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Studying the hydrodynamics in a three-phase electroflotation column

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ABSTRACT

The performance of three phases (liquid, gas and solid) columns is strongly affected by hydrodynamic parameters. In this context, the effect of current density, particle diameter, solid concentration and the ratio of the bubble diameter to the solid diameter in the hydrodynamic parameters were evaluated in an electroflotation column. Experiments were conducted in a cylindrical column of Plexiglas operating in a batch mode. The solid particle used was the olive pomace core with a diameter varying from 160 to 400 µm. While the bubble size and the rise velocities were measured using a high-speed camera, the bubble flow regime was estimated by calculating Reynolds number. The efficiency of the process was evaluated through the determination of the yields relative to the solid suspended abatement. The obtained results revealed that bubbles tend to become larger with the increase in current density, viscosity and decrease in solid diameter. Besides, the bubble rise velocity tends to increase with the increase in current density and decrease in viscosity and collision efficiency. It was shown that the homogeneous regime is favorable for water treatment. The gas hold-up exhibits the same behavior as bubble diameter so it increases with current density and viscosity. To estimate bubble size, bubble rise velocity and Reynolds number, correlations including the effect of solid concentration and operating conditions were developed.

Keywords: Three phases; Hydrodynamic; Current density; Bubble; Electroflotation

1. Introduction

Wastewater generated by industrial processes and its treatment represent a considerable environmental problem. To solve this problem, many technologies are employed, namely electrocoagulation [1], coagulation/flocculation [2], distillation [3], electrolysis [4], flotation [5] and electroflotation. In this study, the focus was on the latest technology using bubble column. In fact, three-phase bubble columns are very employed in chemical and petrochemical industries and environmental process as reactors or absorbers [6,7] due to their simple construction and cheap maintenance [8]. Furthermore, they have various characteristics like high heat exchange and good mass transfer rates [9].

Indeed, electroflotation or electrolytic flotation is one of the techniques used to treat wastewater by the bubble generation method according to these reactions [10]:

Anode (+)

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \quad (1)$$

Cathode (–)

$$2H^+ + 2e^- \rightarrow H_2 \quad (2)$$

The advantages of this process may be summarized as follows:

The good selection of electrode surface and solution conditions permits to obtain optimum results for a specified separation process [11,12].

It leads to obtain very fine and uniform bubbles (with an average bubble diameter of about 20 µm) [13].

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It is possible to control the number and size of bubbles by varying the current density.

Chen [14] proved that the current density and the mass of the formed bubbles are proportional. The rise velocity and the flow regime are also affected by this parameter. Pino et al. [15] and other researchers [16,17] have also demonstrated that bubble behavior affects the hydrodynamic regime of the separation process. Actually, the high separation efficiency of this process could only be obtained in laminar regime. Electroflotation is also affected by both liquid phase and solid phase characteristics particle diameter and concentration. In this way, several authors have investigated the impact of solids in terms of solid concentration and solid particle size and found controversial results. On the one hand, most of the published research works reveal that the gas hold-up diminishes with the addition of solid particle owing to the increase of the apparent viscosity of the slurry phase, which is believed to improve the bubble coalescence [18,19]. On the other hand, there are contradicting studies reporting an increase in the gas hold-up with the increase in solid concentration [20,21].

Therefore, we propose to study the impact of these hydrodynamic parameters on the separation efficiency of an electroflotation column using the image analysis technique.

2. Materials and methods

2.1. Materials

2.1.1. Electroflotation cell and equipment

As shown in Fig. 1, the electroflotation cell is cylindrical, made up of Plexiglas with an internal diameter of 9.4 cm and a height of 54 cm. It is related to the stainless steel cathode and titanium coated with ruthenium oxide anode. These two electrodes are connected to a DC current generator that allows the variation of the current density. The determination of bubble characteristics was done using an analogue camera that was allied to a computer by an acquisition card. A triple 60-watt power halogen spots and a wire of 0.149 mm (used for calibration) were also employed.

2.1.2. Physicochemical characteristics of the model solution

The model solution is prepared by varying the olive pomace core-masses added to a liter of water. Its physicochemical properties are given in Table 1.

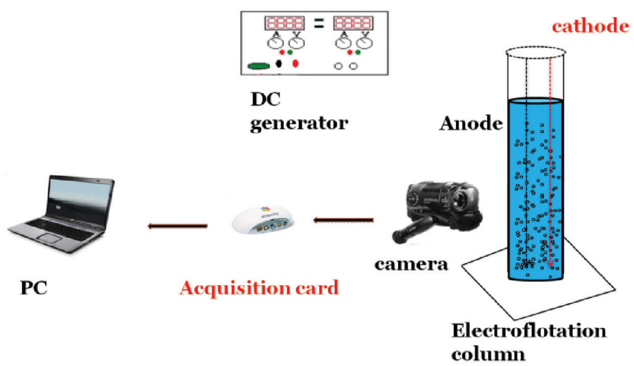

Fig. 1. Electroflotation column operating in batch mode.

Table 1
Physicochemical characteristics of the model solution

Mixture properties	Concentration [g/l]				
	1	2	3	4	5
Density (Kg/m^3)	1000.167	1000.34	1000.4	1000.637	1000.8
Dynamic Viscosity 10^{-3} (Pa·s)	1.001	1.0028	1.003	1.005	1.007

2.2. Methods

The measurement of bubble characteristics, such as diameter and rise velocity, was conducted using video recording. Then, different images that will be filtered by image treatment software (photofilter, Photoshop, virtual dub) were extracted. A wire with a diameter of 0.149 mm was used for calibration. A diffuse back light was employed to illuminate bubbles in order to improve the quality of images, and at least 50 bubbles were measured to have a good representation.

2.2.1. Bubble rise velocity

Bubble velocity is determined using the following equation:

$$V_B = \frac{d}{t} \tag{3}$$

where d is the lap course of bubble at time t. Indeed, a series of images was selected then treated and superposed to calculate the rise velocity of bubble.

2.2.2. Reynolds number

The flow regime is evaluated by the calculation of Reynolds number (Re), which is evaluated by this equation:

$$\mathrm{Re} = \frac{\rho_m V_B d_B}{\mu_m} \tag{4}$$

where the mixture density is estimated by the following equation [18]

$$\rho_m = \rho_s \Psi_s + (1 - \Psi_s)\rho_l \tag{5}$$

The apparent viscosity is calculated by the equation of Barnea and Mizrahi [22]

$$\mu_m = \mu_l \exp\left(\frac{(5/3)\psi_s}{1-\psi_s}\right) \tag{6}$$

In which V_B is the bubble rise velocity, d_B is the bubble diameter, µm is the mixture dynamic viscosity, ρm is the mixture density, Ψ_s is the volume fraction of solids in the mixture and ρ_l is the liquid density. The transition of the bubble flow regime is recognized for $Re = 1$ [23].

2.2.3. Gas hold up

Throughout experiments, gas hold-up is measured by the bed height method. It can be evaluated using Eq. (7):

$$\varepsilon_g = \frac{H_d - H_s}{H_d} \quad (7)$$

where H_d is the dispersion height in column and H_s is the total height in column.

3. Results and discussion

3.1. Effect of operating parameters on bubble characteristics

3.1.1. Effect of current density solid diameter and solid concentration on the bubble diameter

The current density and solid characteristics (concentration and diameter) present a direct influence on bubble's size and number. The influence of current density on the bubbles average diameter, for different concentrations and solid diameter is presented in Figs. 2 and 3.

The average diameter of the bubbles increases as the current density increases, achieving sizes between 0.11 and 0.19 mm. In fact, augmenting the current density improves the generation of hydrogen and oxygen bubbles at the electrode surfaces. This contributes to an increase in the number of gas bubbles inside the column, thus the attachment step between bubbles, which in turn results in promoting the bubbles coalescence, and therefore increasing their sizes. This is in good agreement with the findings of Janssen and Hoogland [24], which proved that the coalescence between the adhering bubbles is more important with the rise in current density. With respect to the effect of particle size on bubble diameter (Fig. 2), we found that the increase of particle diameter led to the decrease of bubble size. This can be explained by the phenomenon of bubble break-up. Actually, Kim et al. [25] have proved that the bubble break-up takes place when the size of particles exceeds half of bubble diameter.

The addition of solids favored the coalescence rate, and therefore the average bubble size increased with the presence of solids. This could possibly have been caused by the increase of viscosity. Indeed, the increase in solution viscosity diminishes turbulence in the liquid phase. As a result, the energy of vortex is reduced and bubble breakage is damped, leading to the increase in the bubble sizes.

Moreover, bubbles are formed at the electrode surface by taking up gas from the surrounding supersaturated solution. As a result, the increase in the solution viscosity leads to obtaining a greater surrounding supersaturated solution. Moreover, the coalescence between the adhering bubbles at the surface is more important, thus obtaining a larger bubble diameter.

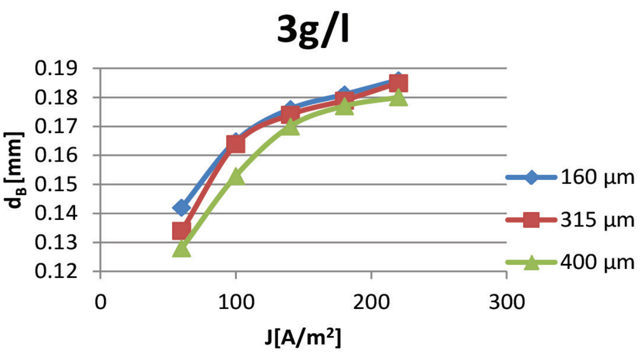

Fig. 2. Effect of current density and solid diameter on bubble diameter at fixed solid concentration.

3.1.2. Effect of current density solid diameter and solid concentration on the bubble velocity

In order to evaluate the impact of operating parameters on bubble rise velocity, the experiments were carried out by varying the current density from 60 to 220 A/m^2 and the solid size (160 µm, 315 µm, 400 µm). The concentration varied from 1 to 5 g/l. The results are shown in Figs. 4 and 5, from which it is clearly noted that the rise velocity of bubbles varied in the range of 4–11 mm/s. Indeed, the current density affects the upward movement of bubbles, whose velocities increased with the increase in current density, which is due to the dominance of buoyancy force. This is in accordance with recent research works [16–26]

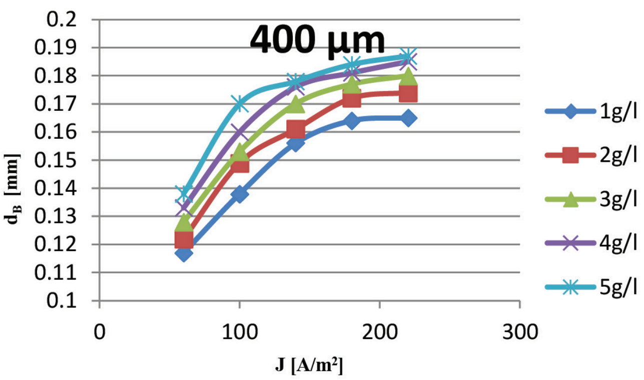

Fig. 3. Effect of current density and solid concentration on bubble diameter at fixed solid diameter.

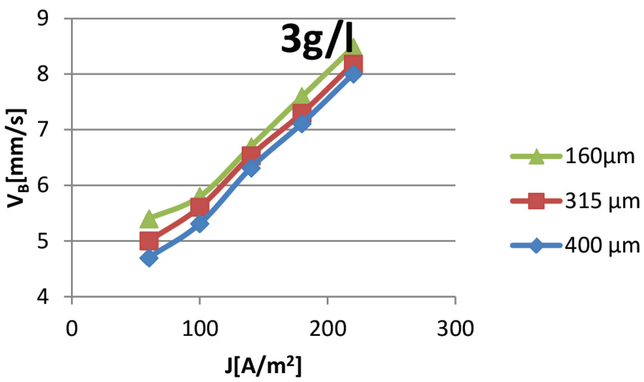

Fig. 4. Effect of current density and solid diameter on bubble rise velocity at fixed solid concentration.

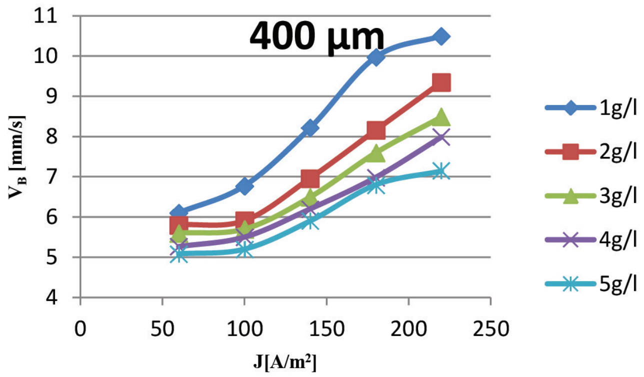

Fig. 5. Effect of current density and solid concentration on bubble rise velocity at fixed solid diameter.

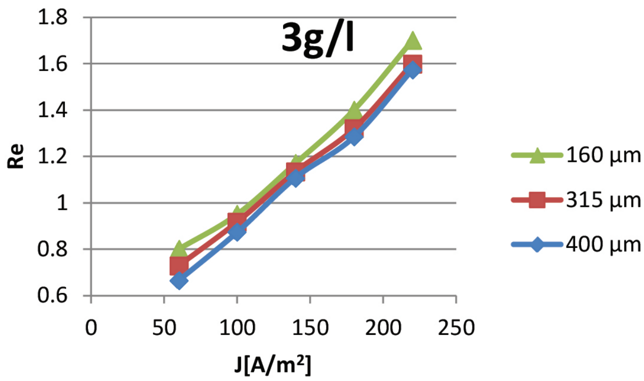

Fig. 6. Effect of current density and solid diameter on Reynolds number at fixed solid concentration.

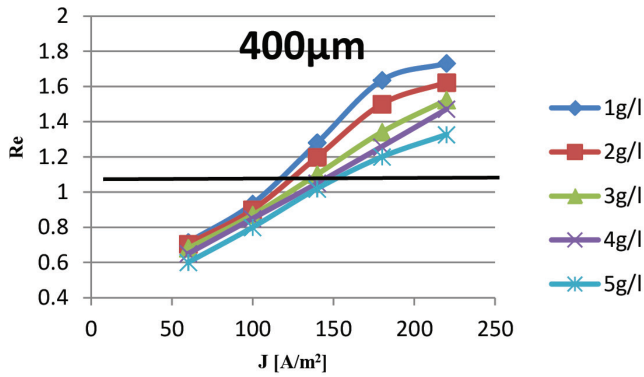

Fig. 7. Effect of current density and solid diameter on Reynolds number at fixed solid diameter.

which have shown that the current density and bubble rise velocity are proportional.

Particle size also impacts the bubble rise velocity. Indeed, the increase in particle size decreases bubbles velocity since the increase of the particle diameter increases collision phenomena, which reduces the velocity of bubbles [27].

Concerning the particle concentration, Fig. 5 shows its negative effect on bubble rise velocity. This may be explained by the fact that the addition of particles changes liquid density and viscosity. In fact, each particle creates a non-slip condition for the liquid where the velocity of the latter must be null. Consequently, the extra velocity gradient takes place and the viscous dissipation augments, resulting in the increase in the apparent viscosity. The bubble rise velocity is reduced as the slurry viscosity increases. The hydrodynamic forces and mutual collision of bubbles and particles also decreases the velocity of bubbles. This is in agreement with Ksentini et al. [16] and Kumar et al. [28], who have revealed that the increase in viscosity helps in increasing drag force, which inhibits bubbles to be faster.

3.1.3. Effect of operating parameters on bubble regime flow

Three types of flow regime (laminar, transitional and turbulent) are identified for bubble column. Each flow regime affects significantly the performance of the column and the hydrodynamic of bubbles. To characterize bubble flow, Reynolds number is determined (see Figs. 6 and 7).

According to Figs. 6 and 7, the current density was found to have a significant effect on the bubble flow characteristics. Its increase leads to an enhancement in the coalescence rate and a decrease in the breakup rate. This gives rise to an early appearance of large bubble, and thus should advance the flow regime transition that is characterized by large bubbles moving with high-rise velocities. It is detected at values greater or equal to 140 A/m^2.

Moreover, small particles give the highest Reynolds number. Indeed, when particle diameter augments, bubble diameter and its rise velocity decreases, which explains the decrease of Reynolds number.

For the increase of particle concentration, we conclude that it leads to the increase in liquid viscosity, which enhances the bubbles diameter and diminishes their velocities. Otherwise, the viscous forces dominate buoyant, gravitational or momentum forces. As a result, more energy is needed to attain turbulent regime, which leads to obtain smaller values of the Reynolds number. To conclude with, the addition of solid has the effect of stabilizing the laminar bubbly flow regime and delaying turbulent flow regime.

3.1.4. Effect of hydrodynamic parameters on the abatement of solid suspended

Electroflotation process is a high-speed removal of pollutant. In fact, the treatment duration is about few minutes (around 25 min). The abatement of suspended solids is efficient on laminar regime (Fig. 8). Indeed, it is characterized by small and slow bubbles as there is neither coalescence nor bubble break-up in this regime. Consequently, a great treatment is imposed since agitation is inexistent and mixing is gentle [29].

The turbulent regime minimizes the effectiveness of solid removal. In fact, we notice that the solid removal efficiency decreases for Reynolds number greater than 1. According to Rupesh et al. [30], the increase of concentration increases the solid removal efficiency, which may be explained by an improvement in the chance of the attachment of bubbles and floating particles.

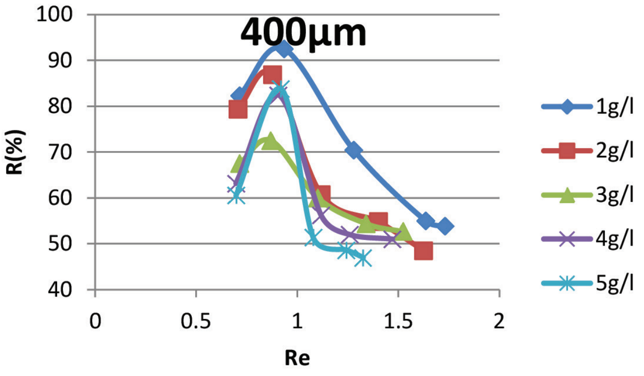

Fig. 8. Effect of solid concentration and Reynolds number on the solid removal efficiency.

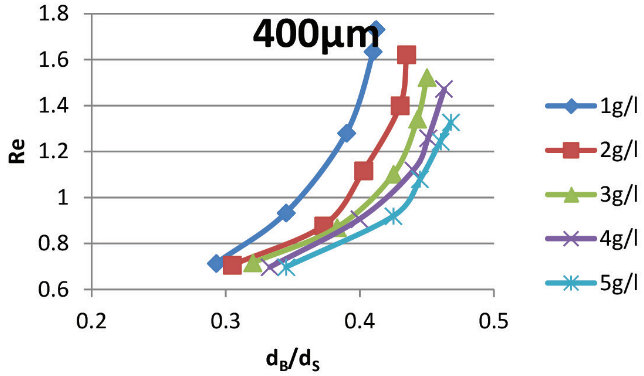

Fig. 10. The variation of Reynolds number with the ratio of the bubble diameter to the solid.

3.2. Effect of the ratio d_B/d_S and solid concentration on hydrodynamic parameters

3.2.1. Effect of the ratio d_B/d_S and solid concentration on the bubble rise velocity

In the flotation process, bubble diameter is the key parameter in controlling bubble-particle interaction. Indeed, it does not only influence collision efficiency, but also affects the attachment behavior. In this context, bubble velocity is affected by the size of solid and bubble. The obtained results are shown in Fig. 9.

It is clearly noted that for a fixed particle concentration increasing the ratio of the bubble diameter to the solid diameter d_B/d_S leads to the increase in bubble rise velocity. In fact, Hassanzadeh [27] found that the collision efficiency showed a decreasing trend with the increase in bubble size and decrease in solid size. Yoon et al. [31] proved that the decrease in the bubble diameter increases the sliding contact time, thus hampering the bubble to be faster.

The presence of solids and solid concentration has also an impact on bubble properties. Actually, it was reported that the presence of solid reduced bubble velocity, which is attributed to the increase in the apparent slurry viscosity with the increase in slurry concentration. The study of [20] has shown that bubble velocity was a decreasing function of solids concentration. Prakash et al. [32] used yeast cells in their column and reported that as the yeast concentration increases, the rise velocity of large bubbles increases, whereas the rise velocity of small bubbles decreases.

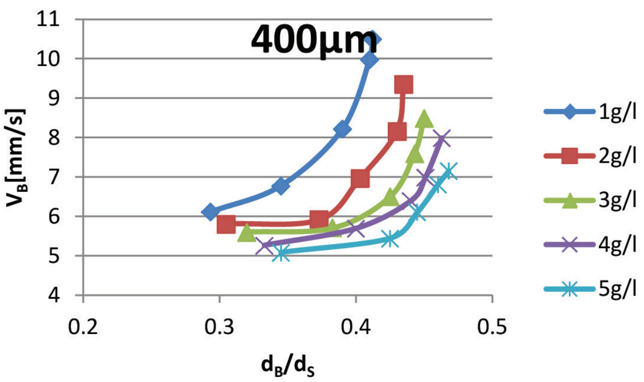

Fig. 9. The variation of bubble rise velocity with the ratio of the bubble diameter to the solid diameter.

3.2.2. Effect of the ratio d_B/d_S and solid concentration on the Reynolds number

Bubble diameter, bubble rise velocity, dynamic viscosity and density of solutions are the main parameters that influence Reynolds number. That is why; we study the effect of bubble diameter on bubble flow regime (Fig. 10).

We remark that for different particle concentrations the increase of the ratio d_B/d_S increases the Reynolds number. Indeed, if bubble diameter increases, the particle detachment and bubble velocity increase which favors the appearance of a turbulent regime, and therefore the increase of Reynolds number. The increase of particle solid concentration leads to the increase in the liquid viscosity, which leads to obtain smaller values of the Reynolds number. In this way, the transition from laminar to turbulent regime for viscous solution ($C_S > 5$ [g/l]) was detected at values of the ratio d_B/d_S higher or equal to 0.45.

3.2.3. Effect of the ratio d_B/d_S and solid concentration on the abatement of the suspended solid

The efficiency of the electroflotation process depends on the capacity of bubbles to collect solids from the suspension and hold them to the surface [33]. In this context, we will study the effect of bubble and solid diameter on the yields of the abatement of suspended solids.

From Fig. 11 we found that small bubbles are more effective in the flotation process. Hence, as the ratio d_B/d_S increases the solid removal efficiency decreases. In fact, the rise of bubble diameter decreases the attachment efficiency and gives a turbulent bubble flow, which leads to the decrease in the suspended solid performance.

3.2.4. Effect of the ratio d_B/d_S and solid concentration on Gas hold-up

Gas hold-up is one of the most interesting parameters that characterize the transport phenomena of bubble column.

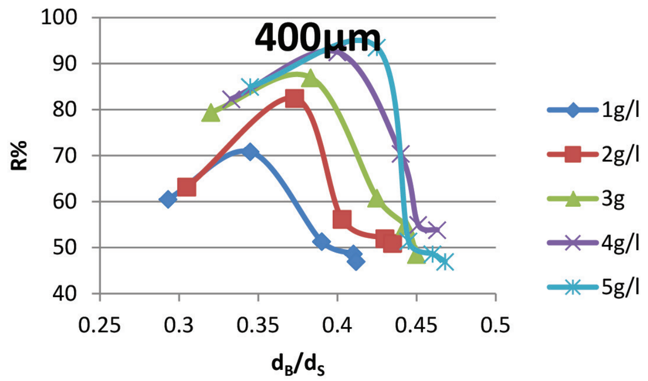

Fig. 11. The variation of solid removal efficiency with the ratio of the bubble diameter to the solid diameter.

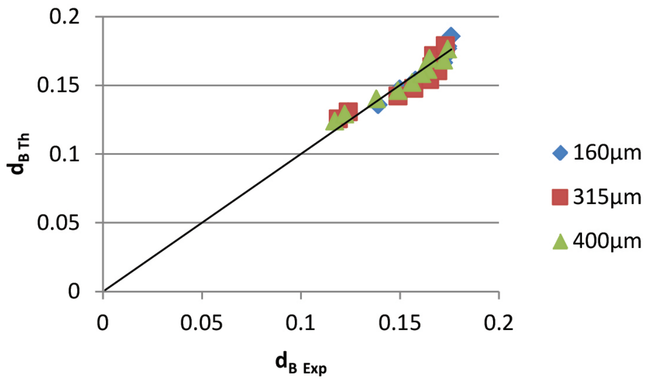

Fig. 13. Comparison between predicted (dB Th) and measured bubble diameter (dB Exp).

It depends on the current density, fluid properties, column design, bubble characteristics and solid phase properties.

As clearly seen from Fig. 12; the increase of the ratio d_B/d_S created by the increase of current density increases gas hold-up. Gas hold-up also depends on particle concentration as it increases with the increase of impurities [34,35]. In fact, the increase of particle concentration decreases bubble velocity, and consequently bubbles spend more time in the column, resulting in high hydraulic retention time of bubbles, which increases the number of bubbles and gas hold-up [36].

3.3. Modeling

Since bubble diameter, bubble velocity and Reynolds number depend on current density (J), solid size (d_s) and solid concentration (C_S), we have tried to find correlations relating the results and operating parameters. Hence, the mathematical software called DataFit version 8.1.69 was used.

$$d_B = 6.467\times10^{-2}\, J^{0.24}\, d_S^{-0.055}\, C_s^{0.058} \tag{8}$$

The comparison between predicted and measured bubble diameter is given by Fig. 13. The average difference is around ±14%, which is considered satisfactory.

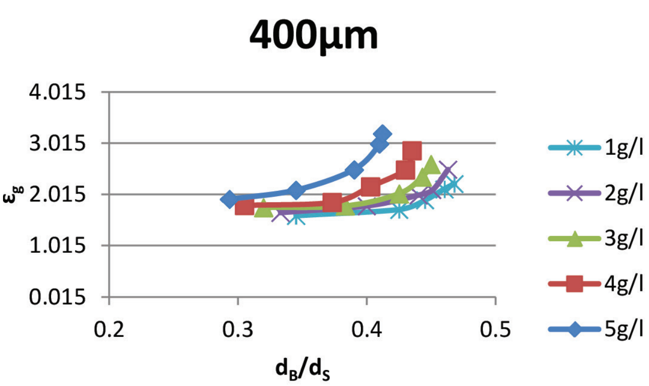

Fig. 12. The variation of gas hold-up with the ratio of the bubble diameter to the solid diameter.

$$V_B = \exp(3.041\times10^{-3}\, J - 4.69110^{-4}\, d_s - 6.01910^{-2}\, C_s + 1.76) \tag{9}$$

The empirical equations fit the experimental data very well. Indeed, the regression coefficients approach unity for every solid diameter are $R^2 = 0.932$, $R^2 = 0.959$ and $R^2 = 0.968$.

$$\mathrm{Re} = 5.099\times10^{-3}\, J - 4.25610^{-4}\, d_s - 0.033C_s + 0.622 \tag{10}$$

The predicted values of Reynolds number fit the experimental ones very well. Actually, the regression coefficients approach unity for every solid diameter are $R^2 = 0.965$, $R^2 = 0.975$ and $R^2 = 0.98$.

4. Conclusions

The search for operating parameters effects, such as current density, solid size and concentration, and the ratio of bubble-solid diameter on the hydrodynamic parameters during the electroflotation process, allowed us to draw the following conclusions:

The rise of the current density leads to obtain larger bubbles with faster velocity. However, the increase of particle diameter decreases bubble diameter and its velocity. Moreover, the increase of the particle concentration augments the viscosity of the solution, thus increasing the bubble diameter and decreasing its velocity.

The evaluation of the flow regime is through the determination of the effect of the characteristics of the solid phase and current density on the Reynolds number. The turbulent regime was obtained for the current density higher or equal to 140 A·m^{-2}.

The study of Reynolds number effect on the solid removal efficiency has proven that the latter is the best in a laminar bubble flow detected for values less than 140 A·m^{-2}.

The study of bubble-solid size proved that the increase in the bubble diameter with decrease in the solid size favors the diminishing of collision efficiency and as a result the increase in the rise velocity.

The transition from laminar to turbulent regime is predicted at values of the ratio of the bubble diameter to the bubble solid d_B/d_S higher or equal to 0.45.

Gas hold-up tends to increase with the increase of the ratio d_B/d_S and the addition of solid particles.

Models predicting the variation of bubble diameter, bubble velocity and Reynolds numbers were established in each case using linear regression method.

Symbols

μ_m — Mixture dynamic viscosity (Pa.s)
C_S — Solid concentration (Kg/m^3)
d — The lap course of bubble (m)
d_B — Bubble diameter (m)
d_s — Solid diameter (m)
ε_g — Gas hold-up
H_d — The dispersion height in column (m)
H_s — The total height in column (m)
J — Current density (A/m^2)
Re — Reynolds number
t — Time (s)
V_B — Bubble rise velocity (m/s)
ρ_l — Liquid phase density (kg/m^3)
ρ_m — Mixture density (Kg/m^3)
ρ_s — Solid phase density (kg/m^3)
Ψ_S — The volume fraction of solids in the mixture

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