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Modeling the hydrodynamic of an electroflotation column for the treatment of industrial wastewaters

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ABSTRACT

In this work, the hydrodynamic study of oxygen and hydrogen bubbles flow generated in an electroflotation column working in batch and continuous mode was performed. The method of video recording and image processing was used to determine the diameter and the rise velocity of bubbles and also the gas retention. The effect of current density applied at the electrodes of the electroflotation column, the liquid phase physicochemical parameters, and the variation of the liquid phase flow has been studied. The overall results were modeled in order to describe the bubble flow regime. These models have been implemented in a code programmed in Visual Basic and allowed the development of an executable application. This application was then used successfully in order to determine the optimum operating conditions for treating industrial wastewaters by electroflotation process.

Keywords: Electroflotation; Hydrodynamic; Modeling; Visual Basic; Wastewaters

1. Introduction

Innovations in wastewater treatment processes are the object of many recent studies. In addition to the traditional processes like coagulation, simple flotation, or sedimentation, new competitive treatment technologies are being used in order to increase the efficiency of such operations. In this context, bubble columns, which are a type of liquid gas exchanger, are considered as one of useful and interesting new processes. Several researches approached various aspects within these columns such as mass transfer, heat, and hydrodynamic [1–4]. In this context, we deal this study with an electroflotation column which is one of bubble column categories.

In fact, electroflotation is the electrochemical version of traditional dissolved air flotation. It is characterized by its mechanism of oxygen and hydrogen bubble formation due to water electrolysis according to these reactions (Eqs. (1) and (2)):

* Anode reaction: water oxidation

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

* Cathode reaction: water reduction

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (2)$$

Recent researches focused on the separation efficiency of the electroflotation column when it is used as

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wastewater treatment process [5]. It is proved that many factors interact in this process. In fact, the current density, applied at the electrodes, is an important factor which has a significant effect on the separation efficiency. This was confirmed in the study of Hosny in which he used insoluble electrodes to separate oil from oil/water emulsions [6]. Other authors have also shown the importance of current density on the whole process [7,8]. Indeed, the current density influences directly the number and the size of bubbles [9]. Chen [10] showed that the current density and the mass of the formed bubbles are proportional. Pino et al. [11] and other workers [12–14] have also shown that bubble behavior affects in turn the hydrodynamic regime of the separation process. In fact, when electroflotation is used to remove the suspended solids (SS) contained in wastewater, it was proved that the high separation efficiency could only be obtained in bubbly laminar regime [15]. Hydrodynamic study involves, particularly, the effect of operating parameters on Reynolds number. In addition to current density, the main parameters which affect Reynolds numbers are the liquid phase physicochemical characteristics in batch mode. The liquid phase flow is added when continuous mode is applied. In this context, we propose in this research to study the effect of all these parameters on bubble hydrodynamic. The method of video recording and image processing is employed in order to determine bubbles diameters and bubble rise velocities which is essential to evaluate Reynolds numbers in different process modes. The results are then modeled in order to obtain nonlinear equations which can be implemented in visual basic code. So, an application which resumes all these models is compiled. Such application will be validated by using it in order to predict the optimal operating conditions for treating a real industrial effluent.

2. Materials and methods

2.1. Materials

2.1.1. Experimental equipment

The measurements were performed in different laboratory-scale electroflotation columns equipped with insoluble electrodes. A schematic diagram of the two electroflotation columns and the equipment used for the determination of bubble characteristics by image analysis in both batch and continuous mode is shown in Figs. 1 and 2.

In both configuration, the electroflotation column is made of cylindrical glass vessel and it is of 9.5 cm internal diameter and 1 m in height. It is equipped with titanium coated with ruthenium oxide anode and stainless steel cathode. They have an active surface of 250 cm. These two electrodes are supplied by a generator of DC current (D.C. Power Supply GPC-M Series from GW-INSTEK-TAIWAN) which makes possible

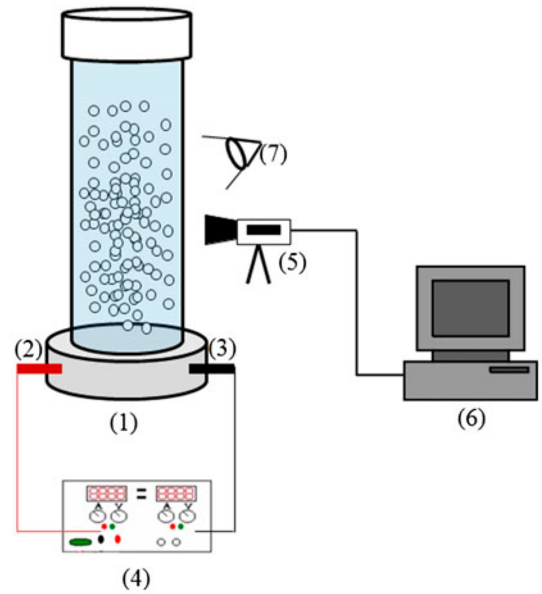

Fig. 1. Electroflotation column and equipment for the determination of bubble characteristic in batch mode.
Note: (1) Electroflotation column, (2) cathode, (3) anode, (4) DC generator, (5) analog video camera, (6) PC equipped with a video acquisition card, and (7) halogen spot.

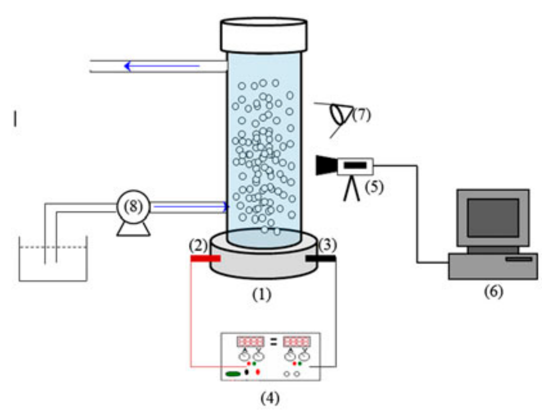

Fig. 2. Electroflotation column and equipment for the determination of bubble characteristic in continuous mode (co-current configuration).
Note: (1) Electroflotation column, (2) cathode, (3) anode, (4) DC generator, (5) analog video camera, (6) PC equipped with a video acquisition card, (7) halogen spot, and (8) metering pump.

the variation of current density in the electrodes. The equipment used for the determination of the bubble characteristics by image analysis are an analog video camera (model NVA3E from Panasonic, Japan), an acquisition card (model Pinnacle PCTV PRO version 4.02 from Pinnacle systems), a PC equipped with appropriate image analysis software (Photoshop version CS4 from Adobe, PhotoFiltre 10.0, Mesurim PRO version 6.0, and Virtual Dub 1.8), and a double 50 watt power halogen spots. These equipment are able to give us satisfactory clear bubble photos in which we can do any measurements [16]. In continuous mode, the column is related to a metering pump (type ProMinentGamma/L) in order to vary the liquid phase flow. Both co-current and countercurrent configurations could be done.

The same column is used in the end of this study to validate the results obtained by treating a real industrial effluent coming from paper washing machines. The volume of effluent used in each experiment is 6 L.

2.1.2. *Industrial effluent*

In order to validate the results of modeling, a real industrial effluent is used. The effluent consists of washing machine wastewaters obtained from paper industry. Table 1 resumes its characteristics:

Table 1
Effluent proprieties

Parameter	Characterization
pH	≈7
Density [$kg\,m^{-3}$]	998.8
Viscosity × 10^{-3} [$kg\,m^{-1}\,s^{-1}$]	1.2
Surface tension × 10^{-3}[$N\,m^{-1}$]	72.54
COD [mg $O_2\,l^{-1}$]	12,300
BOD_5 [mg $O_2\,l^{-1}$]	150
Suspended solids [$mg\,l^{-1}$]	6,440

2.2. *Methods*

2.2.1. *Measuring bubble characteristics with model solutions*

In order to calculate the average bubble diameter at different operating conditions, different model solutions were applied. These solutions were prepared by adding different cationic and anionic surface tension to tap water. This gave us a sufficient experimental interval of work. Table 2 gives the range of all experimental variation intervals.

Table 2
Experimental variation interval

	Interval	
Operating parameter	Min	Max
Viscosity [$kg\,m^{-1}\,s^{-1}$]	0.001	0.02
Surface tension [$N\,m^{-1}$]	0.04	72.75×10^{-3}
Density [$kg\,m^{-3}$]	975	1,000
Temperature [°C]	20	60
pH	4	10
Current densities [$A\,m^{-2}$]	40	300

The video and image technique consists of using a known diameter wire (149 μm) as a calibrate factor. For getting a sufficient representative bubble size, 50 bubbles were at least measured in each operating condition. The reproducibility of results was considered when analyzing data.

In order to have a better image quality and referring to the work of Schafer et al. [17], the bubbles were illuminated with diffuse back light. Bubbles appear then dark on white background (Fig. 3).

Bubbles rise velocities were calculated using equation below:

$$U_B = \frac{H}{t} \tag{3}$$

where H is the bubble course in a lap time t. In fact, series of single bubbles were identified and recorded in their ascension. Then, images were treated and superposed in order to calculate the bubble rise velocity. The same wire with known diameter was also used (Fig. 4).

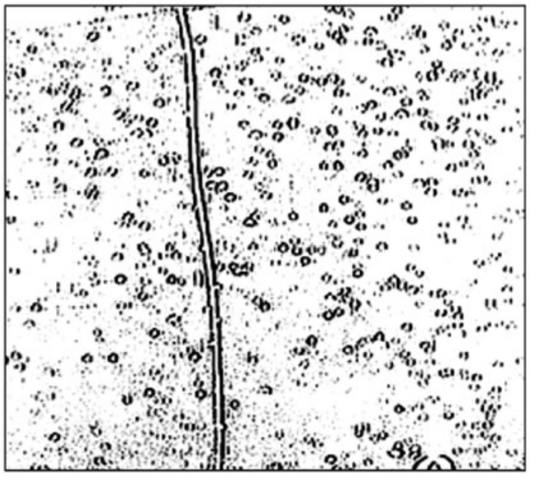

Fig. 3. Image treated for the determination of bubble size.

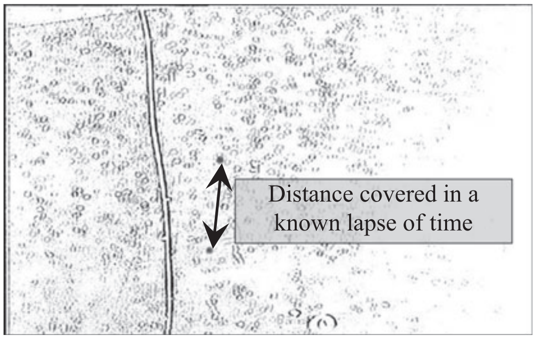

Fig. 4. Images treated and superposed in order to determine the bubble rise velocity.

2.2.2. *Modeling results and compiling the visual basic application*

During experimental process, different operating parameters were taken into consideration. In batch mode, the variation includes current density and liquid phase physicochemical properties which are as follows: density, viscosity, surface tension, pH, and temperature. In continuous mode, the liquid phase physicochemical was not varied (tap water was used). The variation includes current density and liquid phase flow (Q) in both configurations: co-current and counter current. The outputs are bubble diameter and bubble rise velocity, Reynolds number, and gas holdup.

In order to better understand links between these inputs and outputs, models were elaborated using an appropriate method of regression calculus. This was done using DataFit software.

Obtained regression equation was then implemented into a visual basic code in order to obtain an executable application easy for use and which help us to predict optimal operating conditions when used for the treatment of real wastewaters. This was done using Visual Studio (V2012).

3. Results and discussion

3.1. *Modeling the bubble hydrodynamic*

As a major result of this work, the elaboration of the experimental process made us to have a great database which was modeled via DataFit software. The models obtained include the variation of bubble diameter and bubble rise velocity, Reynolds number and gas retention with the variation of liquid phase physicochemical properties and current density applied. Such models give us a great tool to optimize the treatment of different wastewaters. The results of modeling are summarized in Table 3.

Table 3
Regression equation obtained

Batch mode	
Standards conditions	$d = \exp\left(2.98.10^{-3} \times J - 3.01.10^{-3} \times \rho + 4.569 \times \sigma + 85.987 \times \mu + 0.475\right)$
	$U_B = \exp\left(7.54.10^{-3} \times J - 6.74.10^{-3} \times \rho + 6.904 \times \sigma - 14.496 \times \mu + 7.014\right)$
	$\mathrm{Re} = \exp\left(8.377.10^{-3} \times J + 9.508.10^{-2} \times \rho + 3.203 \times \sigma + 28.459 \times \mu - 96.39\right)$
	$\varepsilon_G = \exp\left(5.282.10^{-3} \times J - 1.705.10^{-2} \times \rho - 2.45 \times \sigma + 16.182 \times \mu + 12.689\right)$
pH effect	$d = 3.61.10^{-2} + 1.99.10^{-4} \times J + 1.34.10^{-2} \times pH - 2.89.10^{-7} \times J^2 + 2.29.10^{-5} \times pH^2 + 4.08.10^{-5} \times J \times pH$
	$U_B = 6.079 + 4.46.10^{-3} \times J + 0.113 \times pH + 2.88.10^{-4} \times J^2 - 2.04.10^{-2} \times pH^2 - 6.43.10^{-3} \times J \times pH$
	$\mathrm{Re} = -0.245 - 3.9.10^{-3} \times J + 0.356 \times pH + 6.56.10^{-5} \times J^2 - 2.48.10^{-2} \times pH^2 - 6.44.10^{-4} \times J \times pH$
	$\varepsilon_G = 1.09.10^{-2} \times 1.005^{J \times pH}$
Temperature effect	$d = 0.133 + 3.08.10^{-4} \times J - 5.92.10^{-4} \times T + 9.12.10^{-7} \times J^2 + 7.06.10^{-6} \times T^2 - 6.13.10^{-7} \times J \times T$
	$U_B = 4.538 - 2.6.10^{-2} \times J - 2.21.10^{-2} \times T + 2.62.10^{-4} \times J^2 + 2.63.10^{-4} \times T^2 + 9.94.10^{-5} \times J \times T$
	$\mathrm{Re} = 3.777 - 4.56.10^{-2} \times J - 7.36.10^{-2} \times T + 1.54.10^{-4} \times J^2 + 4.28.10^{-4} \times T^2 + 6.09.10^{-4} \times J \times T$
	$\varepsilon_G = 0.018 - 2.53.10^{-5} \times J - 2.10^{-4} \times T + 4.54.10^{-7} \times J^2 + 3.1.10^{-6} \times T^2 + 1.05.10^{-6} \times J \times T$
Continuous mode	
Counter-current	$U_B = 0.379 + 6.332.10^{-2} \times J - 5.130.10^{-4} \times J^2 + 1.819.10^{-6} \times J^3 + 0.352 \times Q - 2.388.10^{-2} \times Q^2 + 3.294.10^{-4} \times Q^3$
	$\mathrm{Re} = 0.877 - 4.476.10^{-3} \times J - 1.448.10^{-2} \times Q + 6.313.10^{-5} \times J^2 + 1.485.10^{-4} \times Q^2 - 1.691.10^{-4} \times J \times Q$
Co-current	$U_B = 2.957 + 3.697.10^{-2} \times J - 3.265.10^{-4} \times J^2 + 1.484.10^{-6} \times J^3 + 8.958.10^{-3} \times Q + 3.998.10^{-3} \times Q^2 + 3.495.10^{-6} \times Q^3$
	$\mathrm{Re} = 1.17 - 1.011.10^{-2} \times J - 1.587.10^{-2} \times Q + 7.158.10^{-5} \times J^2 + 9.195.10^{-4} \times Q^2 + 9.605.10^{-5} \times J \times Q$

3.2. Using the visual basic application for the resolution of regression equation relative to paper industry effluent treatment

The objective of this application is to avoid the large number of calculus and the resolution of a great number of equations with several parameters. In fact, the VB application was conceived with the logic diagram presented in Fig. 5.

The treatment objective of this effluent is the abatement of SSs rate. So, we focused on Reynolds number $Re = \frac{\rho \times U_B \times d}{\mu}$ which describes the bubble flow regime. A turbulent regime has to be avoided. Actually, by using this application, the introduction of the effluent proprieties predicts an optimal current density of 138 Am^{-2}. This current density corresponds to the resolution of regression equation which takes into consideration a value of Re = 1, which represents the transition point between laminar and turbulent regime. Fig. 6 shows the regime variation when increasing current densities.

Experiments were done at three points (Table 4):

- Transition point:
  - Current density = 138 Am^{-2}
- Laminar regime:
  - Current density < 138 Am^{-2} (125 Am^{-2})
- Turbulent regime:
  - Current density > 138 Am^{-2} (145 Am^{-2})

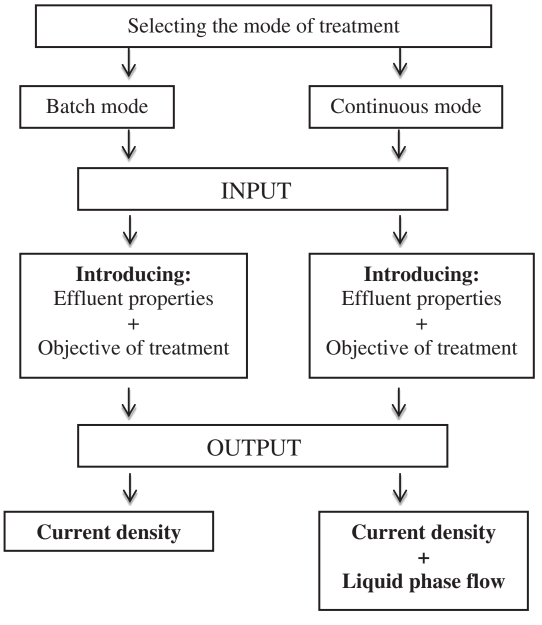

Fig. 5. VB conception diagram.

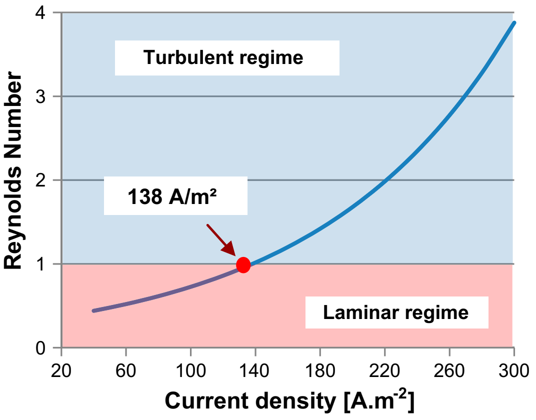

Fig. 6. Variation of Reynolds numbers with applied current density.

Table 4
Results of treatment

Experiment N°	J [A m^{-2}]	Treatment duration [mn]	Suspended solids abatement rate (%)
1	125	15	56
2	125	20	69
3	125	25	84
4	125	40	96.9
5	**138**	**15**	**71**
6	**138**	**20**	**89**
7	**138**	**25**	**97**
8	**138**	**30**	**97.4**
9	145	15	55
10	145	20	70
11	145	25	74
12	145	30	76

We noted that:

- In turbulent regime (J = 145 Am^{-2}), the SSs removal rate has decreased. The agitation created in such regime disadvantages the effluent treatment. This was confirmed in many studies. [18,19]
- In laminar regime (J = 125 Am^{-2}) far from the transition point, the SS removal rate is good, but we need a greater treatment duration compared to the transition point.
- The SS removal rate at the transition point (J = 138 Am^{-2}) is the optimal and lead to very satisfactory results.

Additional analyses were done in these optimal operating conditions and confirm the effectiveness of the adopted process (Table 5).

Table 5
Results of treatment in optimal conditions

Parameters	Before treatment	After treatment	Purification rate %
COD [mg O_2 l^{-1}]	12,300	730	94
BOD_5 [mg O_2 l^{-1}]	150	50	66.6
SS [mg l^{-1}]	6,440	166	97.4

4. Conclusion

An electroflotation column was used in order to study the hydrodynamic of bubbles in both batch and continuous regime. The method of video recording and image treatment was adopted with model solutions. During experimental study, bubbles diameter and bubbles rise velocity were measured in order to evaluate the Reynolds number. Models predicting the main hydrodynamics parameters were established using nonlinear regression method. These models were implemented in a visual basic code in order to create an executable application which was validated successfully by using it in the prediction of optimal operating parameters, when the process is used in the treatment of paper industry effluent. Treatment consists of the abatement of SSs rates which exceeded 97%.

Symbols used

U_B	—	bubbles rise velocity	[L T^{-1}]
d	—	bubble diameter	[L]
J	—	current density	[A L^{-2}]
Re	—	Reynolds number	[–]
ρ	—	density	[M L^{-3}]
μ	—	dynamic viscosity	[M L^{-1} T^{-1}]
SS	—	suspended Solids	[M L^{-3}]
Q	—	volumetric flow rate	[L^3 T]

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