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Optimization of the thickening process of microalgae biomass produced in wastewater

TREBALL FINAL DE MÀSTER

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Abstract

The present work was developed as a part of the EU project “INCOVER-Eco-innovative technologies for the recovery of resources from wastewater". Within this project a pilot plant was constructed in Agropolis UPC Campus, in Viladecans, Barcelona, which is based on the microalgae production from wastewaters for bioproducts and bioenergy generation. One of the main challenges of microalgae production at full-scale is harvesting and thickening of biomass at a low cost. Gravity sedimentation and thickening are most suitable options because their low energy requirements.

The main objective of this Master theses is, therefore, to evaluate and improve gravity thickening of the biomass produced in the pilot plant. The final milestone was to reach a 2% total solids (TS) concentration (from an initial value of 0,2 % TS) in the thickened biomass.

The research work was basically conducted on two types of measurements, stove drying and vacuum filtration, through which the percentage of total solids concentrations of the thickened biomass and of the supernatants flows were analyzed.
Moreover, four sampling campaigns were carried out in order to compare different operations performance.

Initially the analyses were realized during the operation of a single thickener equipped with a stirrer. These measurements were made in the period from 21th to 28th February, 2018.
By comparing the concentrations of TS present in the inlet flow coming from the settler with the TS purged by the thickener, the latter had thickened the biomass up to a value of 0.755% for the day 26th February.
The second period was characterized by the installation of a new thickener to test a series operation. The days of this stage were from 7th to 11th March, 2018. Thanks to this choice the hydraulic impact that the incoming flow caused on the thickened biomass was reduced and the retention time in the first thickener increased. The analysis conducted showed that the first thickener achieved a 0.936% of TS while the second a 1,217% of TS.
The thickening of the microalgae biomass can also increase with the elimination of algae adhering to the wall of the thickener (third period). For this reason, another stirrer was installed in the second thickener to understand how this could affect the results. During the period from 14th to 27th

March, 2018, the second thickener, in fact, reached a TS concentration of 1.28% with a thickened of 0.67% more than the first.

Finally, from 3rd to 17th April we had obtained an optimal thickening value due to the change of the operation time of the two stirrers (fourth period). In fact, a TS percentage of 2.65 from the second thickener has been attained, which exceeds, with a better performance, the percentage required by the main objective.

As regards the percentage of solids analyzed by the filtration of the supernatant, it was concluded that the values obtained were irrelevant for the purpose of the objective since the highest value achieved was 0.0219% of the TS lost by the first thickener.

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1. Introduction

This study illustrates the work carried out during an analysis within 4 months at a wastewater plant installed in the UPC Agrópolis campus, located in the municipality of Viladecans, Barcelona, for the European project INCOVER.

The plant is made up of three horizontal photobioreactors (PBRs) of 10 m^3 each and it produces around 2 kg per day of microalgae biomass, mostly dominated by cyanobacteria, that is harvested in a lamella settler. The biomass harvested is treated together with secondary sewage sludge in an anaerobic digester of 800 L which currently produces around 100 L of biogas per day.

The anaerobic digester produced 22.5 L d^{-1} of sludge that is subsequently treated in a sludge treatment wetland, while the water coming from the settler (6 m^3 d^{-1}) is disinfected by a solar-driven system based on ultrafiltration and then treated in nutrients recovery columns based in sol-gel coating. Resulting effluent is applied for irrigation in an 80 m^2 field planted with rapeseed.

In this study, we focused on the analysis of the functioning of the gravity thickener present in this plant. In figure 1, it is possible to see where the thickener is situated compare to the different areas that are part of the project.

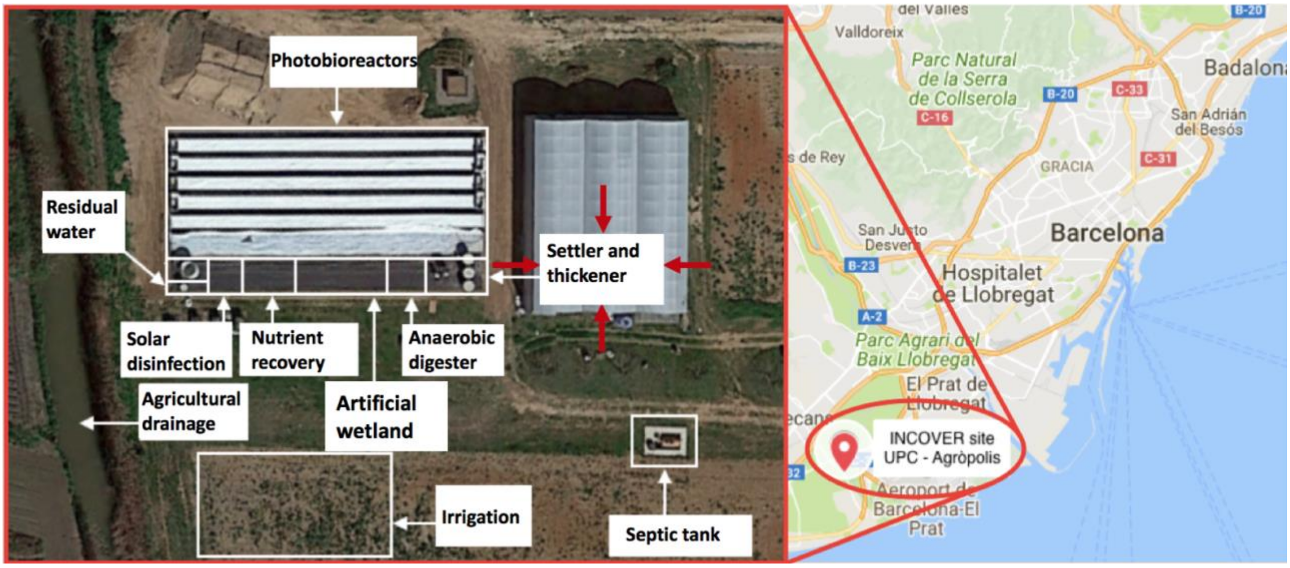


***Figure 1**: Location of the project INCOVER with respect to Barcelona and the different areas which are part of the project.*

Instead, the diagram below (Fig. 2) represents where the thickening phase is located in the flow process.

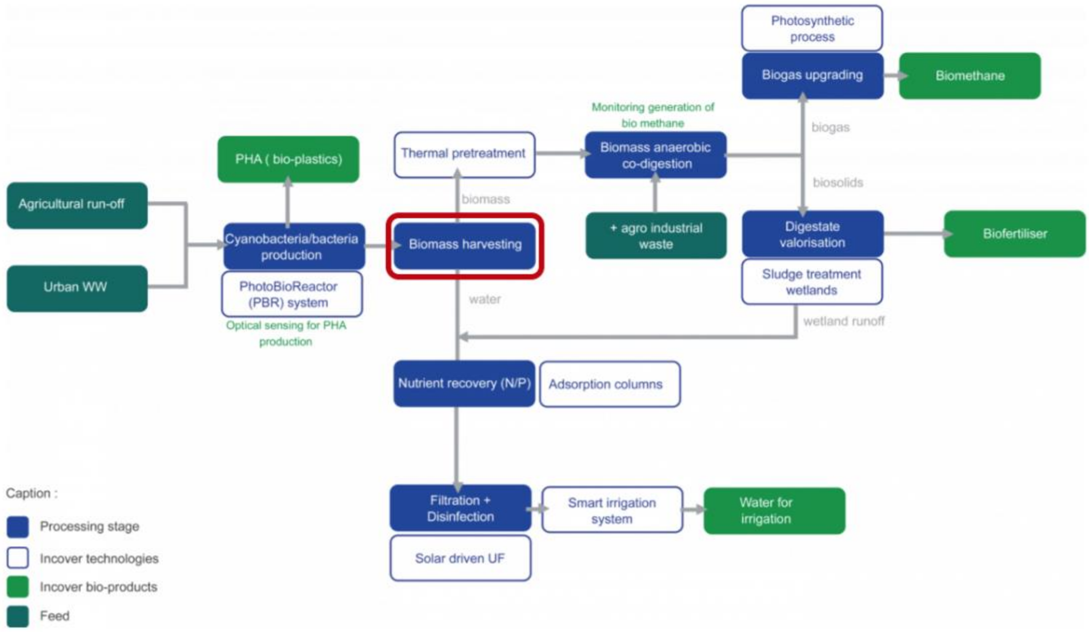


***Figure 2**: Flowchart of the process present in the INCOVER project in Viladecans, Barcelona.*

The thickening of solids from water is an important physical process in a wastewater treatment plants and, for this reason, it is important to know how to increase the thickening capacity of the total solids (TS) during the purge period.

We have tried to find possible solutions to improve the performance of the thickener with the final purpose of increase the density of the particles separating them from the water. The aim was to making them thickened as possible (up to 2% of the final concentration) in TS.

Under these conditions the biomass behaves like a liquid and can still be pumped with conventional equipment.

The increase in solids from 0,5% in the settler purge to 2% in the thickener, although it can be seen small, involves a significant reduction in the volume of material to be treated and therefore a considerable saving in sizes in the subsequent phases, and provides a significant reduction in investment and operating costs of sludge treatment.

It must be considered that the amount of algae produced were mainly determined by the prevailing environmental conditions, at the same time can varied due to the changes in the process operation of the settler.

Analysis data were carried out on the basis of the measurements made during the purge of the thickeners and also with respect to the supernatant. It is important to know if there is a loss of solids with the supernatant because it can influence the purpose of the study.

2. Objectives

The main objective of this study is the optimization of the thickening process of algae biomass produced during the process of phytodepuration of wastewater of a plant installed in the UPC Agrópolis campus, located in Viladecans, Barcelona.
The final practical aim, thus, is to obtain a TS concentration of 2% exiting the purge of the thickener. This is so that the anaerobic digester, that receives the biomass, can work better and is able to produce high quantities of biogas.
In the field of wastewater treatment, biogas production is perhaps the most straightforward option for microalgae biomass valorization.

This goal is achieved through sub-objectives which are:

1. To allow the removal of the layer of microalgae thickened adhered to the wall of the thickener;
2. To have a reduction of the hydraulic impact that the flow conveyed from the settler causes in the thickener;
3. To understand and analyze if many total solids escape with the supernatant flow, and if they have a significant value for the performance of the thickener.

3. State of the art

Coagulation and flocculation are two important steps that occur before thickening. For this reason, they are shortly explained to understand better the functioning of the thickener.

3.1 General aspects

3.1.1 Coagulation-Flocculation

Coagulation involves the addition of a chemical coagulant in order to condition essentially suspended and colloidal matter for subsequent processing. Flocculation involves the aggregation of destabilised particles and the production of larger particles known as flocculant particles or, more commonly, “flocs”.

Coagulation and flocculation can also be differentiated on the basis of time required for each process. Coagulation occurs quickly, typically in less than 10 seconds whereas flocculation occurs over a longer period of time, 20–45 minutes.

Coagulation and flocculation may be initiated through the use of inorganic coagulants, organic coagulants (often polymers) or by using auto flocculation, bio-flocculation, ultrasound and electrocoagulation procedures. Coagulation consists of neutralizing negative surface charges of colloidal particles (in this case microalgae), while flocculation is the aggregation of neutralized particles followed by flocs formation. Coagulation relies on the interaction between the negative ion of microalgae and the coagulant. Consequently, the time for coagulation, the microalgae recovery capacity and costs are ultimately dependent on the microalgae species and initial microalgae concentration, initial surface charge of the microalgae cells, the coagulant(s), the coagulant dose, degree of mixing and cultivation media parameters such as alkalinity, ionic strength, pH and temperature.

In addition, the polymers used to improve the flocculation of particles, which were additionally added to an inorganic coagulant, can be used to provide additional nucleation sites for floc formation and to enhance the floc aggregation process, respectively.

- Inorganic Coagulation-Flocculation

  A number of common inorganic coagulants and their optimal pH ranges which are used in water and wastewater treatment system for removing colloids are shown in Table 1.

Chemical	Formula	Optimal pH range
Alum	$Al_2(SO_4)18H_2O$	4.0-7.0
Ferric chloride	$FeCl_3$	3.5-6.5 and >8.5
Ferric sulphate	$Fe_2(SO_4)3H_2O$	3.5-7.0 and >9.0
Ferric sulphate	$FeSO_47H_2O$	8.5
Aluminium Polychloride	$Al_2(OH)3Cl$	4.5-8.0

***Table 1**: Inorganic chemicals and optimum pH range commonly used in wastewater processing (1).*

The addition of the inorganic coagulants involved the formation and precipitation of inorganic metal hydroxides and calcium carbonate ($CaCO_3$). Optimal coagulant doses are frequently determined by the use of standard jar test and the effectiveness of a dose can be based on the recovery efficiency or the concentration factor.

- Organic Coagulation-Flocculation

  Organic coagulants, which can derive from natural or synthetic substances, are generally polymer based and may contain ionisable functional groups including carboxyl, amino or sulphonic structures or are non-ionisable. Organic coagulants are used to recover microalgae by themselves or more frequently are used in conjunction with inorganic coagulants to aid in interparticle bridging. Bridging, shown in Fig. 3, links small particles and flocs together and thereby produces larger flocs to aid in floc recovery.

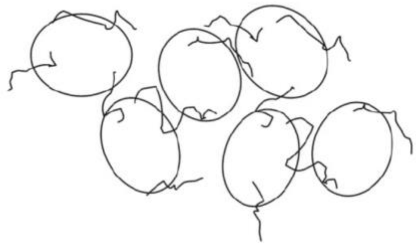


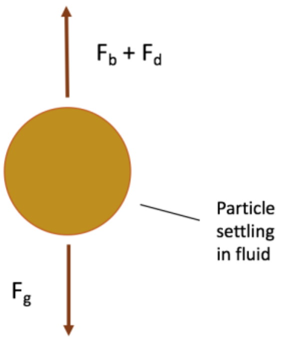
***Figure 3**: Bridging between particles (1).*

However, the chemical substances have a limited application in microalgae systems because they can contaminate downstream products restricting biomass valorization. For this reason, it is preferred the use of natural organic coagulants like tannin based polymers or modified starch which are being increasingly used since the 80s (1).

3.1.2 Thickening

Thickening is a process used to increase the solids content of biomass by removing a portion of the liquid fraction. Gravity separation, typically know as sedimentation, is a process where the particles of solids present in water settle to the bottom of the tank.

The forces exerted on a single particle in a gravitational field are shown in Fig. 4 and include the external force (in this case gravitational) (F_g), buoyancy force (F_b) and drag force (F_d). The net force on the particle determines the direction of movement.



$$\sum F = F_g - F_b - F_d \qquad \textit{Eq. 1}$$

$$F_g = ma = \rho_p V_p g \qquad \textit{Eq. 2}$$

$$F_b = ma = \rho_w V_p g \qquad \textit{Eq. 3}$$

***Figure 4**: Forces exerted on a particle.*

Where

m = mass, kg

a = acceleration, m s^{-2}

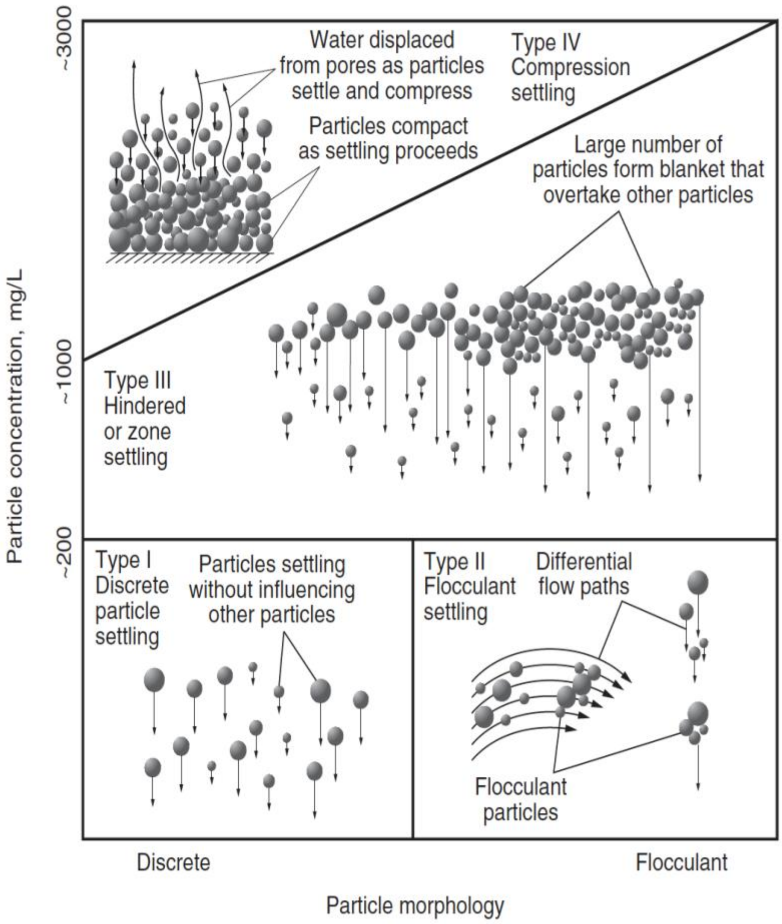
ρ_p = density of particle, kg m^{-3}

ρ_w = density of water, kg m^{-3}

V_p = volume of particle, m^3

g = acceleration due to gravity, 9,81 m s^{-2}

Particles are separated into four classifications based on their concentration and morphology (Fig. 5).



Type I: particles are discrete and not interfere to with one another during settling because the concentration is low and they do not flocculate.

Type II: particles that can adhere to each other if they bump into each other. As particles aggregate and grow in size, they can settle faster.

Type III: particles that forms a blanket of particles (hindered settling). The blanket traps particles below it as it settles; a clear interface is found above the blanket.

Type IV: particles may not really settle (compression settling), and water flows or drains out of a mat of particles very slowly.

Figure 5*: Relationship between settling type, concentration, and flocculent nature of particles (2).*

The primary purpose of thickening is to increase the solids concentration of particles to settle out of the liquid, reaching a final solids concentration of 2–3% generally being maintained.

The top zone consists of relatively clear media (clarified supernatant), and the lower zones consists of particles exposed to free settling, hindered settling and compression settling (2).

Figure 6 shows the relationship between the concentration percentage with the relative volume of the output steam.

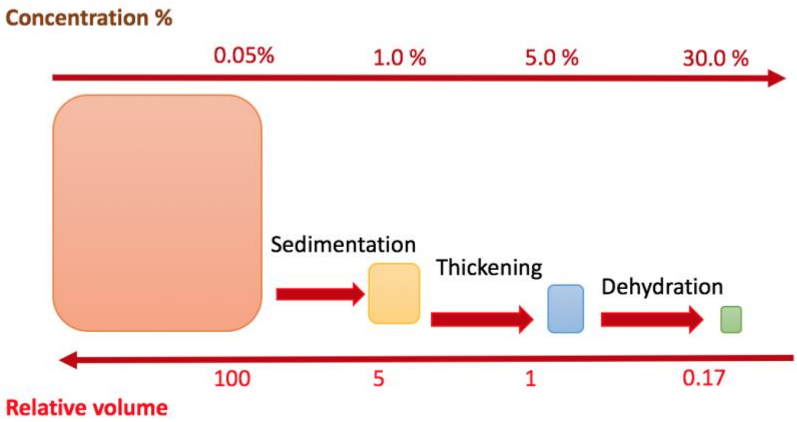


Figure 6*: Block flow for the recovery of microalgae biomass, showing typical biomass concentration achieved and the physical state of the output steam (3).*

The main thickening variables are the concentration of solids C (z, t), that depends on depth (z) and time (t), the solid flow $J_s(z, t) = C\nu_s$, where ν_s is the settling velocity for particle, the volumetric velocity of the biomass $q(t) = -Q_D/S$, where Q_D is the volumetric flow of the discharge and S is the area of the thickener, and the effective effort of solid $\sigma_e(C)$. These variables must comply with the mass and movement balances and result in the following Eq. 4 for the consolidation-thickening:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial z}\left(qC + \rho_f(C)\left(1 + \frac{\sigma_e(C)}{\Delta\rho C g}\frac{\partial C}{\partial z}\right)\right) = 0 \quad \textit{Eq. 4}$$

In this equation, the first term inside the parentheses is the convective flow of the sludge inside the thickener, the second represents the flow due to sedimentation and the third the flow due to the compressibility of the biomass.

Thickening consists of the superposition of two phenomena, *sedimentation* and *consolidation*.

The phenomena of sedimentation and consolidation have different physical behaviors, so it is necessary to analyze them separately. *Sedimentation* consists in the separation of the solids particles from the liquid part of water, due to the force of gravity. In the settler, the diverse particles of a suspension interact between them hindering the trajectory and decreasing the speed of the establishment that each particle would have individually. During sedimentation, the particles are surrounded by fluid and the interaction between them is verified through that fluid.

According to Eq. 4, the main property of a suspension in sedimentation is the solids flux density $J_s(C)$, that is, the product of the concentration and the sedimentation velocity at that concentration (1).

The sedimentation rate is controlled by the net force acting on the microalgae and, for a small inert spherical isolated particle in a Newtonian fluid, the sedimentation rate is governed by Stokes Law, and the terminal velocity for such a particle is given by Eq. 5:

$$v = \frac{g(\rho_s - \rho_f)d^2}{18\mu} \quad \textit{Eq. 5}$$

where v is the terminal velocity (m s^{-1}), g is the acceleration due to gravity (m s^{-2}), ρ_s is the density of the particle (kg m^{-3}), ρ_f is the density of the fluid (kg m^{-3}), d is the diameter of the spherical particle (m) and μ is the fluid viscosity (kg m^{-1} s^{-1}).

Aside from size, shape and density, the sedimentation rate of microalgae can also depend on cell motility, water turbulence and water upwelling. As most microalgae are not spherical a suitable equivalent spherical diameter must be used. Microalgae are usually flocculated to increase the particle size and density (4).

Sedimentation is one of the simplest forms of solid-liquid separation. In the table below we can see the advantages and disadvantages of sedimentation (Table 2).

Major advantages	Major disadvantages
- Low power consumption	- Slow sedimentation rates
- Low design cost	- Large footprint required
- Low requirement for skilled operators	- Low solid concentration achieved

***Table 2**: Advantages and disadvantages of sedimentation.*

The sedimentation ends when the individual particles reach the bottom of the sedimentation column or the thickener and begin to rest on one another forming the biomass. If the particles are compressible, the weight of the flocs begins to affect the inferior flocs compressing them and squeezing the water that remains inside them. This phenomenon of elimination of water by compression is called *consolidation*. The concentration of the suspension that separates sedimentation from consolidation is called critical concentration and the time when it starts is called critical time. Then, when concentrations lower than the critical there is no compression.

In thickener, the solids flux is comprised of the downward movement of particles due to gravity settling and due to fluid flow toward the underdrain, as shown in this expression:

$$J_t = J_s + J_u \quad \textit{Eq. 6}$$

Where:

J_t = TS flux toward the bottom of the basin (kg m^{-2} h^{-1})

J_s = solids flux due to particle settling (kg m^{-2} h^{-1})

J_u = solids flux due to fluid flow from the underflow (kg m^{-2} h^{-1})

To determine the solids flux from gravity settling J_s, the depth of the blanket interface is measured as a function of time in a column that is initially uniformly mixed with a specified solids concentration C. Data from a settling column test is shown on Fig. 7.

The depth of the blanket interface is a function of time in a column with a specified concentration C (Curves shown Fig. 7a).

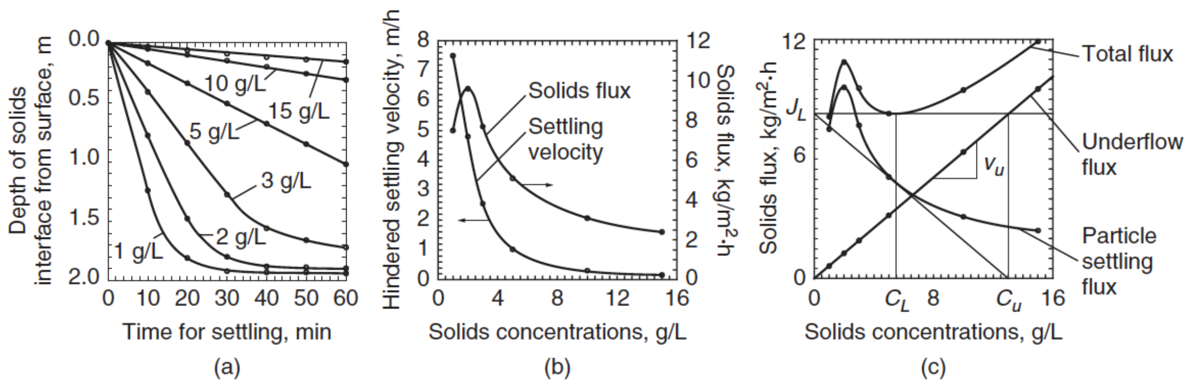


***Figure 7**: Analysis of zone-settling (Type III) data shown in Table 3: (a) interfacial settling velocity as function of concentration, (b) initial settling velocity and solids flux due to settling as function of concentration, and (c) limiting solids flux analysis for Type III settling (2).*

The solids flux values due to particle settling can also be determined by multiplying the concentrations of particles by their respective settling velocities;

$J_s = \nu_s C$ *Eq. 7*

ν_s = settling velocity for particle concentration C (m h^{-1})

C = suspended solids concentration (kg m^{-3})

From data in Fig. 4a the solids flux can be calculated as shown in Table 3.

Solids concentration, C	Initial settling velocities, v_i		Solids flux, J_s
g/L	**m/min**	**m/h**	**Kg/m^{2}h**
1	0,125	7,50	7,5
2	0,080	4,80	9,6
3	0,043	2,55	7,7
5	0,017	1,02	5,1
10	0,005	0,31	3,1
15	0,003	0,16	2,4

***Table 3**: Settling velocity and solids flux values.*

The initial settling velocities and the values for solids flux as a function of solids concentration are presented graphically on Fig. 7b.

The solids flux due to fluid flow from the underflow is defined as

$$J_u = \frac{Q_u C}{A} = \nu_u C \quad \textit{Eq. 8}$$

Q_u = flow rate leaving the bottom of thickener m^3/h

A = cross-sectional area of basin, m^2

ν_u = bulk downward fluid velocity, m/h

The total flux at a suspended solid concentration C can be written as

$$J_t = (\nu_s + \nu_u)\, C \quad \textit{Eq. 9}$$

The solids loading for a basin can be determined from an analysis of Limiting Flux Rate.

The limiting solids flux J_L for a given C_u can be determined by drawing a line from the desired underdrain concentration on the x axis and through the tangent to the particle settling flux curve.

The intersection of the tangent line with the y axis is the value of the limiting solids flux J_L for the given particle settling flux curve and selected underdrain concentration C_u (Fig. 8).

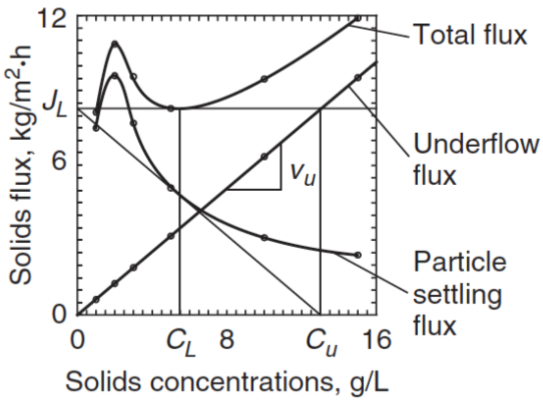


Figure 8: *Limiting solids flux analysis for Type III settling (2).*

The downward velocity of the bulk fluid may be determined using the relationship

$v_u = \frac{J_L}{C_u}$ *Eq. 10*

v_u = downward velocity of bulk fluid, m h^{-1}

J_L = limiting solids flux, flux kg m^{-2} h^{-1}

C_u = concentration of solids I underflow, kg m^{-3}

The area required for solids thickening can be estimated starting from mass balance analysis (stationary model).

$Q_i C_i = (Q_i - Q_u) C_e + Q_u C_u$ *Eq. 11*

Q_i = influent flow rate to basin/thickener (m^3 h^{-1})

C_i = influent suspended solids concentration (mg L^{-1})

Q_u = flow rate leaving the bottom of basin/thickener (m^3 h^{-1})

C_u = solids concentration leaving bottom of basin/thickener (mg L^{-1})

C_e = effluent solids concentration (mg L^{-1})

If it is assumed that C_e C_u and C_e C_i, C_e

$Q_u = \frac{Q_i C_i}{C_u}$ *Eq. 12*

Substituting $\frac{Q_u}{A}$ for ν_u, and solving for A, as shown below:

$A = \frac{Q_u C_u}{J_L} = \frac{Q_i C_i}{J_L}$ *Eq. 13*

where A = area required for thickening, m^2.

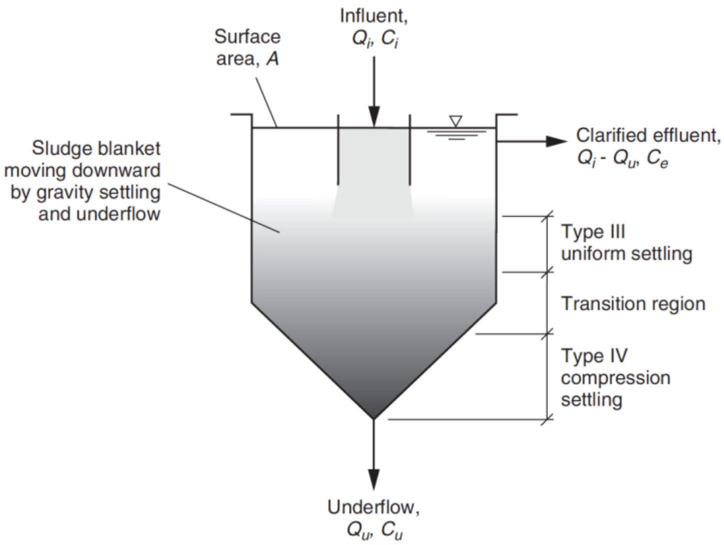


Figure 9: *Diagram of sludge thickener (2).*

Overflow from the unit may be called “overflow” and is on the top. Underflow is called “effluent”, which is on the bottom. We can divide thickener into zones. The clear zone, which is the clear overflow liquor, is essentially free of solids in most applications. The hindered settling zone (transition zone) and the compression zone (compression settling) shows the biomass in compression where dewatering occurs by compression of the solids forcing the liquids out of minute openings in the solids particles.

The thickening process takes place in a settling tank with a long-enough solids retention time (2).

The effectiveness of a solid-liquid separation process can be described in terms of the recovery efficiency (RE) and the concentration factor (CF). The recovery efficiency (see Eq. 14) is defined as the ratio of the mass of cells recovered in the final product to the total mass of cells in the initial culture. Thus, separation processes with high recovery efficiencies capture most of the microalgae biomass present in the feed so that the concentration of microalgae in the dilute stream is low. The concentration factor (see Eq. 15) is the ratio of the concentration of microalgae biomass in the final product to the initial concentration in the culture (5).

Eq. 14

Recovery efficiency (RE) = mass of cells recovered / mass of cells initial culture

Eq. 15

Concentration factor (CF) = concentration algae in final product / initial concentration of algae in culture

The main factors that influence the thickener are:

- Size and shape of the solid particles (generally between 2 and 20 mm in size and filamentous, rods, spheres or chains in shape for algae particles)
- Viscosity and temperature
- Septicity and dissolved oxygen
- Natural electric charge or potential Z (usually negative for algae particles)
- Bioflocculation trends
- Occluded water

A number of controls should be considered in the design and operation of any solids thickening technology. They include:

- Dry weight of solids to thicken
- Downstream solids handling processes
- Period of thickening operation
- Relationship of desired period of operation to downstream process operation
- Pre-and-post thickening storage requirements and capacity
- Solids conditioning requirements

For microalgae particles, these properties depend on the growth conditions and the age of the culture.

So, the potential output changes include volumetric throughput, biomass/solids concentration, particle properties (size, specific gravity, zeta-potential) and the fluid properties (i.e. composition, nutrients, ionic strength, salinity, pH, dissolved gases, specific gravity and temperature).
Multi-stage or sequential processing steps can be designed to increase the microalgae concentration by employing the most suitable, economical and sustainable method for each stage.

- Stage 1 (harvesting/primary concentration): increases the biomass concentration by a concentration factor of 10–20. The material retains its fluid like consistency:
- Stage II (thickening): thickens the primary concentrate by an additional concentration factor of 10 and generates a material with slurry-like consistency.

A thickener has several basic components: a tank to contain the algae, feed piping, a rotating rake mechanism to assist in moving the concentrated solids to the withdrawal points, an underflow solids withdrawal system, and an overflow launder.

Scraper blades or rakes, driven by a suitable mechanism, rotating slowly over the bottom of the tank, which usually slopes gently toward the center, move the material settled on the bottom to a central opening or discharge and scrape deposits away from the base and the walls.
The rakes revolve at a speed sufficient to move the material as fast as it settles without much agitation to interfere with settlement (5).

3.2 Analysis of articles

The beginning of this study was based on the analysis of a series of articles which, most of them, analyzed a clarifier-thickener model for flocculated suspensions as a combination of models for ideal suspensions with the sedimentation-consolidation theory.

According to (1), in a wastewater treatment plant, four types of settling characteristics are normally encountered depending on the nature and concentration of the solid particles.

- *Discrete particle settling*: solids which settle as individual entities with little or no interaction with other particles;
- *Flocculent particle settling*: characterized by the flocculation of solid particles as they settle through the water column;
- *Hindered settling*: the mass of particles settles as a unit;
- *Compression settling*: compression from the weight of particles.

Most of the clarification models, reports in the literature, are based on a statistical analysis relating the effluent suspended solids concentration to a number of process parameters such as mixed-liquor suspended solids, recycle flow rate, overflow rate, detention time, etc.
As stipulated by (1), in the thickening, the settling velocity of the sludge blanket has been found to be a nonlinear function of the solids concentration. As the concentration of solids increases, the mass of solids tends to settle as a unit.
The solids handling capacity of a settler can be assessed by performing a limiting solids flux analysis (7). In a continuous flow settler, the downward solids flux is the sum of the gravity settling flux (J_s) and the solids flux due to the bulk movement of the liquid (J_u), namely the underflow:

$J_t = J_s + J_u$ *Eq. 16*

It is known that a general solid flux J is the product between a concentration C and a settling velocity of the solids v. So, the downward solids flux of a general layer j can be expressed by this equation:

$J_j = C_j v_{sj}, + C_j v_u,$ *Eq. 17*

where J_j = downward solids flux in layer j; J_s = gravity settling flux; J_u, = settling flux due to the bulk movement of the liquid; C_j = solids concentration in layer j; v_{sj} = settling velocity of the solids in layer j; v_u = underflow velocity (2).
Vitasovic's (1986) model predicts the solids concentration profile in the settler by dividing the settler into a number of layers (ten) of constant thickness as shown in Fig. 10, and by performing a solids balance around each layer. All of them are based on the following assumptions:

- incoming solids are distributed instantaneously and uniformly across the entire cross sectional area of the clarifier layer;
- only vertical flow is considered in the model.

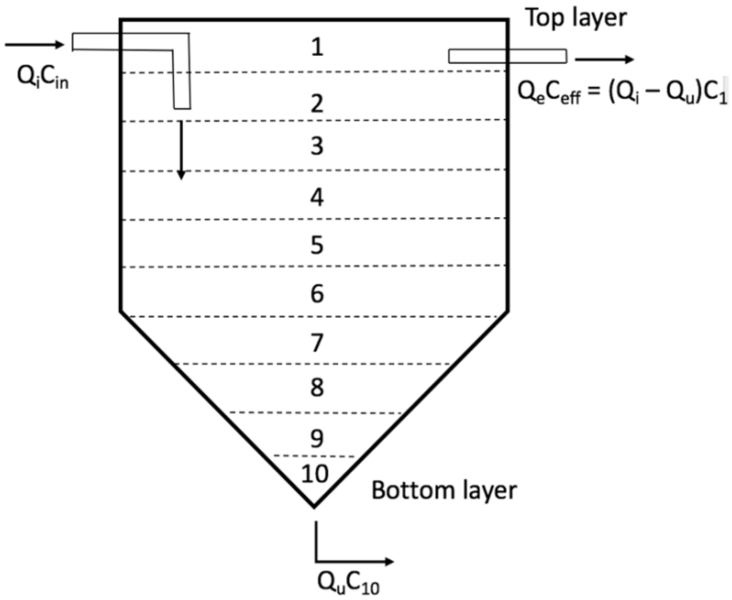


Figure 10*: Layered settler model*

Five different groups of layers are present in the proposed model, depending on their position relative to the feed point. Table 4 summarizes the input and output of solids to each group of layers, while the solids balance around each type of layer which is summarized in Fig. 11, where J_{up} is the upward solids flux due to the bulk movement of the liquid (g $m^{-1}d^{-1}$), J_s is the solids flux due to gravity settling (g m^{-1} d^{-1}), J_u is the downward solids flux due to the bulk movement of the liquid (g m^{-1} d^{-1}), v_s is the settling velocity (m d^{-1}) and A_c is the surface area of the thickener (m).

	Input			**Output**	
Layer	*Feed*	*Settling*	*Bulk liquid flux*	*Settling*	*Bulk liquid flux*
Top layer	-	-	Up	+	Up
Layers above feed point	-	+	Up	+	Up
Feed layer	+	+	--	+	Up - Down
Layers below feed point	-	+	Down	+	Down
Bottom layer	-	+	Down	-	Down

Table 4*: Layered settler model: input output summary with + that is the phenomenon considered and – is the phenomenon not considered (6).*

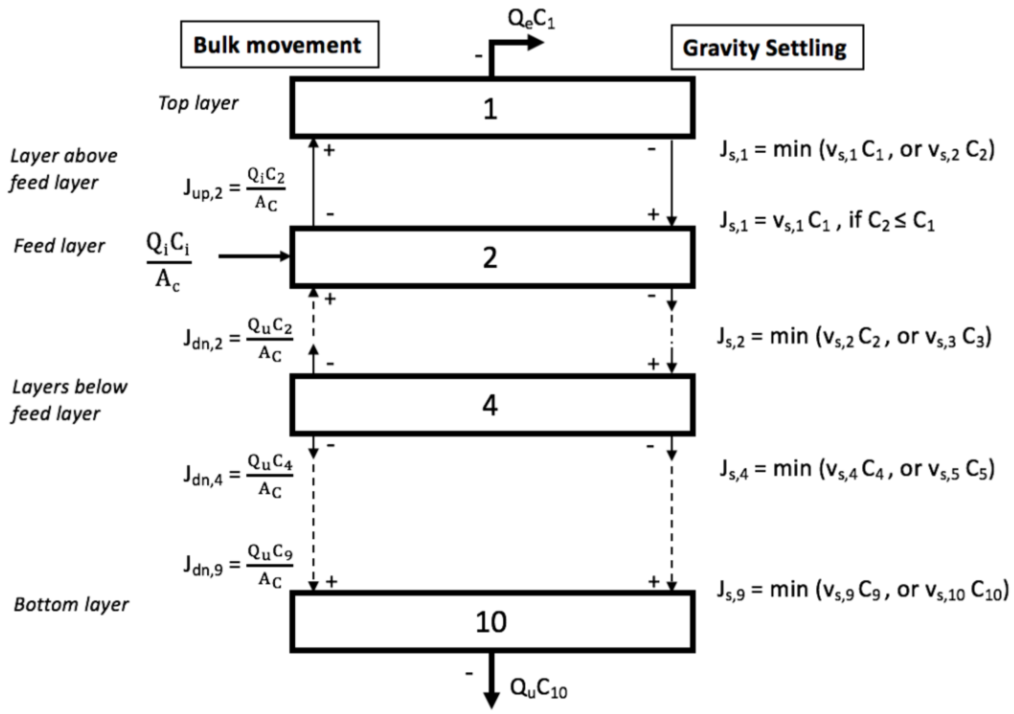


***Figure 11**: Solids balance across settler layers (6).*

The solids flux due to the bulk movement of the liquid is the product of the concentration (C) and the bulk velocity of the liquid (v_b), which can be up or down depending on the position of the layer with respect to the feed point.

The solids flux, due to gravity settling of the solids particles, is given as the product of the concentration (C) and the settling velocity of the solids particles (v_s). Several models have been suggested to describe the settling velocity of a mixed-liquor, one of the more accepted settling velocity equation is that of (9).

$v_s = v_0\, e^{-\alpha C}$ *Eq. 18*

Where v_s = settling velocity of the suspension (m d^{-1}); v_0 = maximum settling velocity (m d^{-1}); C = solids concentration (g m^{-3}); and α = settling model parameter (m^3 g^{-1}).

In a well operating settler, the concentration of solids in the upper layers of a thickener increases with depth. Due to the dynamic forces acting on the floc particles above the feed point, the particle size distribution of the floc particles changes from one layer to another.

An increase in the mean and variance of the log of the particle diameters will also result in an increase in the average settling velocity of the suspension as depicted in region II of Fig. 12.

From a practical standpoint, the correlation between average settling velocity and solids concentration (region II of Fig. 12) is valid for low solids concentration (6).

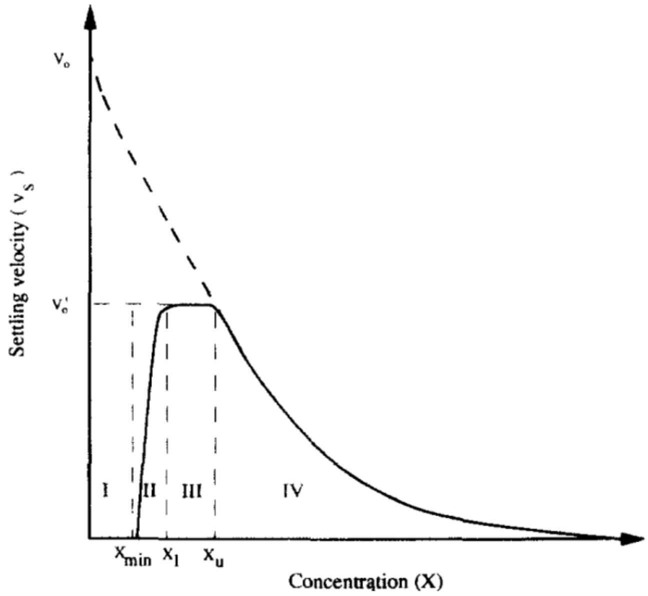


***Figure 12**: Settling velocity model (6).*

As the solids concentration increases, there is a region (region III, Fig. 12) in which the average settling velocity of the suspension reaches a maximum upper limit. This corresponds to the transition zone between the low solids concentration region (region II) and hindered settling conditions (region IV).

The model is designed to predict the solids profile along the settling column, based on the solids flow concept and on a mass balance around each layer of a one-dimensional settler (6).

According to (8), the transportation of the insoluble solids from feed algae to various points in the tank is also governed by the hydrodynamic and turbulent mixing within the feedwell. Unless the feedwell is properly designed, detrimental effects can occur and have negative influence on settling. In the article written by (8), an investigation focused on mixing behaviors of the thickener's feedwell was performed using both numerical and experimental approaches.

Theoretical mean residence time can be written as follows:

$$\tau = \frac{V}{Q} \quad \textit{Eq. 19}$$

where V is the total volume fraction of the feedwell and Q the incoming slurry volumetric flow rate.

Dead volume fraction (V_d), that is the volume of thickened sludge, can be written as follows:

$$\frac{V_d}{V} = 1 - \frac{t_m}{\tau} \quad \textit{Eq. 20}$$

where t_m is the mean residence time which presents the average time of the fluids elements spend in the tank.

Dispersed plug volume fraction (V_p), that is the dispersion of the feedwell inside the thickener, can be written as follows:

$$\frac{V_p}{V} = \frac{t_{max}}{\tau} \quad \textit{Eq. 21}$$

where t_{max} is the time to obtain the maximum of the residence-time distribution E(t).

Mixed volume fraction, that is the volume of mixture between liquid and solids, can be written as follows:

$$\frac{V_m}{V} = 1 - \frac{V_d}{V} - \frac{V_p}{V} \quad \textit{Eq. 22}$$

So, (3)have found that the flow behavior in the feedwell can be described as a combination of dead zone, plug flow zone and mixing flow zone. Furthermore, the flow rate and aspect ratio of feedwell show a strong correlation with the constitution of different types of flow regions in the feedwell. Table 5 by (3), shows the evaluation parameters for three inlet flow rates. It is found that the stagnant volume decreases when the inlet flow rate increases. Furthermore, the increase of the mixing volume as well as the actual residence time with the increase of the inlet flow rate is observed. The case with the highest flow rate (1.2 Q_i) gives the minimum volume fraction of 17.69 % in dead zone, while the volume fraction of 0.8 Q_i in dead zone is significantly increased to 34.77 % (8).

Flow rate	τ/s	t_{max}/s	t_m/s	(V_d/V) %	(V_p/V) %	(V_m/V) %
1,2Q_i	41,20	17	33,91	17,69	41,26	41,04
Q_i	46,54	17	34,30	26,30	36,53	37,17
0,8 Q_i	53,62	19	34,97	34,77	35,43	29,79

Table 5*: Parameters of RTD for different inlet flow rates (8).*

According with the aim of the article written by (9), a mathematical model for continuous sedimentation-consolidation processes of flocculated suspension in clarifier-thickener units was formulate. It was considered a continuously operated axisymmetric clarifier-thickener tank as drawn in the figure below (Fig. 13) with all flow variables depending on depth x and time t only.

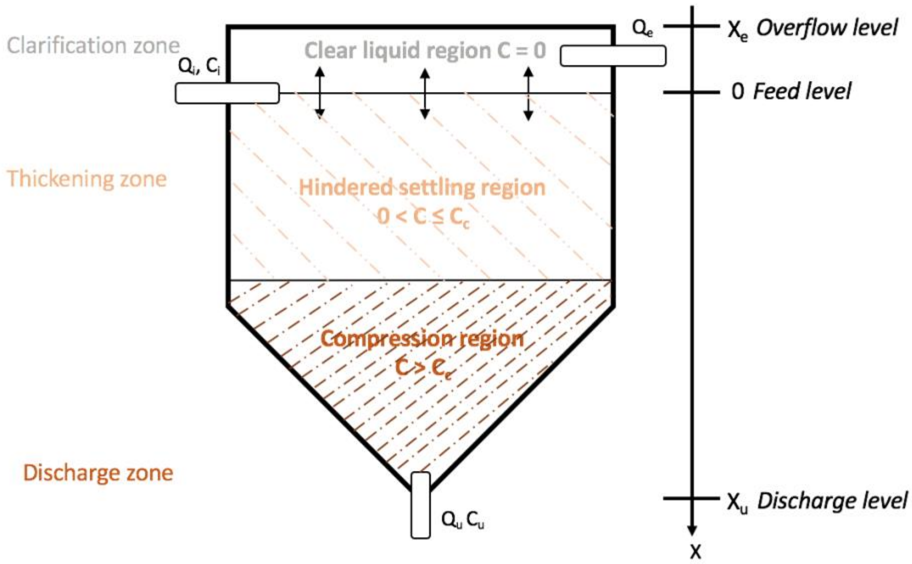


***Figure 13**: Clarifier-thickener units treating a flocculated suspension.*

The tank is subdivided in four different zones: The thickening zone (the zone between feed level (X = 0) and discharge level (X = X_u)), which is usually the unique zone considered in conventional analyses of continuous sedimentation, the clarification zone (the zone between overflow level (X = X_e) and feed level (X = 0)) located above, the underflow zone (X = X_u) and the overflow zone (X = 0). The tank is feed at X=0, the feed level, with a volume feed rate $Q_i(t) \geq 0$. The concentration of the feed suspension is $C_i(t)$. The volume underflow rate, at which the thickened biomass is removed from the unit, is $Q_u(t) \geq 0$. Consequently, the overflow rate is $Q_e(t) = Q_i(t) - Q_u(t)$, where we assume that the two control functions $Q_i(t)$ and $Q_u(t)$ are chosen such that $Q_e(t) \geq 0$. Furthermore, we distinguish between the four abovementioned zones in the clarifier-thickener, which are a property of the equipment modeled, and the clear liquid, hindered settling, and compression regions, in which a suspension at a given point of time has the concentrations zero, $0 < C \leq C_c$, and $C > C_c$, respectively, where C_c is the critical concentration at which the solid flocs start to touch each other. Thus, the time-dependent location of the regions is a property of a particular flow, that is, of the solution to the problem (9).

The convective flux function F incorporates the hindered settling velocity within the total solid suspended (SST) and the two volumetric upward and downward flows:

$$F(C, z, t) = \begin{cases} -\frac{Q_e(t)C}{A} & for\ effluent\ zone \\ v_{hs}(C)C - \frac{Q_e(t)C}{A} & for\ clarification\ zone \\ v_{hs}(C)C - \frac{Q_u(t)C}{A} & for\ thickening\ zone \\ +\frac{Q_u(t)C}{A} & for\ underflow\ zone \end{cases} \quad \text{Eq. 23}$$

Where v_{hs} is the hindered settling velocity (m s^{-1}) and A the cross-sectional area of SST (m^2).

The feed flow is separated into upwards- and downwards-directed bulk flows, which give rise to the linear (in C) terms - Q_e (t) C/A and Q_u (t) C/A, respectively. In addition, we assume that inside the settler (clarification, thickening and discharge zone), the solid and liquid phases separate, which is described by the flux contribution v_{hs} (C) C, where v_{hs} (C) is the solids hindered settling velocity in batch settling. Outside the settler, in the effluent and underflow zones, both phases move at the same velocity (as for flow through a thin pipe), and therefore the term v_{hs} (C) C is "switched off" between overflow and feed level and between feed and discharge level. Eq. 1 indeed attempts to describe (in a one-dimensional fashion) the physical phenomena taking place in a settling tank. In the particular case of a flux like Eq. 23 that is not only non-linear with respect to C, but whose definition depends discontinuously on spatial position z, stationary jumps may appear across the boundaries of the four zones (12).

Mass balance equation

Consider a vessel with a variable cross-sectional area S(x). Since we assume C = C (x, t), the continuity equations for the solids and the fluid are given by:

$S(x)\, C_t + (S(x)\, C\, v_s)_x = 0$ *Eq.24*

$-S(x)C_t + (S(x)\,(1 - C)\, v_f)_x = 0$ *Eq. 25*

Where v_s and v_f are the solids and the fluid phase velocity, respectively, C the concentration, x the depth and t_the time. The mixture flux is the volume average flow velocity weighted with the cross-sectional area at height x. It is given by this equation Q (x, t) = S(x) (C v_s + (1 - C) v_f).

The sum of Eq. 24 and Eq. 25 produces the continuity equation of the mixture, Q_x (x, t) = 0, which implies that Q (· , t) is constant as a function of x. When Q suffers no jumps with respect to x, we obtain Q (x, t) = Q (x_u, t) = Q(t). This equation is equivalent to one of the mass balance equations.

We let it replace Eq. 25 and rewrite Eq. 24 in terms of the flow rate Q (t) and the solid-fluid relative velocity or slip velocity $v_r = v_s - v_f$, for which a constitutive equation will be formulated (9). Observing that

$$S(x)\, Cv_s = S(x)\, [(Cv_s + (1 - C)\, v_f)\, C + C\, (1 - C)\, (v_s - v_f)] = Q(t)\, C + S(x)\, C\, (1 - C)\, v_r \quad \textit{Eq. 26}$$

we obtain from Eq. 24 the equation

$$S(x)\, C_t + (Q(t)\, C + S(x)\, C\, (1 - C)\, v_r)_x = 0 \quad \textit{Eq. 27}$$

The kinematic sedimentation theory is based on the Kynch's theory and also on the assumption that v_r is a function of C only.

Kynch's theory describes the settling of a so-called ideal suspension of small, equal-sized rigid spheres in a viscous fluid. Therefore, the relative velocity is usually expressed in terms of the Kynch batch flux density function b (C), which describe the material- specific properties of the suspension. So $v_r(C) = b(C) / (C(1 - C))$ and Eq. 27 takes the form:

$$S(x)\, C_t + (Q(t)\, C + S(x)\, b(C))_x = 0 \quad \textit{Eq. 28}$$

At the end, we obtain the governing equation:

$$S(x)C_t + (Q(t)C + S(x)b(C))_x = (S(x)A(C)_x)_x \quad \textit{Eq. 29}$$

Where

$$A(C) = \int_0^a a(s)ds \qquad a(c) = \frac{b(c)\sigma_e(C)}{\Delta\rho g C} \quad \textit{Eq. 30}$$

Since $a(C) = 0$ for $C \leq C_c$ and $C = C_{max}$ and $a(C) > 0$ otherwise, Eq. 30 is first-order hyperbolic for $C \leq C_c$ and second-order parabolic for $C > C_c$. Since Eq. 30 degenerates into hyperbolic type on a solution value interval of positive length, the Eq. 30 is called strongly degenerate parabolic. The location of the type-change interface $C = C_c$ (the biomass level) is in general unknown beforehand (9).

The compression function d_{comp} is given by (9),

$$d_{comp}(C) = \frac{\rho_s v_{hs}(C)}{g\,(\rho_s - \rho_f)}\ \sigma_e'(C) \quad \text{Eq. 31}$$

where ρ_s and $\rho_f < \rho_s$ is the (constant) solid and fluid mass densities, v_{hs} is the hindered settling velocity, g is the acceleration of gravity, and $\sigma_e = \sigma_e(C)$ is the so-called effective solid stress function, which satisfies

$$\sigma_e'(C) \begin{cases} = 0 \text{ for } 0 \leq C < C_c \\ > 0 \text{ for } C > C_c \end{cases} \quad \text{Eq. 32}$$

In this equation, C_c is a material-dependent critical concentration or gel point at which the solid particles start to physically touch each other, so that solids stress can be transmitted (9).

What about thickener rakes, they are essential in the transport of biomass bed material to the underflow in conventional thickeners designs (6). Thickeners rakes fulfil three main functions:

1. to move biomass to the underflow;
2. to assist in dewatering biomass that settles onto the thickener bed;
3. to scrape deposits away from the base, and sometimes the wall, of the tank.

According with the study made by (6), the two main factors that determine the movement of the rake are the area that the rake will have to travel and the yield stress of the material through which it is moving. It is also necessary to take into account the achievement of a balance between rake delivery and underflow withdrawal.

4. Material and methods

One of the studies of the European project INCOVER, is a plant installed in the UPC Agrópolis campus, located in the municipality of Viladecans (Barcelona). The plant is composed of three horizontal photobioreactors (PBRs) of 10 m^3 each. PBRs are fed daily with 6.9 m^3 of urban wastewater and agricultural runoff. The plant produces around 2 kg per day of microalgae biomass dominated by cyanobacteria, that is harvested in a lamella settler. The biomass harvested is treated together with secondary sewage sludge in an anaerobic digester of 450 m^3 that currently produces around 80 L of biogas per day. The sludge from the anaerobic digester (22.5 L d^{-1}) is subsequently treated in a sludge treatment wetland, while the water coming from the settler (6 m^3 d^{-1}) is disinfected by a solar-driven system based on ultrafiltration and then treated in nutrients recovery columns based in sol-gel coating. Resulting effluent is applied for irrigation in an 80 m^2 field planted with rapeseed.

The separation of solids from water by gravity sedimentation is one of the most important physical processes in a wastewater treatment plant, and also in the plant installed in Agròpolis. For this reason, this study focused mainly on this mechanism of this process. Solids-liquid separation is a vital process in every biological wastewater treatment system.

The plant, in the UPC Agrópolis campus, is equipped with one thickener, in which the aim is to increase the concentration of microalgae to obtain a bigger particle of solids.
As illustrated in Fig. 14, the thickener is a cylindrical tank with a cone-shaped bottom. The diameter of the tank is 58 cm while the height of the cylindrical part of the thickener is 70 cm and 24 cm for the conical. The feed inlet hole is located at 1 cm from the top of the tank. Inflow is discharged inside the tank through a L-shaped tube. There is a hole for the supernatant, which has been located at almost the same height of the hole for the feed entrance (a little bit lower than the feed entrance).

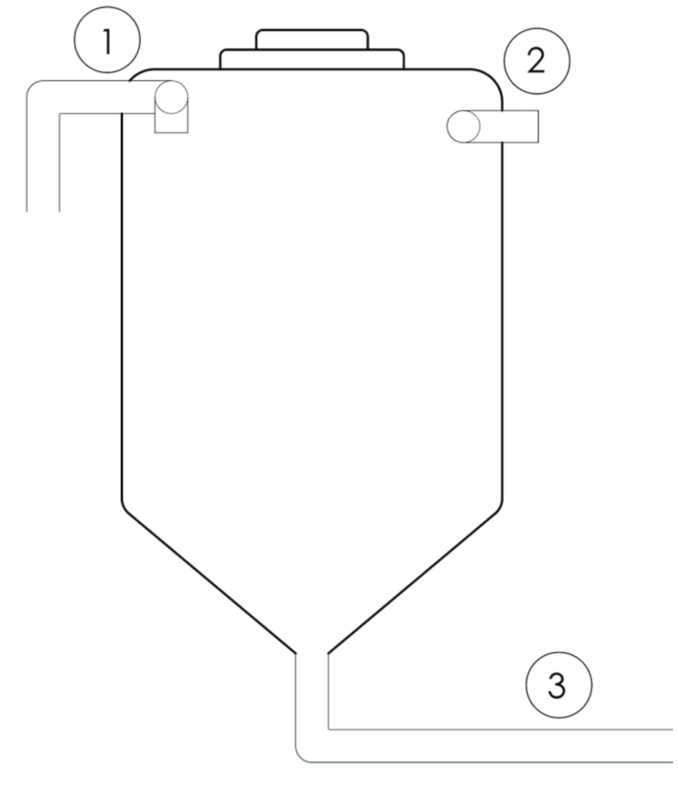


Figure 14: The thickener. 1) L-shape tube for the inlet flow; 2) Supernatant outflow; 3) thickened biomass underflow.

A stirrer was installed in the thickener to improve the performance of the system. It is important to underlined that the stirrer only works when the purge pump was running. A one-meter long pliable iron bar was chosen (cylindrical with a diameter of 5 mm) and molded into the shape of the container (Fig. 15) so that it could scrape the conical wall and part of the cylindrical wall.

The use of malleable iron made it possible to cut, melt and obtain the desired shape. The small diameter is because it occupied little area and interfered as little as possible with the contents of the thickener (Annex 4).

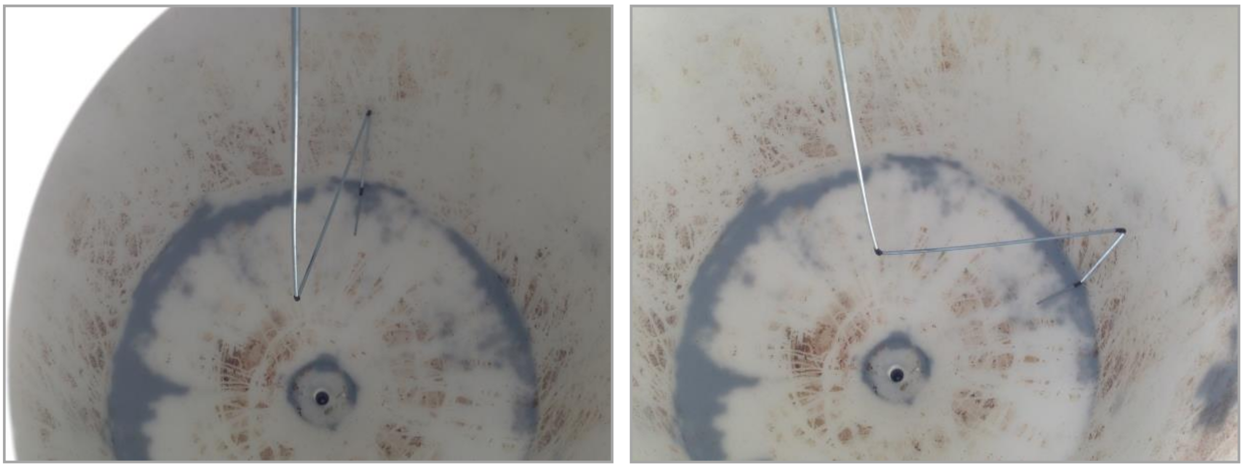


Figure 15: Stirrer installed in the thickener.

Later, a vertical bar has been melted to the horizontal piece of the iron bar, so that would break any flocs with water that were formed.

This iron bar has been connected to a small motor (Fig. 16) collocated on the top in the center of the tank inside a plastic box to protect it from weather events. Thanks to this motor, the bar could be rotate with a velocity of 10 rpm per minute when the purge pump was running.

***Figure 16**: The small engine placed above the thickener inside a plastic box connected to electricity.*

After designing the mixer for the thickener, the second step was to paint it. This choice had been made to obtain an optimal functioning of the thickener.

The first deposit was painted with two coats of fixative followed by several coats of black paint and two white endings.

The black colour was chosen to completely avoid any glimmer of light that could enter, thus creating a totally obscure environment to avoid the microbiology activities. The final white was given because it reflected the sun and helped to maintain a normal temperature. Light conditions and temperature directly effect the growth rate of microalgae (duration and intensity) (Fig. 17).

***Figure 17**: The painted thickener.*

In order to achieve the predefined objectives, the study was divided into four different stages that represent the tests carried out to improve the performance of the thickener.
The stages were developed as follows:

1) Analysis of the operation of a single thickener by the installation of a stirrer for avoid that microalgae can be adhered to the wall during the purge. This analysis was carried out from 21th to 28th February 2018.
2) Construction and installation of a second thickener. This thickener was connected with the thickener previously installed in the system, in order to increase the retention time of the microalgae and reduce the amount of water presented in the cultivation broth. This analysis was carried out from 7th to 11th March 2018.
3) Installation of a stirrer in the second thickener. It is important to underlined that both stirrers only work when the purge pump was running. This analysis was carried out from 14th to 27th March 2018.
4) Change in the operational time of both stirrers. This was made in order to improve the amount of TS produced in both thickeners. This analysis was carried out from 3rd to 17th April 2018.

4.1Measurements

Since the beginning of the process until 3th March, the TS in purge flow were measured three times per week. Since 14th March until the end of the process the TS were measured every day in order to obtain better results and be able to understand the behaviour of the process.
While the TS in the supernatant were carried out twice a week sin the beginning of the process until 13th March. Since 14th March until the end of the process these measurements were made every two days.

Two types of analysis were made in order to do these measurements.

1. Drying in a stove at a defined temperature (103-105 ° C) to measure the total amount of solids (ST) present at the outlet of the purges.

Procedure: collection of a representative sample of the entire duration of the purge. Measurement of the weight in grams of the empty crucible with a capacity of 10 mL. Fill the crucible with the sample taken beforehand. Drying of the crucible in the stove (103-105 C) for a day. Pick up the crucible from the stove and cool down for 30 minutes before measuring the weight (Fig. 18).

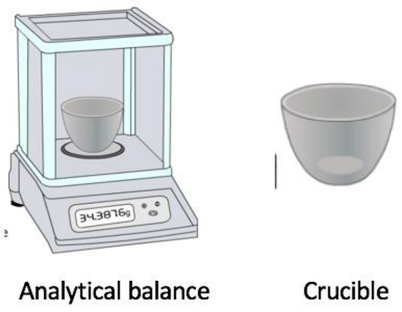


Figure 18: Analytical balance and crucible

TS (g L^{-1}) = $\frac{(M_1 - M_0)}{V}$ 100

M_1= crucible and residue weight after drying (g)

M_0 = crucible weight without residue (g)

V = sample volume subjected to drying (mL)

2. Vacuum filtration to measure the amount of TS present in the supernatant.

Procedure: Collection of a representative sample of the amount of supernatant accumulated during one or two purges or throughout the day. Wet the filter completely with distilled water. Place the filter in the stove to dry. Removal of the filter from the stove and measurement of the weight in grams of the filter. Filling one or two glass tubes of 100 mL of supernatant taken. Adaptation of a filter paper in a system that generates a not too strong vacuum.

This technique requires the use of a vacuum flask and a Buchner funnel, which is a special funnel equipped with a perforated plate that supports the filter (Fig. 19). Through a mechanical pump a partial vacuum was created inside the flask which caused the liquid component of the mixture to rapidly suck through the filter paper.

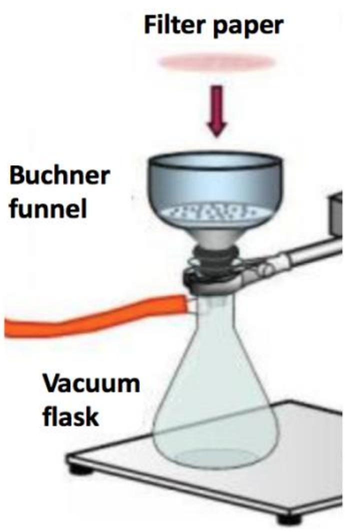


Figure 19*: The vacuum filtration method.*

Weight of the filter with the amount absorbed on it.

$$\text{Suspended solids (g L}^{-1}) = \frac{(M_1 - M_0)}{V} 100$$

M_1= filter and residue weight after drying (g)

M_0 = filter weight before filtration (g)

V = sample volume subjected to filtration (mL)

4.2 Mass balance

The thickener was connected to the lamella settler through a peristaltic pump, through which the tank was fed ($x = 0$).

All the peristaltic pumps were going with the same velocity and the same flow (6,6 L min^{-1}) even if they pumped different concentrations of the mixture between microalgae and water.

The inflow of the first thickener was pumped directly from the settling tank, $Q_i(t) \geq 0$ with a concentration of the feed suspension of $C_i(t)$.

The prescribed volume underflow rate, at which the thickened biomass was removed from the unit, was $Q_u(t) \geq 0$. Consequently, the overflow rate was $Q_e(t) = Q_i(t) - Q_u(t)$, where we assumed that the two control functions $Q_i(t)$ and $Q_u(t)$ were chosen such that $Q_e(t) \geq 0$ (Fig.20).

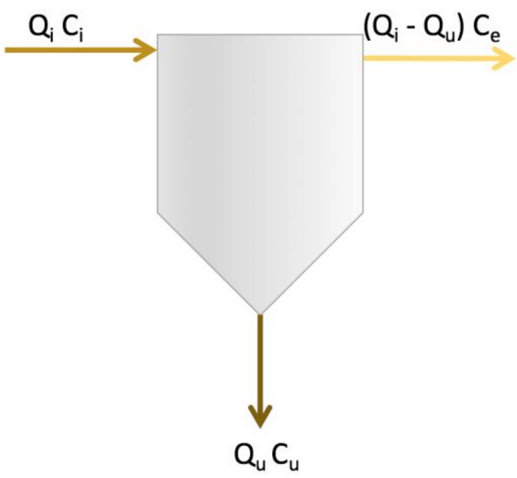


Figure 20*: Mass balance of one thickener.*

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In the mass balance that will be calculated later, it is important to notice that the system considered is not stationary.

Rate of accumulation of mass into the system	=	Rate at which mass enters the system from outside	-	Rate at which mass escape the system from the purge	-	Rate at which mass escape the system from the supernatant

For this reason, the mass entry value will have not been equal with the value of the output mass. This is because the variation in volume, depending on the concentration of solids and depending on the time, will never be zero. So, this equation is considered

$$V\frac{dC}{dt} = Q_i C_i - Q_u C_u - (Q_i - Q_u) C_e \quad \textit{Eq. 33}$$

where V $\frac{dC}{dt}$ represents the accumulation of mass that remains inside the tank. Considering that the value of the supernatant is irrelevant for the purposes of the calculation, it will not be considered and so the equation that is:

$$0 = Q_i C_i - Q_u C_u - V\frac{dC}{dt} \quad \textit{Eq. 34}$$

For this reason, the entry and exit results that will be obtained during the mass balancing will not coincide.

The mass for both thickener is represented in the Fig. 21.

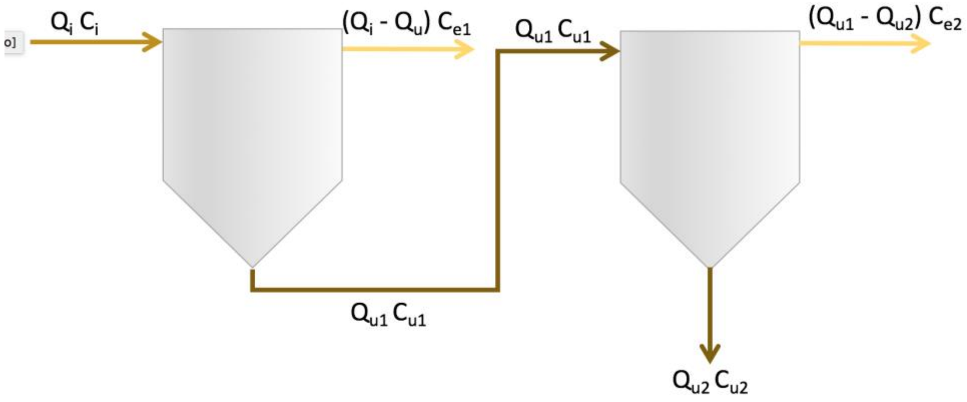

Figure 21*: Mass balance of the two thickeners in series.*

Where:

Q_i = flow of microalgae to thickener (m^3 d^{-1})

Q_{u1} = flow rate of thickened microalgae from the first thickener (m^3 d^{-1})

Q_{u2} = flow rate of thickened microalgae from the second thickener (m^3 d^{-1})

$(Q_i – Q_{u1})$ = supernatant flow of the first thickener (m^3 d^{-1})

$(Q_{u1} – Q_{u2})$ = supernatant flow of the second thickener (m^3 d^{-1})

C_i = percentage of dry of incoming microalgae (g m^{-3})

C_u = percentage of dry of thickened microalgae (g m^{-3})

C_{e1} = percentage of dry microalgae in the supernatant of the first thickener (g m^{-3})

C_{e2} = percentage of dry microalgae in the supernatant of the second thickener (g m^{-3})

5. Results and discussion

5.1 Operation of the single thickener by the installation of a stirrer

5.1.2 Flow

A peristaltic pump discharged 6.6 L min^{-1} from the settling tank to the thickener. The settling tank ran four minutes nine times per day. The flow for every purge was 20 L with a total of 180 L d^{-1}.
The thickener, instead, purge only once a day by another peristaltic pump connected to the anaerobic digester. The flow of the pump of the thickener to the digester ran four minutes with a total of 28 L d^{-1}.
The quantity of micro-algae produced influences directly the time of the purges.
By means of this data, the quantity of supernatant could be calculated through the mass balance. So, the liters, in this case, lost by the supernatant, if the system was stationary, were 152 L per day.

5.1.2 TS percentage

Figure 22 shows the amount of TS obtained during the daily purge of the thickener in 21th, 26th, and 28th February. The comparison of this quantity of solids with the amount of incoming TS from the settler explains the thickening capacity of the tank.
The percentage of TS on 21th, 26th and 28th February were 0,627 %, 0,755 % and 0,533 %, respectively. This last descent can be explained by looking at the small amount of solids which entered into the thickener by the settler.
It can be concluded that, during 26th February, the thickener was working well compared to the other days analyzed. The mixed water-microalgae had increased from a solid percentage of 0,363 % to one of 0,755 %.

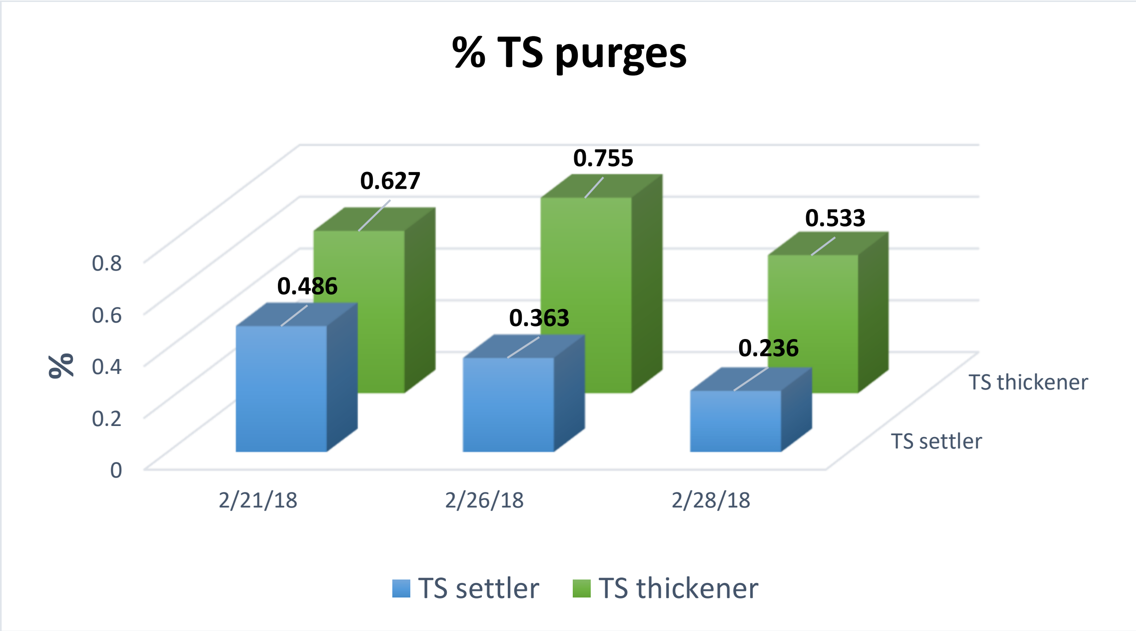

***Figure 22**: Percentage of TS obtained during the daily purge of the thickener during 21th, 26th, and 28th February, 2018 in comparison with the percentage of TS obtained, during the same days, from the settler.*

5.1.3 Mass balance

<u>Mass balance of day 26th February</u>

1° THICKENER

$Q_i = 180$ L d^{-1} $C_i = 0{,}363$ g L^{-1}

$Q_u = 28$ L d^{-1} $C_u = 0{,}755$ g L^{-1}

$(Q_i - Q_u) = 152$ L d^{-1} C_e

$$Q_i\, C_i = Q_u\, C_u + (Q_i - Q_u)\, C_e$$

$$65{,}34 \text{ g L}^{-1} = 21{,}14 \text{ g L}^{-1} + 152\, C_e \text{ g L}^{-1}$$

5.1.4 Considerations

In conclusion, the best performance of the thickener was obtained during 26th February with a 0.755 % of TS. Although there was a low amount of incoming solids into the thickener, it still achieved a higher concentration of thickened solids compared to the concentrations obtained on other days with a higher solids inlet from the settler.

In any case, the percentage of TS obtained does not reach 2% that is the one required by the objective.

5.2 Construction and installation of a second thickener

After analyzing how a thickener goes alone, it had been thought of adding a new one, as a further aid, to try a series of operations (it had been introduced also a second peristaltic pump for the new thickener) (Annex 3).
The operation of the new system was started with the same steps as the first thickener.
In fact, the second thickener was also painted with black and white in the same fashion and reasons as the original.

The series operation, of the two thickeners, was mainly designed for two reasons:

I. To reduce the impact of turbulence that could be generated on the thickened part upon the entrance of water and algae which derive from the purge of the settler;
II. To accumulate more thickened algae in the second thickener, already thickened previously for a short time, in the first thickener, making the process longer.

The turbulent currents, having a high speed, cause a mixing of the microalgae concentrations, in particular, around the feed input. With the problem of turbulence, it was decided to decrease the speed of the peristaltic pump. With a slower inlet flow, less turbulence could be created inside the tank, but the optimal amount of thickened algae that could result from the first thickener cannot be obtained. This is because water had time to create a path and filter in thickened algae.

The purge from the first thickener to the second thickener was performed with the same frequency as the pump which purged from the settler to the first thickener (nine times a day at different times).
To improve the process, the purge from the first thickener to the second was made two minutes before the entrance of settler flow in the first thickener. This decision was taken so that the input flow entering into the second thickener causes the least possible agitation inside the tank.

In fact, simulations indicated that, although dispersion was localized around the inlet, with a 6,6 L min^{-1} velocity of entrance, it influenced all concentrations in the tank. This hydrodynamic dispersion phenomenon smooths the depth-concentration profile.

During the first analysis of this new system of thickening, the stirrer was activated only in the first thickener to see the quantity of thickened solids that could be reached with these assumptions.

An important addition was to place two tanks connected to the respective two thickeners to accumulate the corresponding supernatant (Fig. 23). In this way, it was possible to know the amount of supernatant was accumulated between one purge and another, or throughout a day. Thanks to these two tanks it was also possible to take samples of supernatant. The sample was taken by mixing the supernatant accumulated, to avoid that the solids settles to the bottom.

***Figure 23**: The two tanks that collect the respective supernatants of the two thickeners*

5.2.1 Flow

A peristaltic pump discharged 6.6 L min^{-1} from the settling tank to the thickener. The settling tank ran three minutes nine times per day. The flow for every purge was 20 L with a total of 180 L d^{-1}.

The first thickener purge was one minute, nine times a day to the second thickener with a peristaltic pump. The flow of the pump of the first thickener to the second one ran one minute with a total of 60 L d^{-1}.

The second thickener purged four minutes once a day by a peristaltic pump to the anaerobic digester. The flow of the pump of the second thickener to the anaerobic digester ran four minutes with a total of 28 L d^{-1}.

Like the first situation with only one thickener, the quantity of microalgae produced influenced directly the time of the purges.

By means of this data, the quantity of supernatant can be calculated. So, the liters lost by the supernatant for the first thickener, if the system was stationary, were 120 L d^{-1} while for the second thickener were 32 L d^{-1}.

5.2.2 TS percentage

Figure 24 shows the functioning with these specific characteristics. This system in series was analyzed by taking three samples over a representative week from 7th to 11th March 2018.

Analyzing the data, it is possible to see that, on the first day analyzed, it is the one in which a concentration of greater thickened TS from the first thickener is reached (1,217 %).

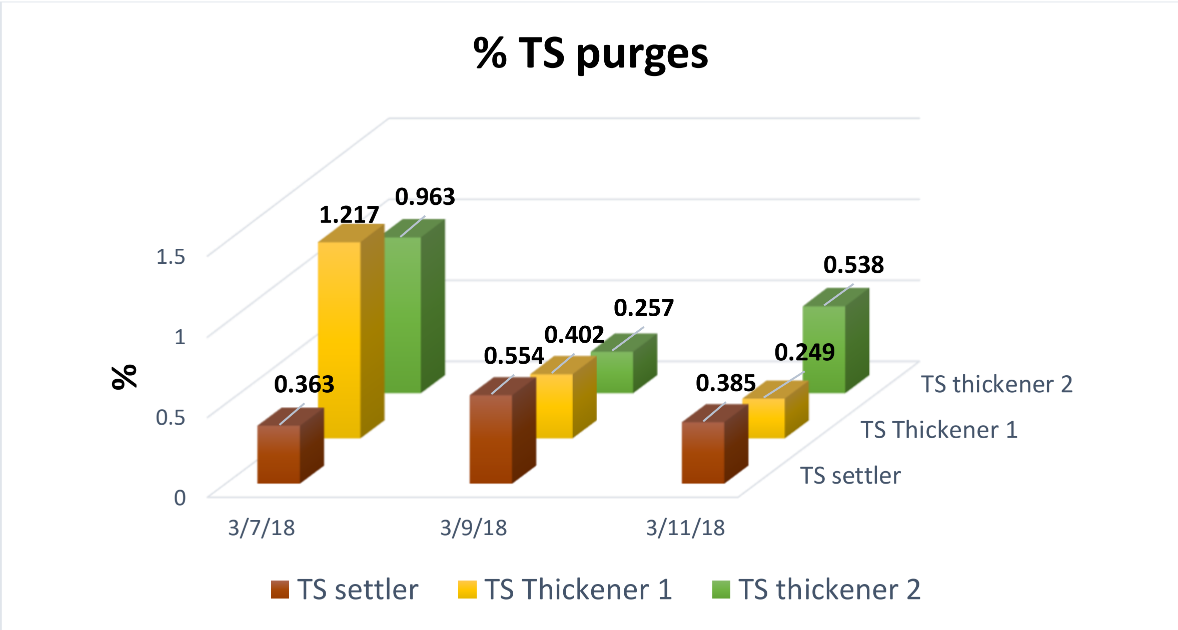

Figure 24: *Percentage of TS obtained from the purges of the two thickeners during 7th, 9th, and 11th March, 2018 in comparison with the percentage of TS obtained, during the same days, from the settler.*

The comparison with the solids achieved from the settler is important because it's an essential indicator of the performance of the two thickeners. In this case, the percentage of solid coming from the settler was almost the same except for the second sample where there was a bit more (≅ 0,434 %). This can be explicated with a greater production of algae or for a better functioning of the settler than normal. In this last case, however, although there was an increase in concentration of microalgae from the settler, the percentage of solids obtained from the two thickeners was poor. This it could have been due to a malfunction of the thickeners or a large loss of algae through the supernatant. The Figure 25, below, can better explain the situation of the samples taken during the two purges for 9th March.

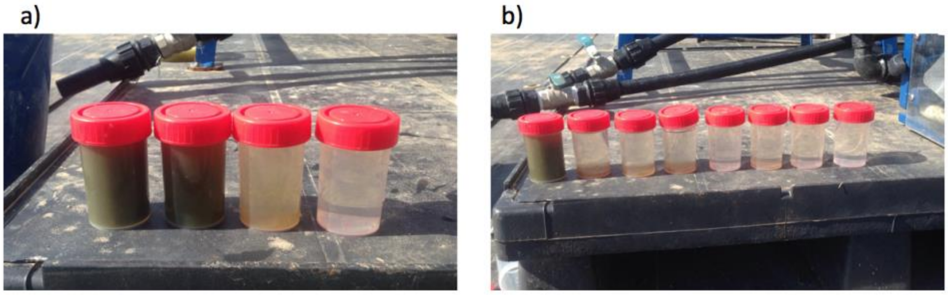

Figure 25: a) Samples of the purge of the first thickener, each taken every 15 seconds for a minute of purge for the day 9th March 2018; b) Samples of the purge of the second thickener, each filled every 30 seconds for 4 minutes of purge for the day 9th March 2018.

The first figure (figure 25a) shows the samples taken during the purge of the first thickener to the second one. The samples were taken every 15 seconds to see the evolution of the purge during its operation. In the second figure (figure 25b), instead, the samples taken during the purge of the second thickener to the digester are shown. Each sample was taken every 30 seconds during 4 minutes of pumping. We can clearly see how, from the first thickener, a higher percentage of microalgae was obtained.

It is important to compare these results with the percentage of solid obtained from the supernatant (Figure 26). This amount can be effect the results we get on the purges.

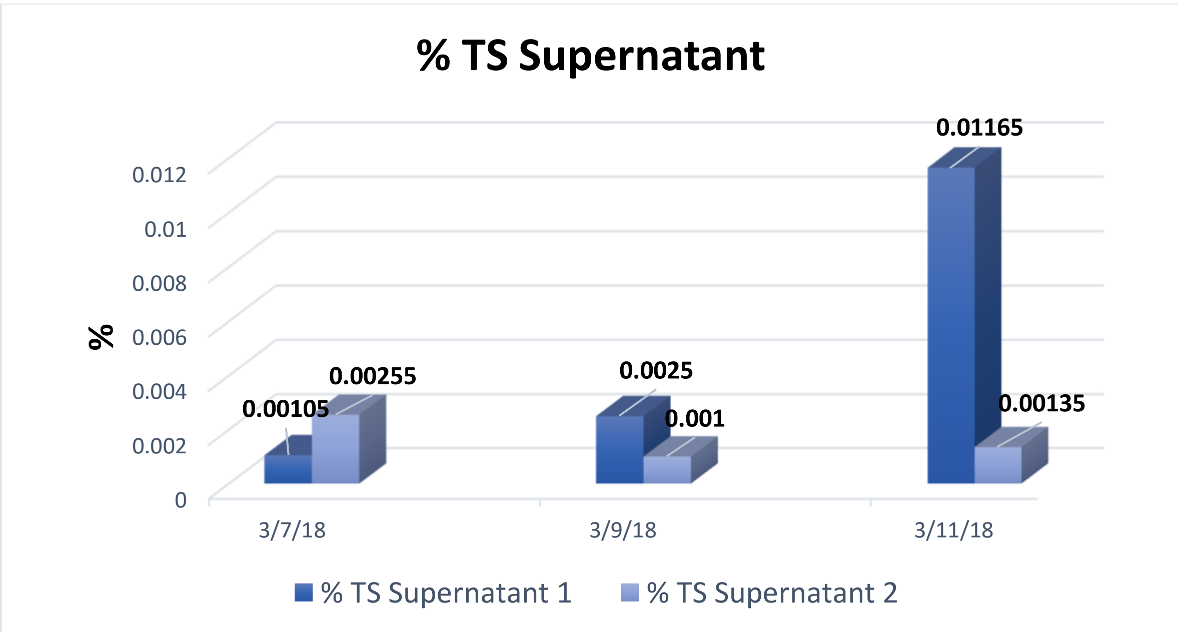

Figure 26: Percentage of TS obtained from the supernatants of the two thickeners during 6th, 8th, and 10th March 2018.

On 7th March, there was a loss of solids of 0,00255 % through the supernatant by the second thickener, a larger amount than the loss of solids obtained from the first thickener. Instead for the next two measures, on 9th and 11th March, there were greater losses to the first thickener (respectively 0,0025 % and 0,01165 %). The peak obtained on 11th March of 0,01165 %, clarifies why the first thickener had obtained, from the purge, a concentration of lower TS compared to that of the second one. This indicates that, in any case, the quantity of TS thickened was always more preponderant for the first thickener.

The good performance of the first thickener was due to the utilization of a stirrer. This mixer, during the purge, helped the outflow of the thickened algae by scraping the wall where they usually remain attached. Only in the last analysis it seems that the mixer did not work optimally, but in reality, this appears for the escaping, with the supernatant, of most of the solids.

This loss of solids from the supernatant was probably due to the introduction of excessive amounts of water which causes the flotation of algae making them more easily induced to exit.

The reason why in some days there was a loss of solids through the supernatant greater than others although the concentration of incoming TS was the same, it could be explained by considering the situation present inside the thickener. If the thickener had more or less algae content in it, it affected the greater or lesser loss of solids through the supernatant. If there was a lot of water and a few microalgae inside the thickener and a dense feed flow, this could be a case with loss of solids from the supernatant. Another example of loss of solids from the supernatant was when there was a high concentration of microalgae inside the thickener and an inlet flow with low concentration of TS.

In Figure 27, there is shown the difference between the thickening capacity of the second thickener relative to the first.

The negative number, as in the case of the day 7th March, represented that the second thickener did not thicken more than the first thickener, how it should happen. In fact, the percentage of concentration obtained from the first one was lost in the second one obtaining a compression of 0.254 % less than the first one.

The positive number, on the other hand, represents the opposite; the second thickener thickened more than the first. During the day 11th March, the second thickener increased the percentage of TS of 0,289 % more than the thickened biomass obtained from the first one.

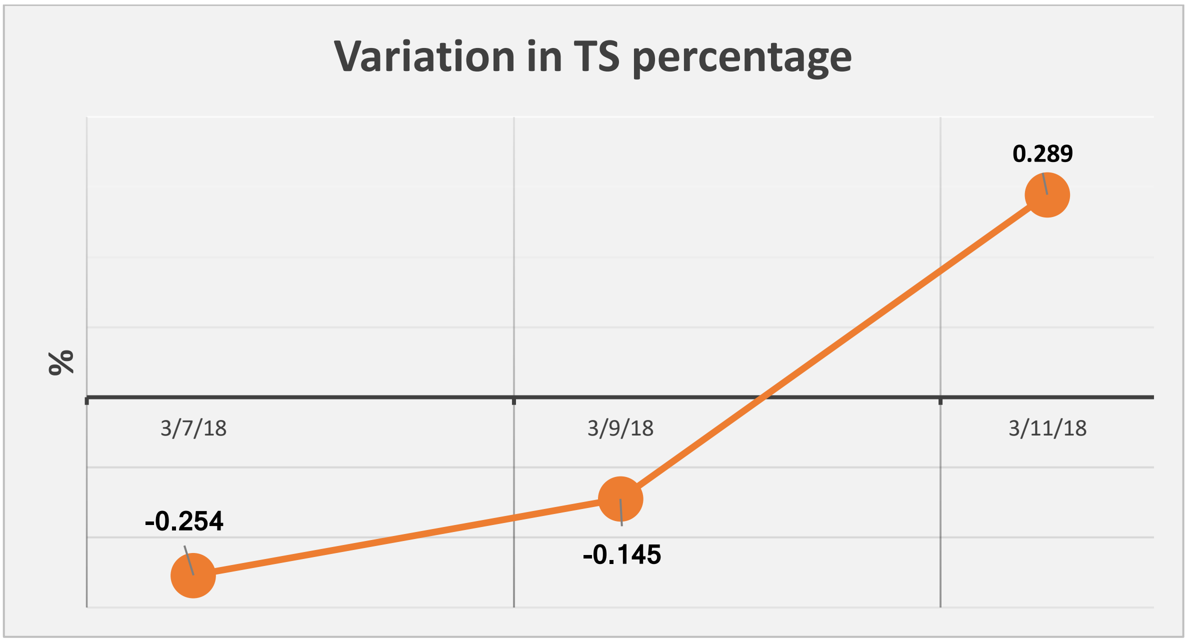

Figure 27: *Variation in TS percentage from the second thickener to the first one during the 7th, 9th and 11th March, 2018.*

5.2.3 Mass balance

Mass balance of day 7th March

1° THICKENER

$Q_i = 180\ L\ d^{-1}$	$C_i = 0{,}363\ g\ L^{-1}$
$Q_{u1} = 60\ L\ d^{-1}$	$C_{u1} = 1{,}217\ g\ L^{-1}$
$(Q_i - Q_{u1}) = 120\ L\ d^{-1}$	$C_{e1} = 0{,}00105\ g\ L^{-1}$

$$Q_i\ C_i = Q_{u1}\ C_{u1} + (Q_i - Q_{u1})\ C_{e1}$$

$$65{,}34\ g\ L^{-1} = 73{,}02\ g\ L^{-1} + \cancel{0{,}126}\ g\ L^{-1}$$

2° THICKENER

$Q_{u1} = 60\ L\ d^{-1}$	$C_{u1} = 1{,}217\ g\ L^{-1}$
$Q_{u2} = 28\ L\ d^{-1}$	$C_{u2} = 0{,}963\ g\ L^{-1}$
$(Q_{u1} - Q_{u2}) = 32\ L\ d^{-1}$	$C_{e2} = 0{,}00255\ g\ L^{-1}$

$$Q_{u1}\ C_{u1} = Q_{u2}\ C_{u2} + (Q_{u1} - Q_{u2})\ \mu_{e2}$$

$$73{,}02\ g\ L^{-1} = 26{,}96\ g\ L^{-1} + \cancel{0{,}0816}\ g\ L^{-1}$$

Mass balance of day 9th March

1° THICKENER

$Q_i = 180$ L d^{-1} $C_i = 0{,}554$ g L^{-1}

$Q_{u1} = 60$ L d^{-1} $C_{u1} = 0{,}402$ g L^{-1}

$(Q_i - Q_{u1}) = 120$ L d^{-1} $C_{e1} = 0{,}0025$ g L^{-1}

$$Q_i\, C_i = Q_{u1}\, C_{u1} + (Q_i - Q_{u1})\, C_{e1}$$

$$99{,}72 \text{ g L}^{-1} = 24{,}12 \text{ g L}^{-1} + \cancel{0{,}3} \text{ g L}^{-1}$$

2° THICKENER

$Q_{u1} = 60$ L d^{-1} $C_{u1} = 0{,}402$ g L^{-1}

$Q_{u2} = 28$ L d^{-1} $C_{u2} = 0{,}257$ g L^{-1}

$(Q_{u1} - Q_{u2}) = 32$ L d^{-1} $C_{e2} = 0{,}001$ g L^{-1}

$$Q_{u1}\, \mu_{u1} = Q_{u2}\, \mu_{u2} + (Q_{u1} - Q_{u2})\, \mu_{e2}$$

$$24{,}12 \text{ g L}^{-1} = 7{,}19 \text{ g L}^{-1} + \cancel{0{,}032} \text{ g L}^{-1}$$

Mass balance of day 11th March

1° THICKENER

$Q_i = 180$ L d^{-1} $C_i = 0{,}385$ g L^{-1}

$Q_{u1} = 60$ L d^{-1} $C_{u1} = 0{,}249$ g L^{-1}

$(Q_i - Q_{u1}) = 120$ L d^{-1} $C_{e1} = 0{,}01165$ g L^{-1}

$$Q_i\, C_i = Q_{u1}\, C_{u1} + (Q_i - Q_{u1})\, C_{e1}$$

$$69{,}3 \text{ g L}^{-1} = 14{,}94 \text{ g L}^{-1} + \cancel{1{,}40} \text{ g L}^{-1}$$

2° THICKENER

Q_{u1} = 60 L d^{-1} C_{u1} = 0,249 g L^{-1}

Q_{u2} = 28 L/d^{-1} C_{u2} = 0,538 g L^{-1}

(Q_{u1} – Q_{u2}) = 32 L d^{-1} C_{e2} = 0,00135 g L^{-1}

$$Q_{u1}\, C_{u1} = Q_{u2}\, C_{u2} + (Q_{u1} - Q_{u2})\, C_{e2}$$

$$14{,}94 \text{ g L}^{-1} = 15{,}06 \text{ g L}^{-1} + \cancel{0{,}0432} \text{ g L}^{-1}$$

The values of solids concentration of supernatant multiplied by its flow is strikethrough because it is considered an insignificant value for the purposes of the study of mass balance, as mentioned previously.

5.2.4 Considerations

To conclude, the operation of two thickeners in series had achieved better results than using only one thickener. In fact, with the use of a single thickener a TS percentage of 0.755 was reached, while with a series operation of 1.217 for the first thickener and 0.936 for the second one. The better functioning of the first with respect to the second thickener is due to the fact that the first was equipped with a stirrer which helps the output of the microalgae thickened during the purging.

5.3 Installation of a stirrer in the second thickener

The series operation of the two thickeners led to an improvement in the concentration of biomass obtained during the purges of the two thickeners. However, this was not enough to achieve a 2 TS percentage. For this reason, it was decided to introduce a stirrer also in the second thickener, of the same shape and material as the one in the first one (refer to figure X).

The operating time of the new mixer coincided with the period of extraction of the thickened biomass of the pertinent thickener.

5.3.1 Flow

A peristaltic pump discharged 6.6 L min^{-1} from the settling tank to the thickener. The settling tank ran four minutes nine times per day. The flow for every purge was 26,7 L with a total of 240 L d^{-1}. The first thickener purged two minutes nine times a day to the second thickener by a peristaltic pump. The flow of the pump of the first thickener to the second one ran two minutes with a total of 120 L d^{-1}.

The second thickener purged four minutes once a day by a peristaltic pump to the anaerobic digester. The flow of the peristaltic purge of the second thickener to the anaerobic digester ran four minutes with a total of 28 L d^{-1}.

Like the first situation with only one thickener, the quantity of microalgae produced influenced directly the time of the purges.

By means of this data, the quantity of supernatant can be calculated. So, the liters, in this case, lost by the supernatant for the first thickener, if the system was stationary, are 120 L d^{-1} while for the second thickener were 92 L d^{-1}.

5.3.2 TS percentage

As previously analyzed, the concentration of TS coming from the settler is compared with that coming out from the purge of the two thickeners.

Through Figure 28, is viable to observe that, in the period analyzed, the percentage of thickened solids was greater for the second thickener. Except for the day 27th March, it had reached a 1,729 % of TS for the first thickener and 1,38 % for the second one.

The percentage of TS obtained from the second thickener went in parallel with the percentage of TS coming from the settler. This indicates that the good functioning of the second thickener was remained constant during the measurement period.

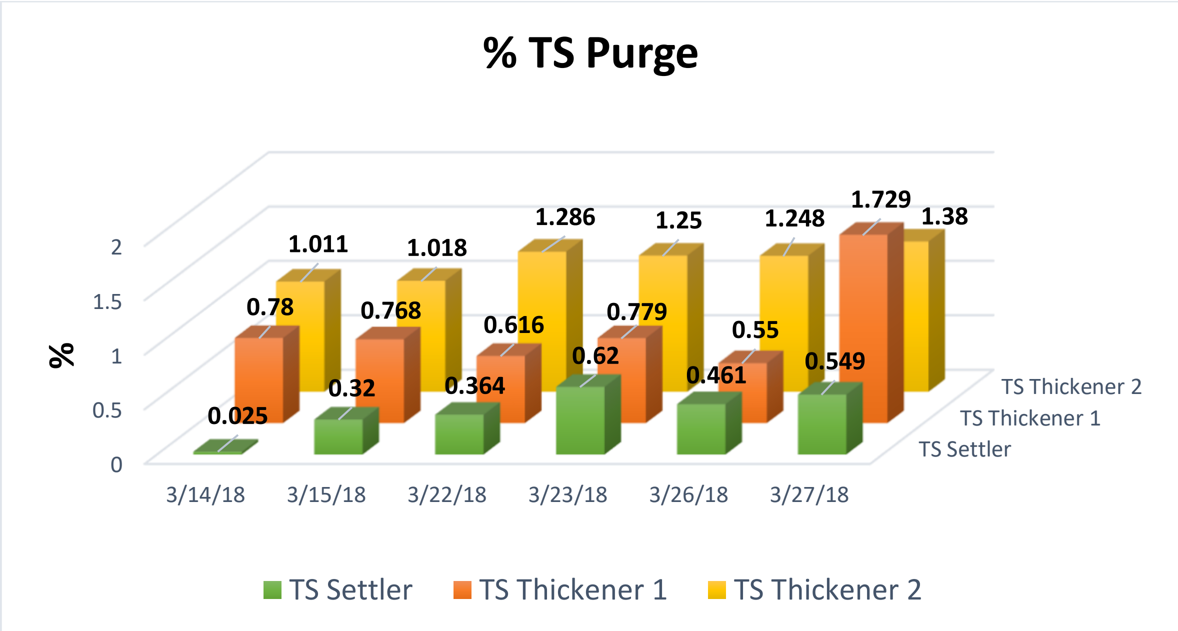

Figure 28*: Percentage of TS obtained from the purges of the two thickeners during 14th, 15th, 22th, 23th, 26th and 27th March, 2018 in comparison with the percentage of TS obtained, during the same days, from the settler.*

Regarding the supernatant analysis, it was decided to consider only two significant days, 26th and 27th March (Figure 29). In fact, as it is possible to see in figure 28, for 26th March the gap between solids outflow from first thickener and from second was greater (0,55 % for the first one and 1,248 % for the second one). This can be explained by analyzing the filtration of solids from the supernatant, in which a greater loss of solids for the first thickener was encountered (0,00785 % and 0,0019 % respectively).

During 27th March, however, the opposite happened; there was a higher loss of solids through the supernatant from the second thickener than the first one. This was probably due to the fact that by entering a high concentration of thickened solids in the second thickener, it could increase the amount of solids that mix with water and float.

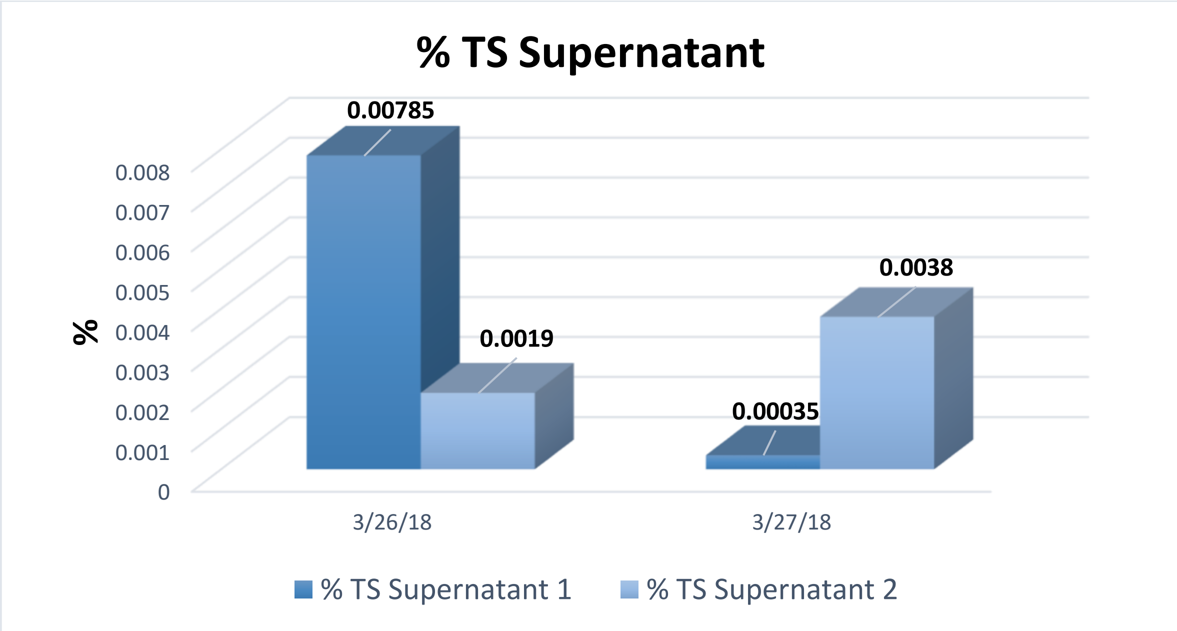

Figure 29: *Percentage of TS obtained from the supernatant of the two thickeners during 26th and 27th March, 2018.*

In all cases, a larger concentration of TS was obtained in the second thickener. This means that with the use of the stirrer, the thickener operation was improved, reaching considerable results.

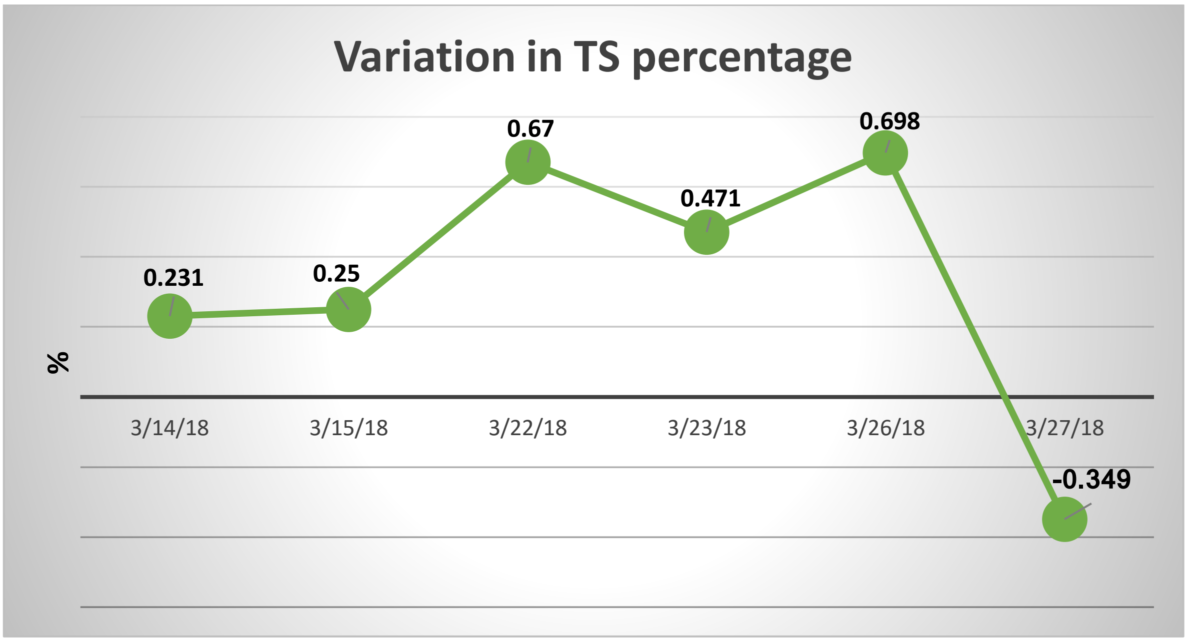

Figure 30: *Variation in TS percentage from the second thickener to the first one during 14th, 15th, 22th, 23th, 26th and 27th March, 2018.*

As a result of this latest graph (Figure 30), it is indicated how the relationship between the two thickeners was not uniform. On 22th March, is presumed there had been an event similar to the day 26th.

In these two specific days, in fact, there was a greater raising of concentration of solids for the second thickener compared to the first one. This last had lost more solids through the supernatant because the flow coming from the settler held a greater quantity of water which caused turbulence in the superficial areas of the thickener. This explains the spike in the second thickener.

Instead, there was a normal increase for 23th compared to14th and 15th March, because it is in line with the increase in solids deriving from the settler purge. Finally looking at 26th and 27th, the difference reflects the comment made before. This accounts for the drastic drop on 27th March (the second thickener has compressed less than a 0,349 % of ST).

To better understand the difference of the percentage of algae thickened by the two thickeners, the photos are shown of the samples analysed for 27th March (Fig. 31).

On this day, it can be seen the high concentration of algae coming out from the two purges, although the first purge had a slightly higher percentage than the second.

a) b)

Figure 31*: a) Samples of the purge of the first thickener, each taken every 15 seconds for 2 minutes of purge during the day 27th March, 2018; b) Samples of the purge of the second thickener, each filled every 30 seconds for 4 minutes of purge during the day 27th March, 2018.*

The first image shows the samples taken every 15 seconds during two minutes of the functioning of the purge. It can be seen how the second purge (figure 31b) was more thickened than the first one.

5.3.3 Mass balance

Mass balance of day 26th March

1° THICKENER

$Q_i = 240$ L d^{-1} $C_i = 0{,}461$ g L^{-1}

$Q_{u1} = 120$ L d^{-1} $C_{u1} = 0{,}55$ g L^{-1}

$(Q_i - Q_{u1}) = 120$ L d^{-1} $C_{e1} = 0{,}00785$ g L^{-1}

$$Q_i\, C_i = Q_{u1} C_{u1} + (Q_i - Q_{u1})\, C_{e1}$$

$$110{,}64 \text{ g L}^{-1} = 66 \text{ g L}^{-1} + \cancel{0{,}942} \text{ g L}^{-1}$$

2° THICKENER

$Q_{u1} = 120$ L d^{-1} $C_{u1} = 0{,}55$ g L^{-1}

$Q_{u2} = 28$ L d^{-1} $C_{u2} = 1{,}248$ g L^{-1}

$(Q_{u1} - Q_{u2}) = 92$ L d^{-1} $C_{e2} = 0{,}0019$ g L^{-1}

$$Q_{u1}\, C_{u1} = Q_{u2}\, \mu_{u2} + (Q_{u1} - Q_{u2})\, C_{e2}$$

$$66 \text{ g L}^{-1} = 35 \text{ g L}^{-1} + \cancel{0{,}1748} \text{ g L}^{-1}$$

Mass balance of day 27th March

1° THICKENER

$Q_i = 240$ L d^{-1} $C_i = 0{,}549$ g L^{-1}

$Q_{u1} = 120$ L d^{-1} $C_{u1} = 1{,}729$ g L^{-1}

$(Q_i - Q_{u1}) = 120$ L d^{-1} $C_{e1} = 0{,}00035$ g L^{-1}

$$Q_i\, C_i = Q_{u1}\, C_{u1} + (Q_i - Q_{u1})\, C_{e1}$$

$$131{,}76 \text{ g L}^{-1} = 207{,}48 \text{ g L}^{-1} + \cancel{0{,}042} \text{ g L}^{-1}$$

2° THICKENER

$Q_{u1} = 120\ L\ d^{-1}$ $C_{u1} = 1{,}729\ g\ L^{-1}$

$Q_{u2} = 28\ L\ d^{-1}$ $C_{u2} = 1{,}38\ g\ L^{-1}$

$(Q_{u1} - Q_{u2}) = 92\ L\ d^{-1}$ $C_{e2} = 0{,}0038\ g\ L^{-1}$

$$Q_{u1}\ C_{u1} = Q_{u2}\ C_{u2} + (Q_{u1} - Q_{u2})\ C_{e2}$$

$$207{,}48\ g\ L^{-1} = 38{,}64\ g\ L^{-1} + \cancel{0{,}35}\ g\ L^{-1}$$

5.3.4 Considerations

In conclusion, with the introduction of a stirrer in the second thickener, identical to the one present in the first thickener, the operation improves sharply. The two mixers operate simultaneously with the running of the respective peristaltic pumps. For the reason of this new introduction, greater thickened microalgae values were achieved compared to those obtained in the previous conditions. In fact, the achievement of 1% of TS for the second thickener had become habitual.

5.4 Change in the operational time of both stirrers

A change on the operating time of the stirrers was made because, analyzing the inside of them, especially in the second thickener, the amount of thickened algae at the outlet of the pump did not reflect at all the amount of algae present inside.

This was attributed to the incorrect timing of the mixer. In fact, if the stirrer worked during the whole pumping period, it would move the thickened part slightly, causing it to float. It is desirable that this does not happen, because it destroys the thickened algae. Therefore, it was necessary to change the timing of the mixer to achieve a purge with the most thickened biomass as possible.

For the first minute of pumping the mixer did not stir, during which there was certainly an outflow of thickened algae. The stirrer was then activated starting from the second minute up to one minute before the pumping time ended.

When the mixer was not on for the first minute, but the pump was, it was found that all of the algae at the bottom of the thickener was not disturbed, but just pulled out by the pump. When the stirrer was turned on after one minute, the stirrer removed the algae that was attached to the walls of the thickener. The stirrer was turned off one minute before pumping ended. This because if turbulence and floating algae were created, the last minute would have allowed the floating algae the time, even if very limited, to flow down.

5.4.2 Flow

The flow conditions remained the same as in the previous phase.

5.4.1 TS percentage

This change effects the analysis of the TS taken during the two purges. Analyzing Figure 32, it is clear that the yield of both thickeners was much better than previous situations. The percentage of TS obtained from the second thickener reached upwards of 2%.

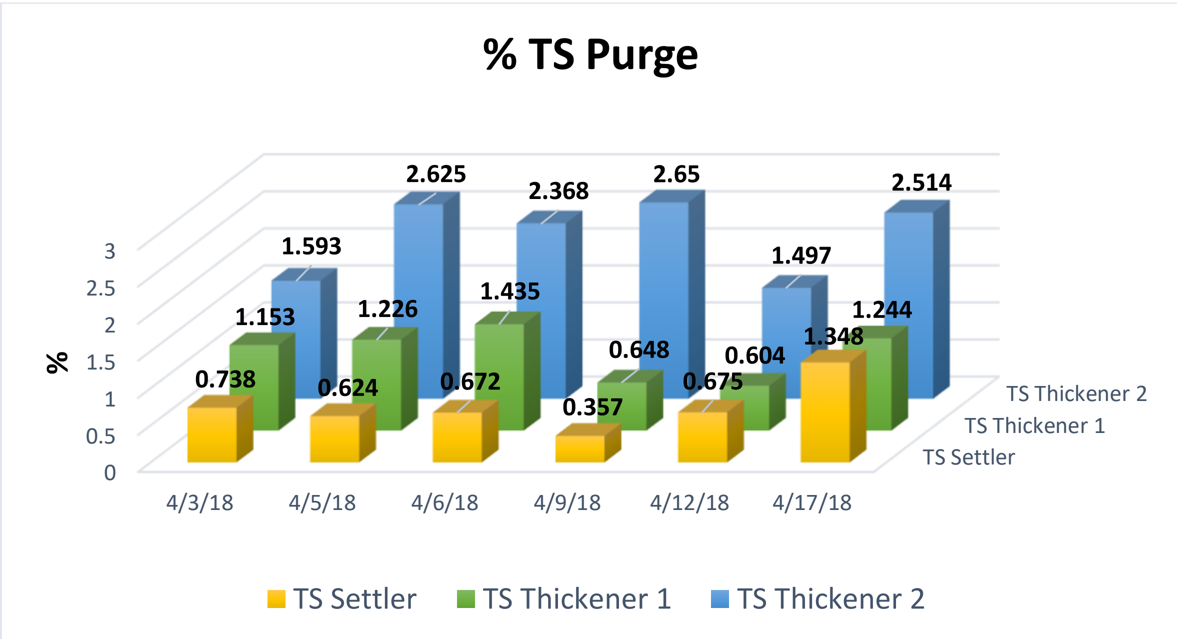

***Figure 32**: Percentage of TS obtained from the purges of the two thickeners during 3th, 5th, 6th, 9th, 12th and 17th April in comparison with the TS obtained, during the same days, from the settler.*

The second thickener had reached the best yield on 9th April with a 2,65 % of TS. The latter had a very small loss of solids through to the supernatant (Figure 34) and, given the low quantity of solids deriving from the settler (0,357 %), the 2.65 % of TS was directly due to its excellent operation.

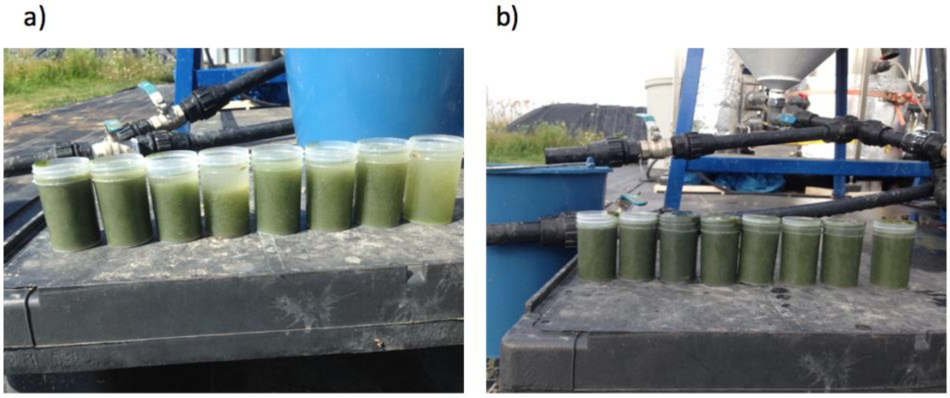

Figure 33: a) Samples of the purge of the first thickener, each taken every 15 seconds for 2 minutes of purge during the day 9th April, 2018; b) Samples of the purge of the second thickener, each filled every 30 seconds for 4 minutes of purge during the day 9th April, 2018.

Figure 33 shows how the second thickener (Figure 33b) managed to obtain a thickened biomass concentration better than the first thickener (Figure 33a), during the day 9th April, 2018.

Comparing the percentage of TS obtained with the filtration process of the two supernatants (Figure 34), on the last day measured, 17th April, it is noted that a great loss of algae from the supernatant occurred. It can be clearly seen, not only from the figure 34, but also from the comparison between the high quantity of algae coming from the settler and the small quantity obtained by the purges of the two thickeners (Figure 33). During 9th April, a small loss of thickened algae was measured for both thickeners.

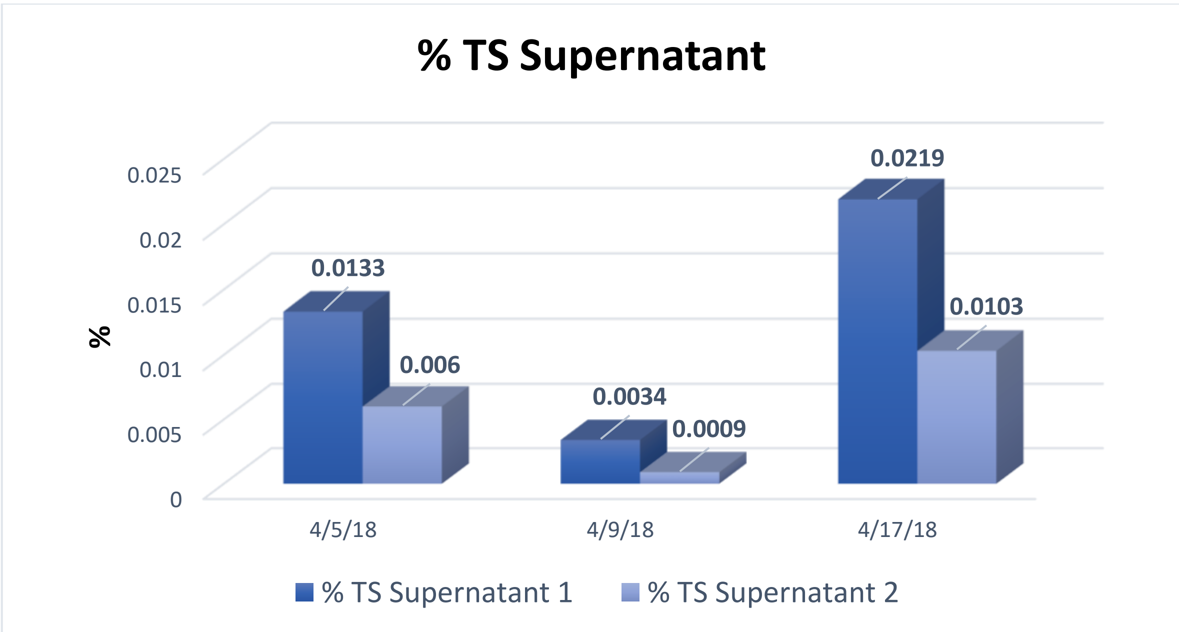

Figure 34: Percentage of TS obtained from the supernatant of the two thickeners during 5th, 9th and 17th April, 2018.

The difference in percentage of the TS obtained from the second thickener with respect to the first one is found in the Figure 35. For the first day considered, 3rd April, the performance of the two thickeners was almost the same, with a percentage greater than 0.44 % of TS present in the purge of the second thickener with respect to the first.

Falling cases may occur, such as for 6th and 12th April, that can be due or for a good thickening obtained already by the first thickener, or for a malfunction of the first thickener that caused an introduction of a turbulent flow into the second thickener, preventing it from operating in the best possible way. (On fall days the second thickener has increased the thickened of microalgae compression only by 0.933 % and 0.893 % respectively).

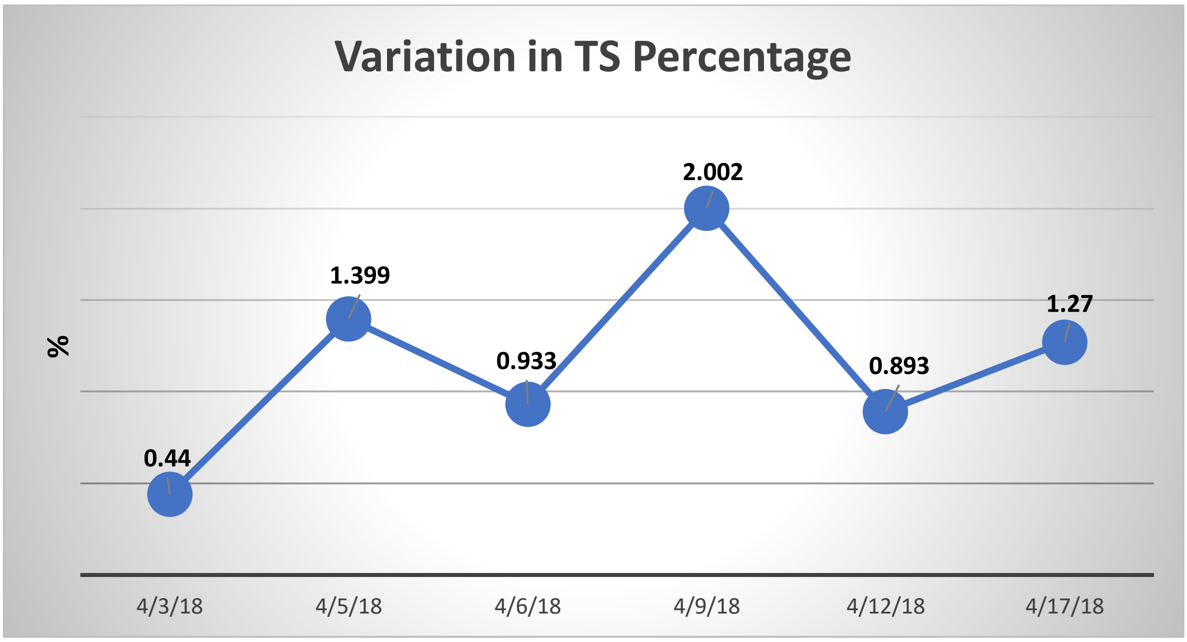

***Figure 35**: Variation in solid percentage from the second thickener to the first one during 3th, 5th, 6th, 9th, 12th and 17th April, 2018.*

5.4.3 Mass balance

Mass balance of day 5th April

1° THICKENER

$Q_i = 240$ L d^{-1} $C_i = 0{,}624$ g L^{-1}

$Q_{u1} = 120$ L d^{-1} $C_{u1} = 1{,}226$ g L^{-1}

$(Q_i - Q_{u1}) = 120$ L d^{-1} $C_{e1} = 0{,}0133$ g L^{-1}

$$Q_i\, C_i = Q_{u1}\, C_{u1} + (Q_i - Q_{u1})\, C_{e1}$$

$149{,}76\ g\ L^{-1} = 147{,}12\ g\ L^{-1} + 1{,}6\ g\ L^{-1}$

2° THICKENER

$Q_{u1} = 120\ L\ d^{-1}$ $C_{u1} = 1{,}226\ g\ L^{-1}$

$Q_{u2} = 28\ L\ d^{-1}$ $C_{u2} = 2{,}625\ g\ L^{-1}$

$(Q_{u1} – Q_{u2}) = 92\ L\ d^{-1}$ $C_{e2} = 0{,}006\ g\ L^{-1}$

$Q_{u1}\ C_{u1} = Q_{u2}\ C_{u2} + (Q_{u1} – Q_{u2})\ C_{e2}$

$147{,}12\ g\ L^{-1} = 73{,}5\ g\ L^{-1} + \cancel{0{,}552}\ g\ L^{-1}$

<u>Mass balance of day 9th April</u>

1° THICKENER

$Q_i = 240\ L\ d^{-1}$ $C_i = 0{,}357\ g\ L^{-1}$

$Q_{u1} = 120\ L\ d^{-1}$ $C_{u1} = 0{,}648\ g\ L^{-1}$

$(Q_i – Q_{u1}) = 120\ L\ d^{-1}$ $C_{e1} = 0{,}00034\ g\ L^{-1}$

$Q_i\ C_i = Q_{u1}\ C_{u1} + (Q_i – Q_{u1})\ C_{e1}$

$85{,}68\ g\ L^{-1} = 77{,}76\ g\ L^{-1} + \cancel{0{,}038}\ g\ L^{-1}$

2° THICKENER

$Q_{u1} = 120\ L\ d^{-1}$ $C_{u1} = 0{,}648\ g\ L^{-1}$

$Q_{u2} = 28\ L\ d^{-1}$ $C_{u2} = 2{,}65\ g\ L^{-1}$

$(Q_{u1} – Q_{u2}) = 92\ L\ d^{-1}$ $C_{e2} = 0{,}0009\ g\ L^{-1}$

$Q_{u1}\ C_{u1} = Q_{u2}\ C_{u2} + (Q_{u1} – Q_{u2})\ C_{e2}$

$77{,}76\ g\ L^{-1} = 74{,}2\ g\ L^{-1} + \cancel{0{,}08}\ g\ L^{-1}$

Mass balance of day 17th April

1° THICKENER

$Q_i = 240\ L\ d^{\cdot 1}$ $\quad$ $C_i = 1{,}348\ g\ L^{-1}$

$Q_{u1} = 120\ L\ d^{-1}$ $\quad$ $C_{u1} = 1{,}244\ g\ L^{-1}$

$(Q_i – Q_{u1}) = 120\ L\ d^{-1}$ $\quad$ $C_{e1} = 0{,}0219\ g\ L^{-1}$

$$Q_i\ C_i = Q_{u1}\ C_{u1} + (Q_i – Q_{u1})\ C_{e1}$$

$$323{,}52\ g\ L^{-1} = 149{,}28\ g\ L^{-1} + 2{,}6\ g\ L^{-1}$$

2° THICKENER

$Q_{u1} = 120\ L\ d^{-1}$ $\quad$ $C_{u1} = 1{,}244\ g\ L^{-1}$

$Q_{u2} = 28\ L\ d^{-1}$ $\quad$ $C_{u2} = 2{,}514\ g\ L^{-1}$

$(Q_{u1} – Q_{u2}) = 92\ L\ d^{-1}$ $\quad$ $C_{e2} = 0{,}0103\ g\ L^{-1}$

$$Q_{u1}\ C_{u1} = Q_{u2}\ C_{u2} + (Q_{u1} – Q_{u2})\ C_{e2}$$

$$149{,}28\ g\ L^{-1} = 70{,}4\ g\ L^{-1} + \cancel{0{,}95}\ g\ L^{-1}$$

5.4.4 Considerations

To conclude, the second thickener had reached the maximum yield during the days 5th and 9th of April with a percentage of TS of 2,625 and 2,65 respectively. Instead, the first thickener had attained a quantity of thickened solids of 1,435 as maximum value. The latter had a loss of solids through the supernatant greater than the second thickener with a 0.0133% for the day 5th April. During 9th April, the second thickener thickened more than the first of a 2.002% in TS.

The ratio of concentration (R_c) that is between dry concentration of the microalgae thickened and dry concentration of the microalgae entrants is very important in thickened process.
The last phase of this study is clearly the best also because if we calculate R_c we find that it is between 1,5 and 2,0, which are optimal values for a thickener. For example, the R_c during 5th April was 2,14 while for the 17th April was 2,02.

Surely it emerges that, with the new operating hypotheses, it is no longer possible to reach negative differences between the solids concentration obtained from the second thickener with respect to the first. This last consideration is no less important, on the contrary, it helps us to understand how any kind of change can have a positive and negative influence on the final results that we want to achieve.

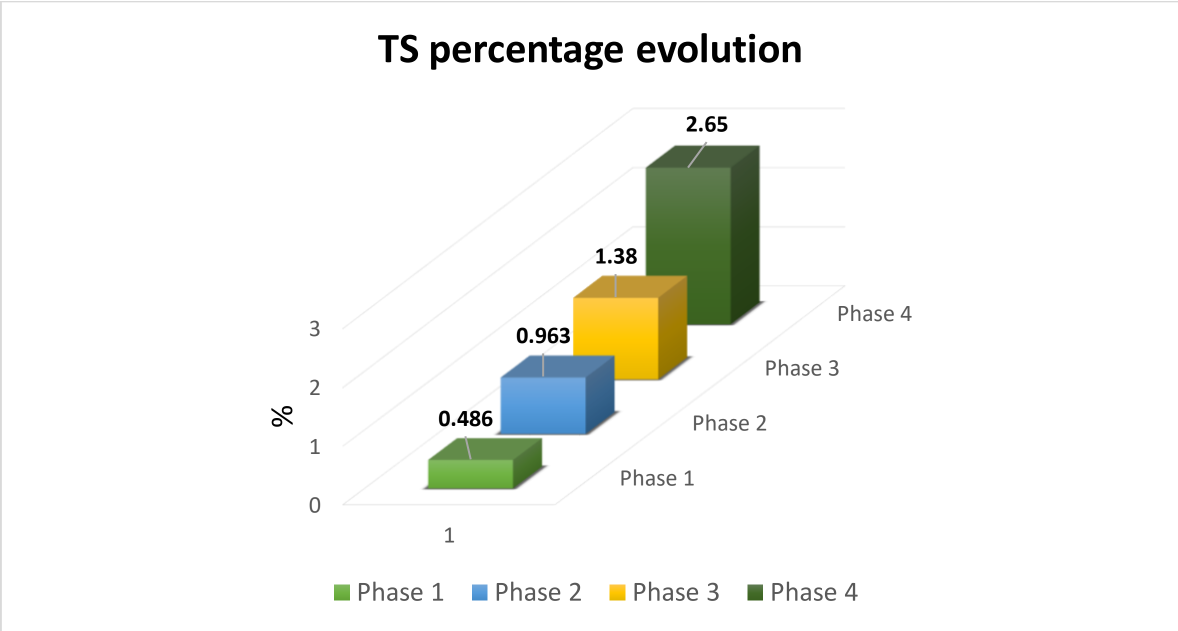

Figure 36: *The evolution of TS percentage during the different phases analysed (Phase 1 = Operation of the single thickener by the installation of a stirrer; Phase 2 = Construction and installation of a second thickener; Phase 3 = Installation of a stirrer in the second thickener; Phase 4 = Change in the operational time of both stirrers).*

In Figure 36, it is possible to see the increasing improvement of the performance of the second thickener during the four distinct phases of the study. Starting from a 0.4% thickening, a 2% was reached, which was the final objective of the work.

6. Conclusion

In this study, a real model of microalgae thickening is analyzed in a wastewater phytodepuration system. Based on the solids flux concept and mass balance of one and later of two thickeners, this study is designed to predict and analyze the percentage of TS concentration present in the feed flow and underflow of a thickener with the final aim of reaching 2% of ST.
The conclusions of this work can be summarized as follows:

1. After carrying out an analysis of the thickener function, studying not only the mass of the thickened algae coming out of the purge, but monitoring the change that occur inside the thickener after a purge transpires, it has been noted that its performance had to be improved. The principal fault was based on the fact that part of the thickened microalgae remained adhered to the wall during the purge period. For this reason, a stirrer has been installed, that scraped the algae attached to the wall during the purge period. The choice of the material and the shape of the mixer have been well studied to achieve the best functionality. Thanks to the introduction of the stirrer, it was possible to obtain an improvement, even though limited, with the achievement of a maximum of 0.755% of TS at the exit of the purge.
2. Given that even with the introduction of a stirrer, a sufficient thickened concentration had not been reached, it was decided to find a new solution. The latter was based on the addition of a new thickener. With a series system obtained from the introduction of a new thickener identical to the first, the impact that the algae-water flow had during the entry into the thickener was reduced. The good functioning in series was also dictated by the fact that the thickened algae reached a longer retention period in the thickener. So, the biomass, having already passed a period in the first thickener, even though short, left the second more concentrated. The stirrer, for a first analysis, was placed only in the first. The first thickener in these analyses, in fact, resulted with a better performance than the second. It even reached a total of 1.217% of TS at the output while the second one remained below 1%.
3. Furthermore, it was decided to place two deposits connected to the supernatant of the relative thickeners so that even the solids that escaped through it could be calculated. The percentage of TS escaping from the supernatant varied according to the amount of microalgae present in the inlet flow to each thickener, to a possible high input flow and to a possible malfunction of the stirrer. For these causes, the first thickener was always being the one with higher values. In fact, the flow that entered was always more liquid than the one entering into the second

thickener and always with a greater flow, which caused a higher flotation of the algae in the water.

In any case, it was concluded that these numbers were irrelevant because they were too small for the final purpose. For this reason, it was not given much importance or dedication to the change of these values.

4. With the considerations previously made on the better functioning of the first thickener as regards the second one, a conclusion was made, to place an identical stirrer in the second thickener following the same series in form, material and stirring time. Thanks to this introduction, the analysis of the second thickener was reaching better concentrations of ST percentage, which were greater than those achieved by the first (1.217% of TS for the first thickener were reached and 0.936 % for the second one).

   Having seen that the introduction of a second mixer was not enough to reach a 2 % of thickened solids, it was decided to change the mixer time: from a period of agitation that worked for all pumping period to a limited period. The stirrer, therefore, functioned for a minute after the purge was in action till a minute before it was stopped.

   However, with the change in mixer periods during the purge period, it was possible to bring the second thickener to concentrate the microalgae to the desired thickening of 2% in TS. Exactly the second thickener managed to get a 2,6 % of TS.

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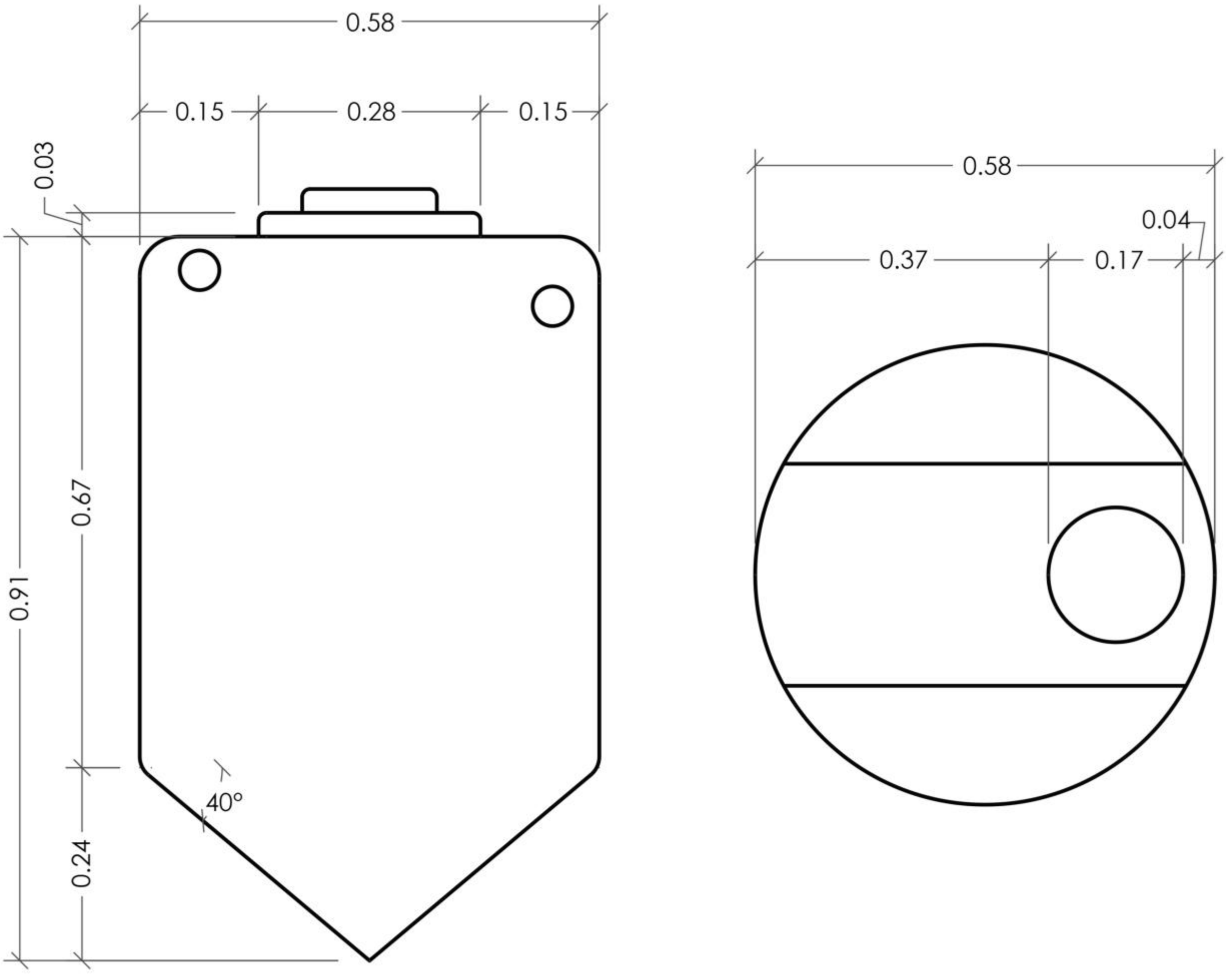
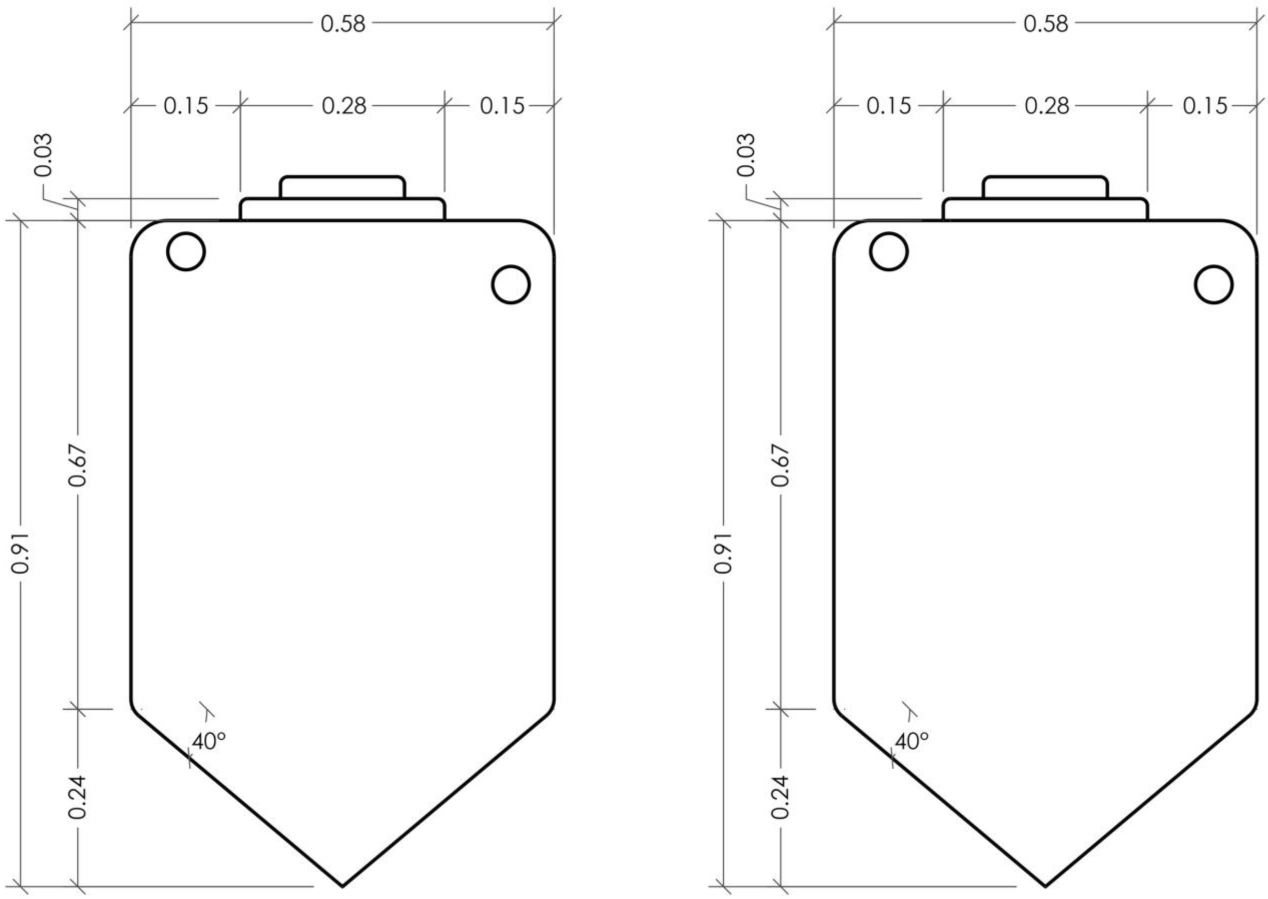
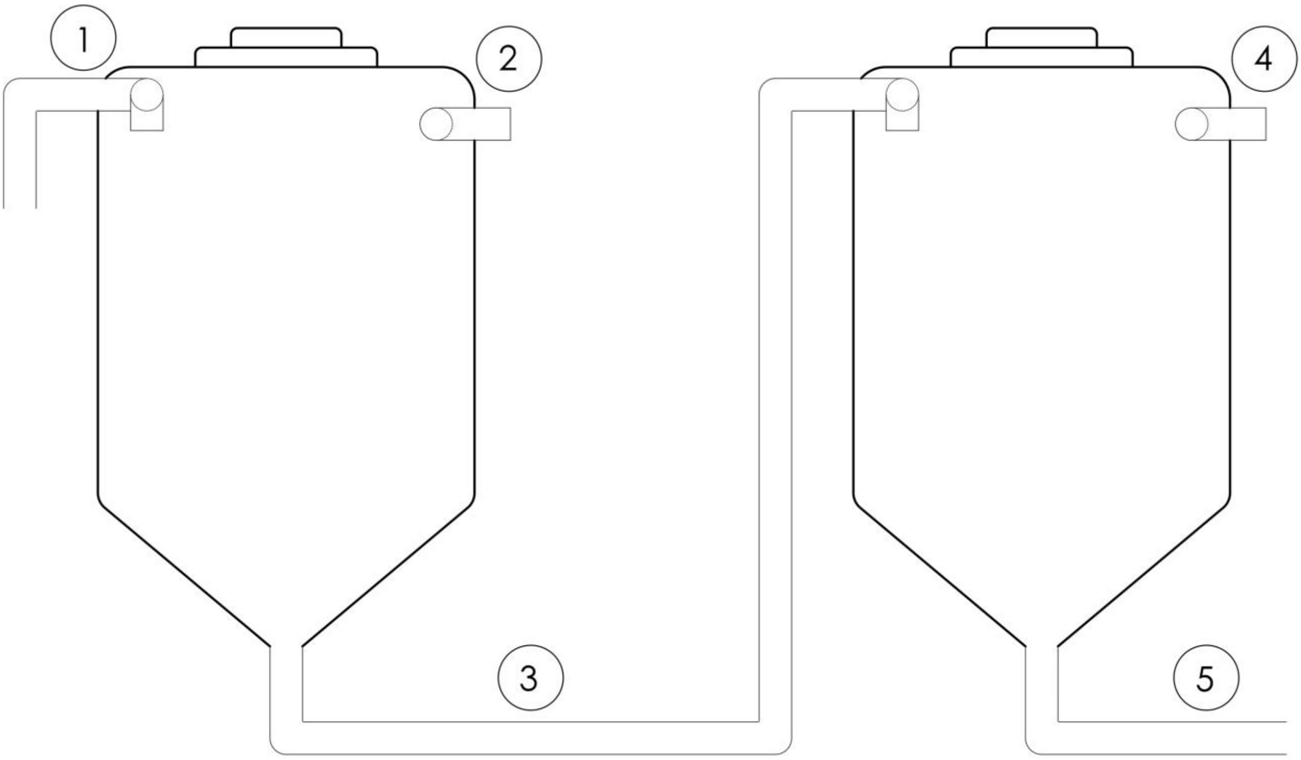
Annexes



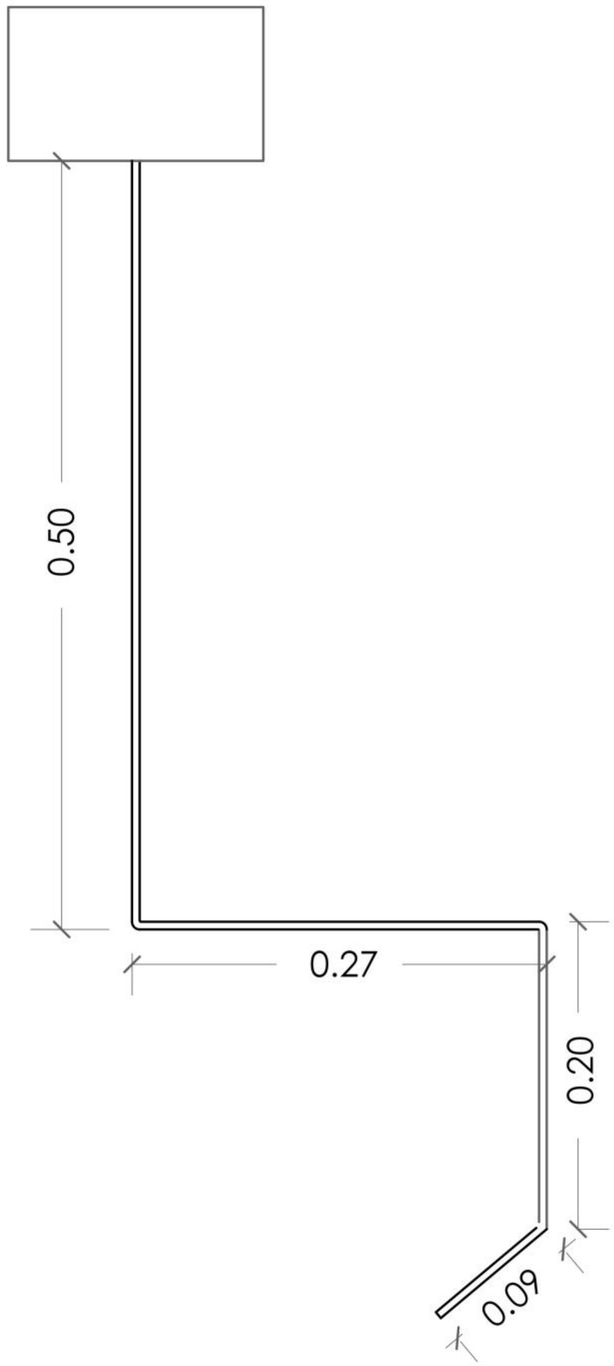
***Annex 1**: Measures of the thickener of the horizontal and top projection.*



***Annex 2**: Measurements of the two thickeners that will be placed in series*



***Annex 3**: The two thickeners operating in series. 1) Inlet flow; 2) and 4) Outflow of supernatant; 3) Underflow of thickened biomass from the first thickener to the second thickener. 5) Underflow of thickened biomass from the second thickener to the anaerobic digester.*



Annex 4: *Measures of the stirrer.*