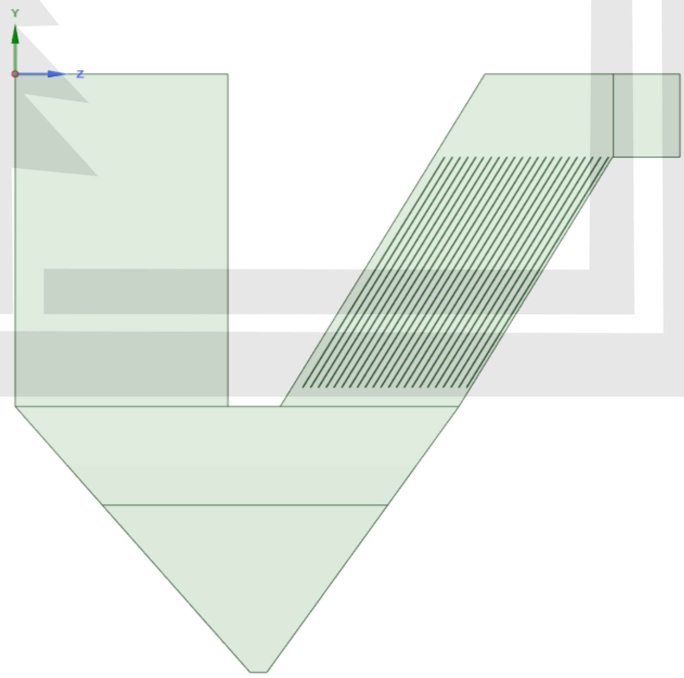


Figure 24. Decanter design with 22 lamellae.

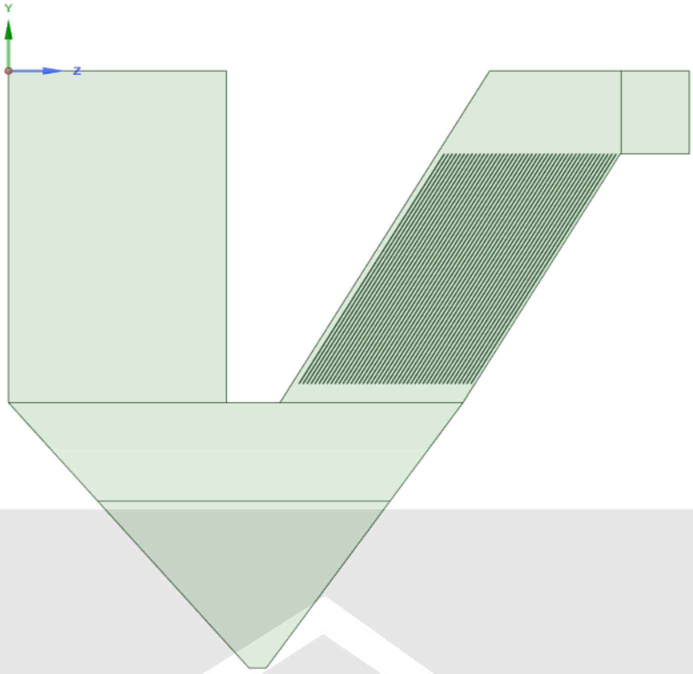


Figure 25. Decanter design with 44 lamellae.

Finally, the design of the decanter with the lamellae inclined at 120 degrees is included and shown in Figure 26. This arrangement ensures that the plates are oriented against the flow.

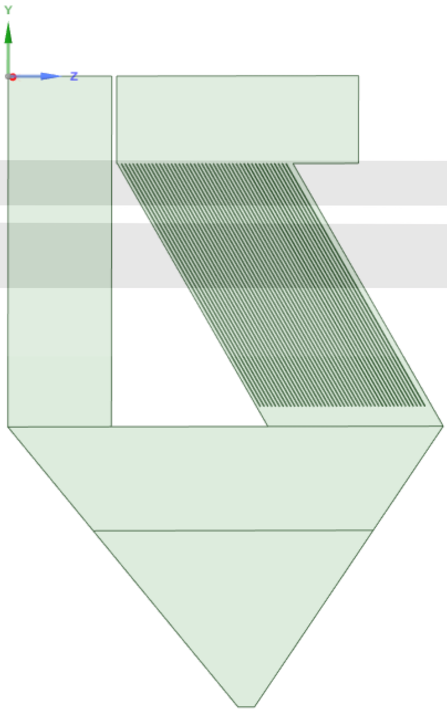


Figure 26. Decanter design with the lamellae oriented 120º, which causes the plates to be oriented against the flow.

Appendix C. MATLAB codes.

This section will present all the MATLAB codes developed for the purpose of performing the sensitivity analysis and calculating the settling efficiency. In addition, the script used to justify the importance of the particle diameter will be presented.

The data imported into MATLAB from Ansys Fluent has a dimension of 400 rows and 3 columns, so the data matrix has been replaced by ellipses inside the square brackets: […].

C.1. Code to justify the importance of particle diameter.

```
%%-----------------------PARTICLE DIAMETER---------------------%%
%--D1<D2<D3<D4
%--22 LAMELLAS, 60°
%--Q = 500 L/h


clear all ; clc


%% RESULTS IMPORTED FROM ANSYS FLUENT
% As the matrices consist of at least 800 rows, they shall be simplified with
ellipses.
% The first column of the matrix is the iteration number.
% The second column of the matrix is the ink concentration value in the cone
(in g/L).
% The third column of the matrix is the time value (in seconds).


RESULTS_CONE_D1 = [...];


RESULTS_CONE_D2 = [...];


RESULTS_CONE_D3 = [...];


RESULTS_CONE_D4 = [...];






%% DATA EXTRACTION


concentration_cone_D1 = RESULTS_CONE_D1(:,2); %g/L
time_cone_D1          = RESULTS_CONE_D1(:,3); %s
```

```
concentration_cone_D2 = RESULTS_CONE_D2(:,2); %g/L
time_cone_D2          = RESULTS_CONE_D2(:,3); %s


concentration_cone_D3 = RESULTS_CONE_D3(:,2); %g/L
time_cone_D3          = RESULTS_CONE_D3(:,3); %s


concentration_cone_D4 = RESULTS_CONE_D4(:,2); %g/L
time_cone_D4          = RESULTS_CONE_D4(:,3); %s



%%PLOTS


figure (1)


plot(time_cone_D1/3600,concentration_cone_D1)
axis([0 2 20 45])
xlabel('Time (h)','Fontsize',12)
ylabel('Cone concentration (g/L)','Fontsize',12)


hold on


plot(time_cone_D2/3600,concentration_cone_D2)
plot(time_cone_D3/3600,concentration_cone_D3)
plot(time_cone_D4/3600,concentration_cone_D4)


hold off


legend('D1','D2','D3','D4','Fontsize',11)
```

C.2. Code for determining the number of lamellae.

```
%%-----------------------NUMBER OF LAMELLAE--------------------%%
%-Q1 = 500 L/h; Q2 = 1500 L/h--%


clear all ; clc


%% RESULTS IMPORTED FROM ANSYS FLUENT
% As the matrices consist of at least 400 rows, they shall be simplified with
ellipses.
% The first column of the matrix is the iteration number.
% The second column of the matrix is the ink concentration value in the cone
(in g/L).
% The third column of the matrix is the time value (in seconds).



RESULTS_CONE_11_LAMELLAE_Q1 = [...];


RESULTS_CONE_11_LAMELLAE_Q2 = [...];


RESULTS_CONE_22_LAMELLAE_Q1 = [...];


RESULTS_CONE_22_LAMELLAE_Q2 = [...];


RESULTS_CONE_44_LAMELLAE_Q1 = [...];


RESULTS_CONE_44_LAMELLAE_Q2 = [...];



%% DATA EXTRACTION


concentration_cone_11_LAMELLAE_Q1 = RESULTS_CONE_11_LAMELLAE_Q1(:,2); % g/L
time_cone_11_LAMELLAE_Q1          = RESULTS_CONE_11_LAMELLAE_Q1(:,3); % s




concentration_cone_11_LAMELLAE_Q2 = RESULTS_CONE_11_LAMELLAE_Q2(:,2); %g/L
time_cone_11_LAMELLAE_Q2          = RESULTS_CONE_11_LAMELLAE_Q2(:,3); %s
```

```
concentration_cone_22_LAMELLAE_Q1 = RESULTS_CONE_22_LAMELLAE_Q1(:,2); %g/L
time_cone_22_LAMELLAE_Q1          = RESULTS_CONE_22_LAMELLAE_Q1(:,3); %s



concentration_cone_22_LAMELLAE_Q2 = RESULTS_CONE_22_LAMELLAE_Q2(:,2); %g/L
time_cone_22_LAMELLAE_Q2          = RESULTS_CONE_22_LAMELLAE_Q2(:,3); %s


concentration_cone_44_LAMELLAE_Q1 = RESULTS_CONE_44_LAMELLAE_Q1(:,2); %g/L
time_cone_44_LAMELLAE_Q1          = RESULTS_CONE_44_LAMELLAE_Q1(:,3); %s



concentration_cone_44_LAMELLAE_Q2 = RESULTS_CONE_44_LAMELLAE_Q2(:,2); %g/L
time_cone_44_LAMELLAE_Q2          = RESULTS_CONE_44_LAMELLAE_Q2(:,3); %g/L



%%PLOTS


figure (1)


plot(time_cone_11_LAMELLAE_Q1/3600,concentration_cone_11_LAMELLAE_Q1)
axis([0 2 20 31])
xlabel('Time (h)','Fontsize',12)
ylabel('Cone concentration (g/L)','Fontsize',12)


hold on


plot(time_cone_22_LAMELLAE_Q1/3600,concentration_cone_22_LAMELLAE_Q1)
plot(time_cone_44_LAMELLAE_Q1/3600,concentration_cone_44_LAMELLAE_Q1)



hold off


legend('11 LAMELLAE','22 LAMELLAE','44 LAMELLAE')


figure(2)


plot(time_cone_11_LAMELLAE_Q2/3600,concentration_cone_11_LAMELLAE_Q2)
```

```
axis([0 2 20 31])
xlabel('Time (h)','Fontsize',12)
ylabel('Cone concentration (g/L)','Fontsize',12)

hold on

plot(time_cone_22_LAMELLAE_Q2/3600,concentration_cone_22_LAMELLAE_Q2)
plot(time_cone_44_LAMELLAE_Q2/3600,concentration_cone_44_LAMELLAE_Q2)


hold off

legend('11 LAMELLAE','22 LAMELLAE','44 LAMELLAE')
```

C.3. Code for determining the inlet volumetric flow rate.

The following script was carried out in order to determine, among the possible minimum and maximum volumetric input flows that the company is able to provide to the decanter, where the optimal could be located to, later, make a more detailed study.

```
%%------------------------INLET VOLUMETRIC FLOW RATE----------------------%%
%-Q1 = 250 L/h; Q2 = 500 L/h; Q3 = 750 L/h; Q4 = 1500 L/h
%-44 Lamellae

clear all ; clc

%% RESULTS IMPORTED FROM ANSYS FLUENT
% As the matrices consist of at least 400 rows, they shall be simplified with
ellipses.
% The first column of the matrix is the iteration number.
% The second column of the matrix is the ink concentration value in the cone
(in g/L).
% The third column of the matrix is the time value (in seconds).

RESULTS_CONE_Q1 = [...];

RESULTS_CONE_Q2 = [...];

RESULTS_CONE_Q3 = [...];
```

```
RESULTS_CONE_Q4 = [...];

%% DATA EXTRACTION

concentration_cone_Q1 = RESULTS_CONE_Q1(:,2); % g/L
time_cone_Q1          = RESULTS_CONE_Q1(:,3); % s



concentration_cone_Q2 = RESULTS_CONE_Q2(:,2); %g/L
time_cone_Q2          = RESULTS_CONE_Q2(:,3); %s



concentration_cone_Q3 = RESULTS_CONE_Q3(:,2); %g/L
time_cone_Q3          = RESULTS_CONE_Q3(:,3); %s



concentration_cone_Q4 = RESULTS_CONE_Q4(:,2); %g/L
time_cone_Q4          = RESULTS_CONE_Q4(:,3); %s



%% PLOTS

figure (1)

plot(time_cone_Q1/3600,concentration_cone_Q1)
axis([0 2 20 32])
xlabel('Time (h)')
ylabel('Cone concentration (g/L)')

hold on

plot(time_cone_Q2/3600,concentration_cone_Q2)
plot(time_cone_Q3/3600,concentration_cone_Q3)
plot(time_cone_Q4/3600,concentration_cone_Q4)

hold off

legend('250 L/h','500 L/h','750 L/h','1500 L/h')
```

In this second script, other flow rates closer to where the optimum could be found were used. In addition, the calculation of the efficiency was included, as well as the calculation of the slope of each flow rate (considering that the results obtained can be approximated to straight lines) to have an idea of the increase of ink concentration in the cone per hour.

```
%%-----------------------INLET VOLUMETRIC FLOW RATE---------------------%%
%-Q1 = 600 L/h; Q2 = 750 L/h; Q3 = 850 L/h; Q4 = 1000 L/h; Q5 = 1250 L/h; Q6 =
1500 L/h
%-44 Lamellae


clear all ; clc


%% RESULTS IMPORTED FROM ANSYS FLUENT
% As the matrices consist of at least 400 rows, they shall be simplified with
ellipses.
% The first column of the matrix is the iteration number.
% The second column of the matrix is the ink concentration value in the cone
(in g/L).
% The third column of the matrix is the time value (in seconds).


RESULTS_CONE_Q1 = [...];


RESULTS_CONE_Q2 = [...];


RESULTS_CONE_Q3 = [...];


RESULTS_CONE_Q4 = [...];


RESULTS_CONE_Q5 = [...];


RESULTS_CONE_Q6 = [...];


%% DATA EXTRACTION


concentration_cone_Q1 = RESULTS_CONE_Q1(:,2); % g/L
time_cone_Q1          = RESULTS_CONE_Q1(:,3); % s
```

```
concentration_cone_Q2 = RESULTS_CONE_Q2(:,2); %g/L
time_cone_Q2          = RESULTS_CONE_Q2(:,3); %s



concentration_cone_Q3 = RESULTS_CONE_Q3(:,2); %g/L
time_cone_Q3          = RESULTS_CONE_Q3(:,3); %s



concentration_cone_Q4 = RESULTS_CONE_Q4(:,2); %g/L
time_cone_Q4          = RESULTS_CONE_Q4(:,3); %s



concentration_cone_Q5 = RESULTS_CONE_Q5(:,2); %g/L
time_cone_Q5          = RESULTS_CONE_Q5(:,3); %s



concentration_cone_Q6 = RESULTS_CONE_Q6(:,2); %g/L
time_cone_Q6          = RESULTS_CONE_Q6(:,3); %s

%% EFFICIENCY AND SLOPE

efficiency_Q1 = (1-(RESULTS_CONE_Q1(1,2)/RESULTS_CONE_Q1(360,2)))*100
efficiency_Q2 = (1-(RESULTS_CONE_Q2(1,2)/RESULTS_CONE_Q2(360,2)))*100
efficiency_Q3 = (1-(RESULTS_CONE_Q3(1,2)/RESULTS_CONE_Q3(360,2)))*100
efficiency_Q4 = (1-(RESULTS_CONE_Q4(1,2)/RESULTS_CONE_Q4(360,2)))*100
efficiency_Q5 = (1-(RESULTS_CONE_Q5(1,2)/RESULTS_CONE_Q5(360,2)))*100
efficiency_Q6 = (1-(RESULTS_CONE_Q6(1,2)/RESULTS_CONE_Q6(360,2)))*100
slope_Q1      = (RESULTS_CONE_Q1(360,2)-RESULTS_CONE_Q1(1,2))/2;
slope_Q2      = (RESULTS_CONE_Q2(360,2)-RESULTS_CONE_Q2(1,2))/2;
slope_Q3      = (RESULTS_CONE_Q3(360,2)-RESULTS_CONE_Q3(1,2))/2;
slope_Q4      = (RESULTS_CONE_Q4(360,2)-RESULTS_CONE_Q4(1,2))/2;
slope_Q5      = (RESULTS_CONE_Q5(360,2)-RESULTS_CONE_Q5(1,2))/2;
slope_Q6      = (RESULTS_CONE_Q6(360,2)-RESULTS_CONE_Q6(1,2))/2;



VolumetricFlowRate     = [600 750 850 1000 1250 1500];
efficiency_global = [efficiency_Q1 efficiency_Q2 efficiency_Q3 efficiency_Q4
efficiency_Q5 efficiency_Q6];
slope              = [slope_Q1 slope_Q2 slope_Q3 slope_Q4 slope_Q5 slope_Q6]
```

```
%% PLOTS

figure (1)

plot(time_cone_Q1/3600,concentration_cone_Q1)
axis([0 2 20 33])
title('INLET VOLUMETRIC FLOW RATE')
xlabel('Time (h)')
ylabel('Cone concentration (g/L)')

hold on

plot(time_cone_Q2/3600,concentration_cone_Q2)
plot(time_cone_Q3/3600,concentration_cone_Q3)
plot(time_cone_Q4/3600,concentration_cone_Q4)
plot(time_cone_Q5/3600,concentration_cone_Q5)
plot(time_cone_Q6/3600,concentration_cone_Q6)

hold off

legend('600 L/h','750 L/h','850 L/h','1000 L/h','1250 L/h','1500 L/h')

figure(2)
plot(VolumetricFlowRate,slope,':o')
xlabel('Inlet volumetric flow rate (L/h)')
ylabel('Slope (g/L/h)')
```

C.4. Code for determining the inclination of the lamellae.

```
%%-----------------------INCLINATION OF LAMELLAE---------------------%%
%-Q = 1000 L/h
%-44 Lamellae

clear all ; clc

%% RESULTS IMPORTED FROM ANSYS FLUENT
% As the matrices consist of at least 400 rows, they shall be simplified with
ellipses.
% The first column of the matrix is the iteration number.
% The second column of the matrix is the ink concentration value in the cone
(in g/L).
% The third column of the matrix is the time value (in seconds).
```

```
RESULTS_CONE_60 = [...];

RESULTS_CONE_50 = [...];

RESULTS_CONE_70 = [...];

RESULTS_CONE_120 = [...];

%%PLOTS

concentration_cone_60 = RESULTS_CONE_60(:,2);
time_cone_60          = RESULTS_CONE_60(:,3);

concentration_cone_50 = RESULTS_CONE_50(:,2);
time_cone_50          = RESULTS_CONE_50(:,3);

concentration_cone_70 = RESULTS_CONE_70(:,2);
time_cone_70          = RESULTS_CONE_70(:,3);

concentration_cone_120 = RESULTS_CONE_120(:,2);
time_cone_120          = RESULTS_CONE_120(:,3);

figure (1)

plot(time_cone_50/3600,concentration_cone_50)
axis([0 2 20 35])
xlabel('Time (h)','Fontsize',12)
ylabel('Cone concentration (g/L)','Fontsize',12)

hold on

plot(time_cone_60/3600,concentration_cone_60)
plot(time_cone_70/3600,concentration_cone_70)
plot(time_cone_120/3600,concentration_cone_120)
```

```
hold off

legend('50°','60°','70°','120°')
```

Appendix D. Explanation of the cftool function.

MATLAB gives the user the option of fitting curves and surfaces to data and viewing graphs. This is possible thanks to an application that has the platform integrated for all versions equal to or greater than MATLAB R2006a, called Curve Fitting.

This toolbox can be opened by entering in the command window the function cftool, which when executed leads to an interface like the one shown in Figure 27.

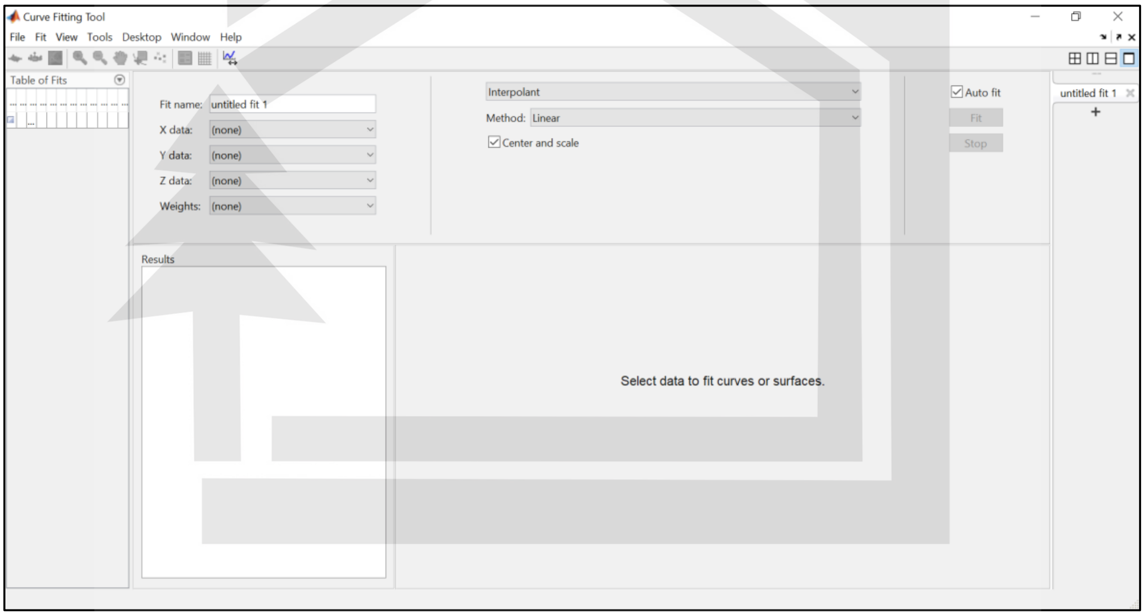


Figure 27. Curve Fitting application interface.

The Curve Fittting application allows you to select which data you want to represent, giving you the option to have 2D and 3D graphics. In addition, it allows you to delete outliers, as well as interpolate or extrapolate data.

Subsequently, one can study which model is the best fit to the data. You can choose from the following fit models: polynomial, exponential, Fourier series, Gaussian models, power series, rational, sum of sines and Weibull distribution. Once the model that best fits the data has been chosen, this tool provides the equation of that model.

You also have the option to see the goodness of fit, know the residual values and know the confidence intervals.

Finally, it is possible to generate a code automatically and save it to recreate the settings and graphs in order to work with them from the MATLAB editor.

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