

# MODELLING OF THE DISPERSED AIR FLOTATION PROCESS APPLIED TO DAIRY WASTEWATER TREATMENT

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**Abstract** - The aim of this work was to develop a mathematical model for a continuously operating flotation tank to provide the scale-up and optimization of the separation system. The fluid dynamic of the tank was assumed to be a perfect mixture and the flotation kinetics to be a first-order reaction, as suggested by the batch operation. The experiments were carried out in a continuously operating 60 L tank, used in the treatment of a synthetic dairy waste at its isoelectric point. A mathematical model that describes the behavior of a continuously operating flotation tank used in the treatment of a synthetic dairy waste at its isoelectric point is not only proposed, but also validated with experimental data.

*Keywords:* flotation, dairy waste, continuous operation.

## INTRODUCTION

Dairy products are of major importance in the food industry. Despite their economical advantages, these processes have considerable potential for polluting, so one must be aware of the need to treat the waste before discharging it. As environmental laws become stricter, new technologies and strategies for wastewater treatment need to be developed. Currently, much effort is being devoted to studying the feasibility of flotation systems as a pretreatment path for dairy wastes.

Flotation processes have been widely and successfully used for mineral treatment. Recently, these processes have also been employed as an alternative strategy for wastewater treatment. Unlike other technologies, flotation processes can be successfully applied to systems where differences between the density of the continuous phase and of

the particulate phase are small, classic examples are flocculent emulsions and suspensions.

In this work, a mathematical model that describes the behavior of a continuously operating flotation tank used in the treatment of a synthetic dairy waste at its isoelectric point was not only proposed, but also validated with experimental data.

## EXPERIMENTAL

### Experimental Setup

In this work, an acrylic rectangular flotation tank was used. This tank was built at LSP/COPPE and its main characteristic is the porous air sparger located at its bottom through which air is fed into the vessel. Waste feed and discharge are located across from one another, the waste feed line is connected nearly

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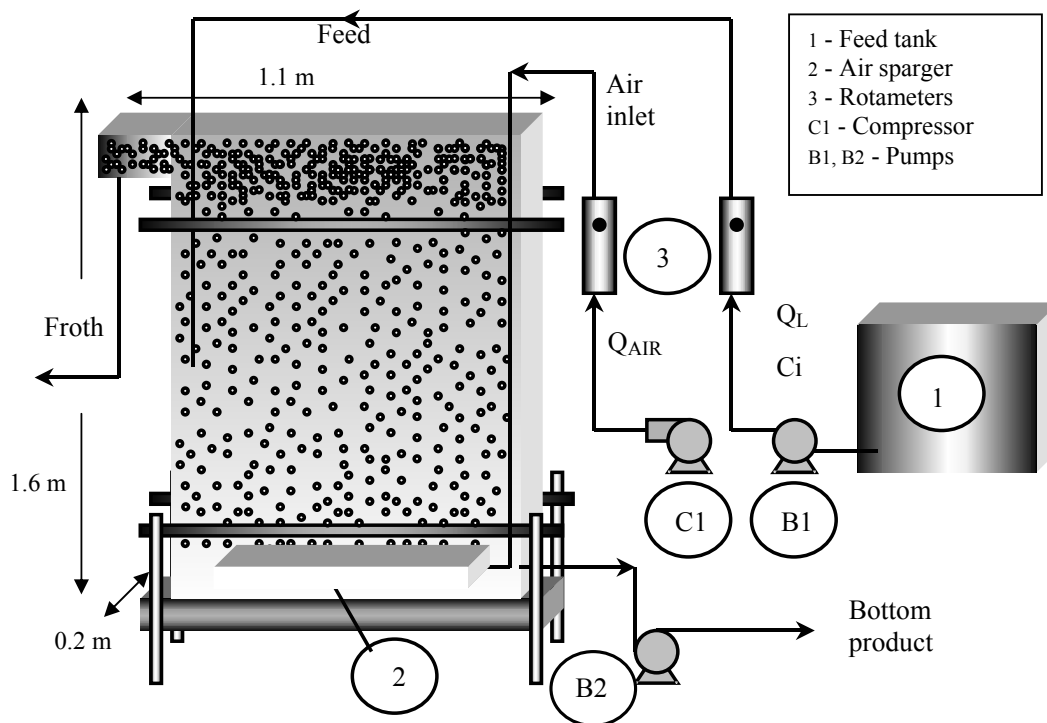
halfway up the tank, while the discharge line is connected close to the bottom of the tank. Figure 1 contains a schematic representation of the experimental setup used in this study. It is composed of a 75 L tank used to feed the flotation tank, a centrifugal pump (B1, ½ HP), a peristaltic pump (B2; Cole & Palmer), an air compressor (C1; CETT378) and rotameters (GILMONT), used to measure both the air and the waste flow rate into the flotation tank.

The experimental apparatus can be operated either in batch or continuous mode. In batch operation, the flotation tank is purged with air and then it is charged with the desired amount of waste. Once the airflow rate is set, samples are regularly withdrawn from the tank for spectrophotometrical analysis. Continuous mode operation is different.

The tank is initially operated in batch mode until the clarified reaches a specific concentration set point. Then, both the waste feed pump and the discharge tank pump are turned on without changing the air flow rate. Samples were also withdrawn from the flotation tank.

### Dairy Wastewater

The synthetic wastewater used in this work was prepared by the addition of powdered milk (specified in Table 1) to water under mechanical shaking. Proteins and fats were precipitated by slowly adding an aqueous 1:10 HCl solution until the isoelectric pH point of the waste was reached. The final synthetic dairy waste can be characterized as a homogeneous suspension at a concentration of 0.1%.



**Figure 1:** Experimental Set-up (Height = 1.4 m, Width = 0.5 m, Thickness = 0.1 m)

**Table 1:** Powdered milk La Serenissima, Mastellone Hnos S.A., Argentina

Powdered Milk Composition (100 g)	
Lipids	26.0 g
Proteins	26.0 g
Lactose	38.0 g
Ash	7.0 g
Moisture	3.0 g

**Table 2: Operating Conditions**

Waste feed concentration (m/v)	0.1%
Waste feed flow rate (L/min)	0.95 and 3.0
Airflow rate (L/min)	6.3; 11.2 and 14.6
PH (Isoelectric point)	4.5-4.7

## Experimental Section

### a) Waste Flocculent Structure Characterization

Using Malver Mastersizer Micro Plus (MAF 501) equipment, the average diameter of the waste flocks,  $D_f = 34.9 \mu\text{m}$ , was obtained. Using the centrifugal technique presented by França (2000), the density of the flocks was determined and a value at  $\rho = 1.13 \pm 0.05 \text{ g/cm}^3$  was found.

### b) Average Bubble Diameter

Average bubble diameter was measured using an image analyzer software in order to examine the photographs taken of the system.

### c) Concentrations of Milk and Dyes

These concentrations were measured through spectrophotometrical analysis. The equipment used was a Hach DR/2000 spectrophotometer operating at 400 nm. Aiming to correctly determine the concentration of the milk, strong shaking was necessary to break the flocks.

### d) Process Efficiency ( $\eta$ )

Process efficiency was calculated based upon the concentration of milk in the feed and discharge streams. Equation (1) defines the efficiency of separation.

$$\eta (\%) = \left( 1 - \frac{C}{C_a} \right) \times 100 \quad (1)$$

where  $C_a$  and  $C$  are the concentration of flocculated milk in the feed and discharge streams, respectively.

### e) Operating Conditions

Operating conditions for the experimental runs are reported in Table 2.

### Residence-Time Distribution

Residence-time distribution is an important tool in acquiring knowledge of the fluid dynamics of the tank and should be used in tank design and scale-up. If a pulse input analysis is done, the residence-time distribution function, the mean residence time and the variance are given, respectively, by Equations (2) to (4) (Fogler, 1970).

$$E(t) = \frac{C_{\text{pulse}}(t)}{\int_0^{\infty} C_{\text{pulse}}(t) dt} \quad (2)$$

$$\bar{t}_c = \int_0^{\infty} t \cdot E(t) dt \quad (3)$$

$$\sigma_t^2 = \int_0^{\infty} t^2 \cdot E(t) dt \quad (4)$$

These variables can be experimentally obtained through a careful analysis of the evolution of a tracer concentration after its pulse injection into the system. Considering “N” well-mixed tanks in series, the distribution function, using dimensionless variables is given by

$$E(\theta) = \frac{N \cdot (N \cdot \theta)^{N-1}}{\Gamma(N)} \cdot e^{-\theta} \quad (5)$$

The number of tanks in series can be calculated using Equation (6), where  $\sigma_0^2$  corresponds to the variance of the experimental curve  $E(\theta)$  versus  $\theta$ .

$$N = \frac{1}{\sigma_0^2} \quad (6)$$

For only one well-mixed tank, Equation (5) becomes

$$E(\theta) = e^{-\theta} \quad (7)$$

The residence-time distribution of the tank used in this work was experimentally determined. The tank was operated continuously, with prespecified air and water flow rates. Once the desired operating conditions were achieved, a volume of 500 mL of tracer (methylene blue) was added at the top of the tank, starting the test. Samples were withdrawn at the bottom (cleaned stream) of the tank and the tracer concentration was determined through spectrophotometrical analysis.

### Flotation Kinetics

Knowledge of flotation kinetics is an important tool not only in determining process feasibility but also in achieving a good design and scale-up. Many approaches used to determine flotation kinetics can easily be found in literature; however, the easiest and most frequently used approach relates the flotation process to a chemical reaction. Based on this approach, the consumption of particles by the flotation process is given by Equation (8):

$$\frac{dC}{dt} = -k \cdot C^n \quad (8)$$

where  $C$  is the concentration of particles inside the tank and  $k$  is the flotation kinetic constant.

### Modeling

Assuming the flotation tank to be a series of “ $N$ ” well-mixed tanks, a material balance of the flocculated milk was calculated in these tanks adopting a generic kinetic expression. We also assumed the porosity of the liquid ( $\varepsilon_L$ ) to be close to one because of the operating conditions used. The system of equations presented below describes the start-up of the continuous operation mode.

$$\begin{cases} V_i \cdot \frac{dC_i(t)}{dt} = Q_a \cdot [C_{i-1}(t) - C_i(t)] - \\ -k \cdot [C_i(t)]^n \cdot V_i \\ t = t_0, C_i(t_0) = C_F \\ C_0 = C_a \\ \sum_{i=1}^N V_i = V_T, i = 1, 2, \dots, N \end{cases} \quad (9)$$

where  $C_a$  and  $Q_a$  are the concentration and flow of the waste feed stream, respectively;  $k$  is the kinetic constant, and  $V_i$  and  $C_i$  are the volume and concentration of tank  $i$ , respectively.  $C_F$  corresponds to the concentration at the end of the batch and prior to start-up of the continuous operation mode ( $t_0$  is the instant when the continuous operation mode was started) and  $V_T$  is the total volume of liquid in the tank (60 L).

The initial batch can be modeled using the following equation:

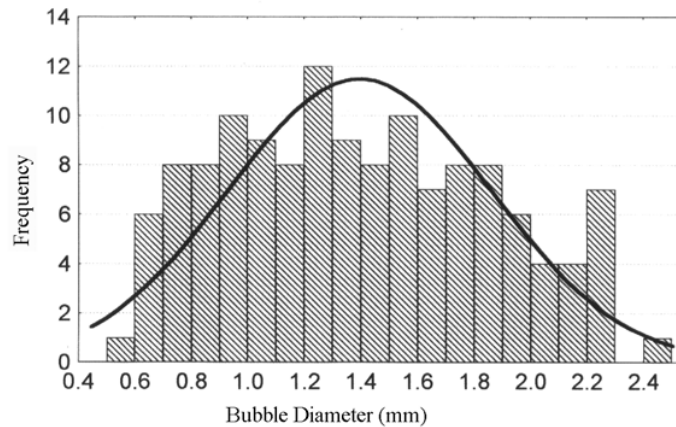
$$\begin{cases} \frac{dC(t)}{dt} = -k \cdot [C(t)]^n \\ t = 0, C(0) = C_a \end{cases} \quad (10)$$

## RESULTS AND DISCUSSION

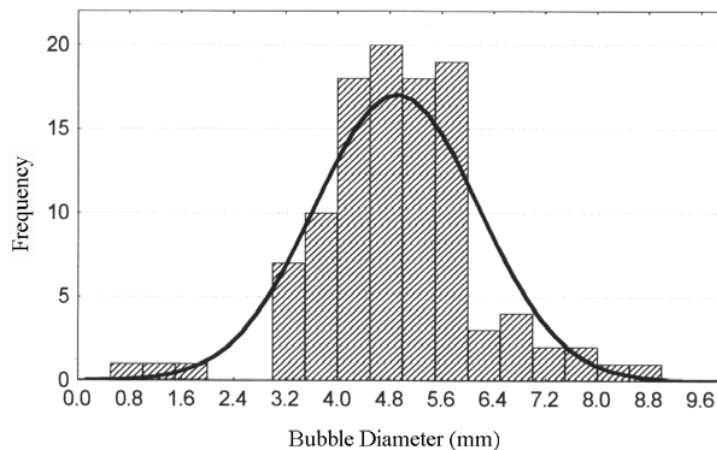
### Average Bubble Diameter

Generation of bubbles is a key step in the flotation process, mainly for the separation of small particles (10-30 $\mu$ m). When the ratio between particle diameter and bubble diameter is too small, the particle tends to flow around the bubble thus making impossible its collision and consequently its separation. Figures 2 and 3 below show the bubble size distribution when the flotation tank was operated with airflow rates ( $Q_{air}$ ) of 6.3 and 14.6 L/min, respectively.

Although an increase in the airflow rate increases the number of bubbles and consequently the number of efficient collisions, it can be observed that higher airflow rates produce larger bubble diameters, which may reduce the efficiency of the flotation process. The airflow rates used in this work, 6.3 and 14.6 L/min, produced bubbles with average diameters of 1.49 mm and 4.90 mm, respectively.



**Figure 2:**  $Q_{air} = 6.3$  L/min; Average Diameter = 1.49 mm; Standard Deviation = 0.47



**Figure 3:**  $Q_{air} = 14.6$  L/min; Average Diameter = 4.9 mm; Standard Deviation = 1.26

### Residence-Time Distribution

The residence-time distributions for the liquid feed flow rates used in this work are presented in Figures 4 and 5. The airflow rate was kept constant at 14.6 L/min throughout the experimental runs carried out. It must be emphasized that in this work the flotation tank fluid dynamics was assumed to be a series of “N” well-mixed tanks. The mean residence time and the number of tanks were calculated using Equations 3 and 6. For both cases studied, it was concluded that the flotation tank could be assumed to be a well-mixed tank.

### Flotation Kinetics

Similarly to other cases reported in the literature, such as the studies of Santos (1996) and Rajinder

and Maslyah (1990), the flotation process was assumed to be a first-order chemical reaction. With this result, Equation (8) can be rewritten as

$$\frac{dC}{dt} = -k \cdot C \quad (11)$$

When the batch operation mode is used, the kinetic constant can be obtained from Equation (12):

$$-\ln\left(\frac{C}{C_a}\right) = k \cdot t \quad (12)$$

Figure 6 contains the experimental data used to determine the kinetic constant of the flotation process. It can be seen that an increase in airflow rate results in an increase in the flotation kinetic constant value, i.e., higher rates of particle removal.

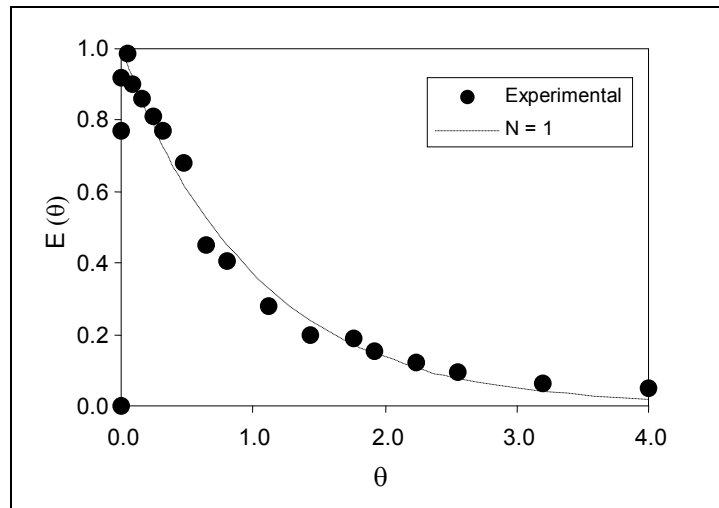


Figure 4: Residence-Time Distribution ( $Q_{air} = 14.6$  L/min;  $Q_a = 0.95$  L/min; and  $\bar{t}_C = 63$  min,  $\sigma_\theta^2 = 0.72$ )

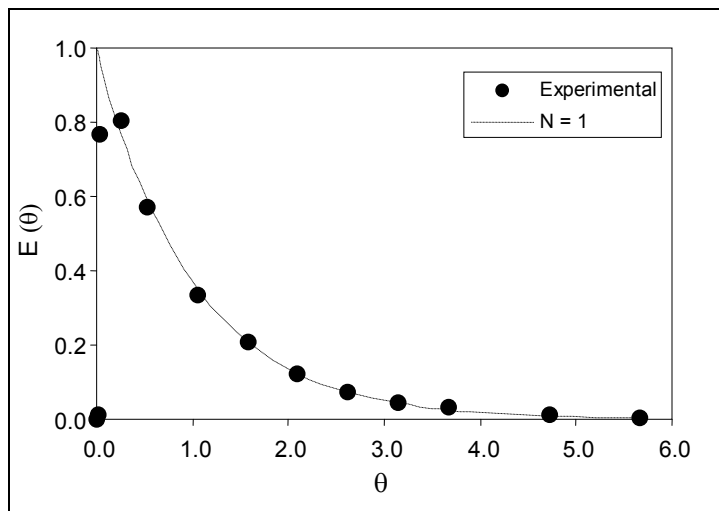


Figure 5: Residence-Time Distribution ( $Q_{air} = 14.6$  L/min;  $Q_a = 3.0$  L/min; and  $\bar{t}_C = 19$  min,  $\sigma_\theta^2 = 0.99$ )

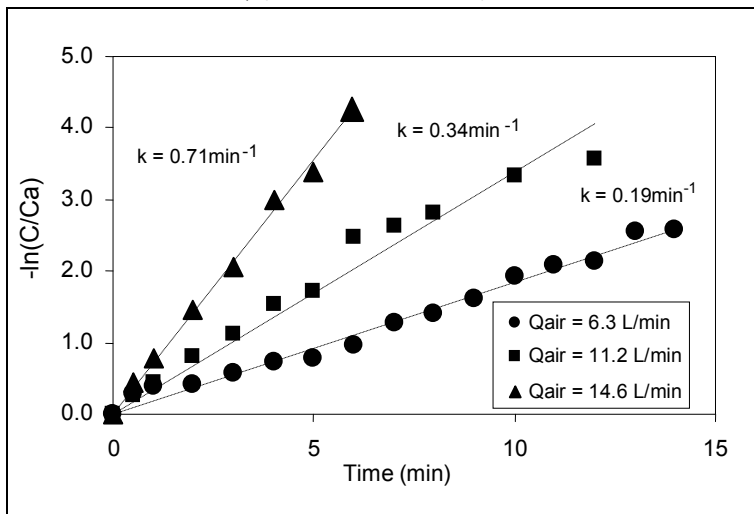


Figure 6: Determination of the flotation kinetic constant for batch operation

### Continuous Flotation

As discussed above, the flotation tank was assumed to be a well-mixed tank. Assuming the flotation process to be a first-order chemical reaction, the material balance of the flocculated milk yields the equation below, which is a particular case of Equation (9) when  $N=n=1$ .

$$\begin{cases} V_T \cdot \frac{dC(t)}{dt} = Q_a \cdot [C_a - C(t)] - k \cdot C(t) \cdot V_T \\ t = t_0, C(t_0) = C_F \end{cases} \quad (13)$$

The analytical solution of Equation (13) is given by

$$C(t) = \frac{C_a}{1+k \cdot \tau} \left[ e^{-\frac{(1+k \cdot \tau)(t-t_0)}{\tau}} \right] + \left[ \frac{C_a - C_F \cdot (1+k \cdot \tau)}{1+k \cdot \tau} \right] \quad (14)$$

where  $\tau$  is the mean residence time ( $\bar{t}_c$ ).

For the initial batch, the behavior of the concentration is given by the solution of Equation 10 assuming the flotation process to be a first-order

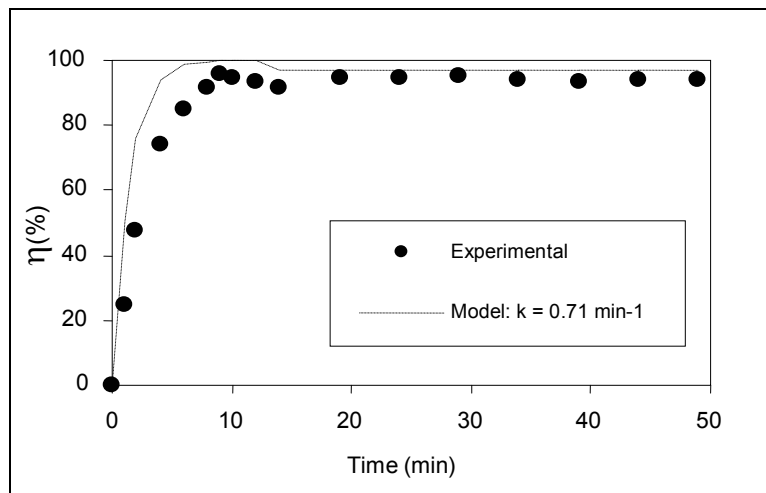
chemical reaction.

$$C(t) = C_a \cdot e^{-k \cdot t} \quad (15)$$

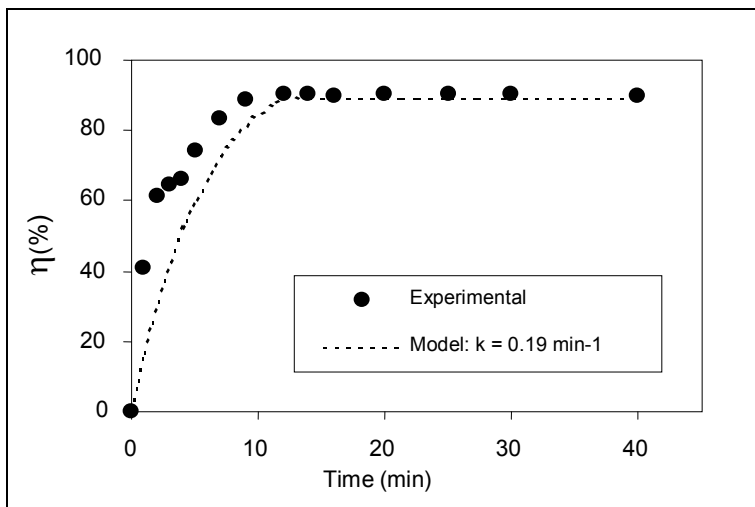
Figure 7 contains the results of an experimental run carried out continuously with an airflow rate of 14.6 L/min and a waste feed flow rate of 0.95 L/min. It can be observed that operating under these conditions the experimental setup could remove 95 % of the suspended matter of the waste.

The experimental data obtained show good agreement with the simulation results (Equations 14 and 15). A flotation kinetic constant of  $0.71 \text{ min}^{-1}$ , obtained in batch mode, was used for model simulation. Figures 8 and 9 contain the results of experimental runs carried out with an airflow rate of 6.3 L/min, using a feed flow rate of 0.95 and 3.0 L/min, respectively. In these experiments, the simulation results are also in good agreement with the experimental data.

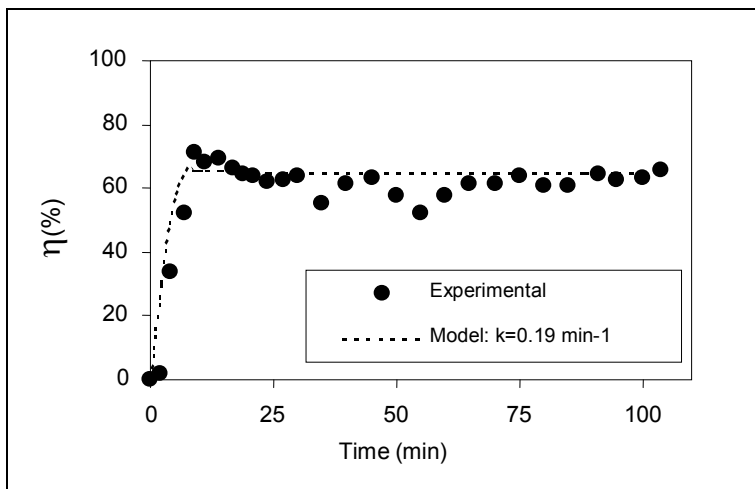
It can also be observed that the efficiency of the flotation process is lower with an airflow rate of 6.3 L/min than with an airflow rate of 14.6 L/min. The most probable reason for this result is that an increase in the airflow rate leads to an increase in the number of efficient collisions. On the other hand, an increase in the waste feed flow rate, keeping the airflow rate constant, reduces the efficiency of the flotation process because the mean residence time of the particles inside the tank is reduced.



**Figure 7:** Continuous Flotation:  $Q_{air} = 14.6 \text{ L/min}$  and  $Q_a = 0.95 \text{ L/min}$  ( $t_0 = 10 \text{ min}$ ;  $C_a = 1000 \text{ ppm}$ ;  $\tau = 63 \text{ min}$ )



**Figure 8:** Continuous Flotation:  $Q_{ar} = 6.3$  L/min and  $Q_a = 0.95$  L/min ( $t_0 = 10$  min;  $Ca = 1000$  ppm;  $\tau = 63$  min)



**Figure 9:** Continuous Flotation:  $Q_{ar} = 6.3$  L/min and  $Q_a = 3.0$  L/min ( $t_0 = 10$  min;  $Ca = 1000$  ppm;  $\tau = 19$  min)

## CONCLUSIONS

This work presents the use of flotation processes as an alternative tool for wastewater treatment. The studies were performed with a synthetic dairy waste at its isoelectric point and the flotation technique obtained good results.

Using a waste feed flow rate of 0.95 L/min and an airflow rate of 14.6 L/min process efficiencies higher than 90% could be achieved. Experimental data were well fitted to the simulation results of a well-mixed tank and the hypothesis of first-order chemical reaction like kinetics.

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## NOMENCLATURE

$Ca$	Feed concentration	[M/L <sup>3</sup> ]
$C$	Tank concentration	[M/L <sup>3</sup> ]
$C_i$	$i^{\text{th}}$ Tank concentration	[M/L <sup>3</sup> ]
$C_F$	Concentration at the end of a batch run	[M/L <sup>3</sup> ]
$C_{\text{imp}}$	Tracer concentration during a pulse test	[M/L <sup>3</sup> ]
$D_f$	Average diameter of the flocks	[L]
$E(t)$	Residence-time distribution function	$\theta^{-1}$



$E(\theta)$	Residence-time distribution function with dimensionless variables	[-]
$k$	Flotation kinetic constant	$[\theta^{-1}]$
$N$	Number of tanks in series	[-]
$n$	Reaction order	[-]
$Q_a$	Waste feed flow	$[L^3/\theta]$
$Q_{air}$	Air inlet flow	$[L^3/\theta]$
$t$	Time	$[\theta]$
$t_0$	Time when operation of the experimental setup is shifted from batch to continuous mode	$[\theta]$
$\bar{t}_c$	Mean residence time	$[\theta]$
$V_i$	$i^{th}$ Tank volume	$[L^3]$
$V_T$	Total tank volume	$[L^3]$
$\varepsilon_L$	Liquid porosity	[-]
$\Gamma$	Gamma function	[-]
$\eta$	Process efficiency	[-]
$\rho$	Flock density	$[M/L^3]$
$\sigma_t^2$	Residence time variance	$[\theta^2]$
$\sigma_\theta^2$	Residence time variance with dimensionless time	[-]
$\theta$	Dimensionless time ( $t/\bar{t}_c$ )	[-]

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