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Experimental study of temperature effects on bubble characteristics and gas holdup in electroflotation column

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ABSTRACT

The study of hydrodynamic in bubble column has widely caught the attention of several research studies. The hydrodynamic aspects in electroflotation column by using a model solution as oil/water emulsion were studied. In this paper the impact of current density, the physicochemical characteristics and temperature of liquid phase on hydrodynamic parameters were evaluated. A method of video image process was used to determine bubbles size, bubbles velocity and gas holdup. It was found that the different parameters depend on current density and oil concentration. The results reveal that bubble characteristics depend strongly on different factors. In fact bubble size increases when current density and oil concentration increase and it is controlled by coalescence/breakup phenomenon. Reynolds number is affected by current density and oil concentration and its increase gives rise to the appearance of turbulent regime. On the other hand, temperature has a significant effect on bubble size and gas holdup; however it does not have a significant effect on bubble rise velocity. A mathematical model was used to predict bubble's characteristics and the Reynolds number in order to characterize the different bubble flow regimes at fixed temperature.

Keywords: Electroflotation; Hydrodynamic; Flow regime; Emulsion.

1. Introduction

In the last few years, numerous works have been devoted to industrial effluents containing oily residues and their impact on the environment. This pollutant is caused by various industries for instance: metallurgical and petroleum. Waste waters may contain different types of oils such as; cutting oil, whole oil, vegetable oil, etc. Thus the safety of the environment has become one of the key issues for economic growth [1].

In a set of processes pertaining to the treatment of wastewater we used bubble column. It is a multiphase reactor and can be used in chemical, biochemical and biological processes [2] Moreover it is endowed with a large number of advantages such as simple construction, low maintenance and operating costs, etc [3] Understanding the hydrodynamics of bubble columns is necessary with respect to their designs which rely on fluid dynamic namely bubble characteristics; bubbles size distribution, shape, diameter and rise velocity. Many parameters have an impact on the operation of bubble columns such as pressure, temperature, gas and liquid superficial velocities. Besides, several authors using predicting models in order to describe the effect of operating parameters on hydrodynamic characteristics such as Khadem-Hamedani et al. [4] and Papari et al. [5].

Electrochemical technology indicates electrochemical processes or methods to eliminate impurities from liquids or minimize environmental pollution and thus providing generally a cleaner environment and covering a very wide range of technologies. The application of electrochemical

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processes in the treatment of wastewater has become more advantageous compared to other methods owing to the simplicity of construction and lower operating costs. [6]

The electro-flotation process is a technique based on the electrolysis of water and the suspension of particles. It is an electrochemical process characterized by the mechanism of microbubbles formation, generated by electrolysis of the effluent. In the literature numerous researchers focused on this process to highlight its efficiency for the separation and purification of waste waters [7,8].

The chemical reactions for generating the bubbles are as follows [7]:

Anode reaction:

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

Cathode reaction:

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

Electroflotation process can be affected by a set of factors such as electrode material [9] and current density [10]. Electrodes arrangement is also an important factor affecting electroflotation efficiency, that is, electrode surface state can affect significantly the size of bubbles. Moreover gas bubbles depend on the current density which has a major role in the dispersion of bubbles and the control of their size by coalescing or breakup.

In this work, the hydrodynamic aspect in a rectangular electroflotation column operating in batch mode has been studied. The effects of temperature on bubble characteristics and on gas holdup were evaluated.

2. Materials and methods

The schematic setup used for the determination of bubbles characteristics is shown in Fig. 1:

The electroflotation column is related to two electrodes, operating at a batch regime, made of Plexiglas having rectangular base with double walls with 90 cm height. The inner column is equipped with two electrodes and a stainless steel cathode equipped with titanium coated by ruthenium oxide anode. These electrodes are related to a generator which allows varying the values of intensity applied at the electrodes. A JULABO ED-5 heating circulator with open bath is connected to the outside wall. Its role is to circulate water at a fixed temperature in the outer column. This water will be used to heat and maintain the temperature of the liquid phase, which is putted in the inner column.

To evaluate the different hydrodynamic parameters a model solution as an oil/water emulsion was applied. A video file was obtained by using an analogue camera connected to a computer with a video capture, as well as an acquisition card from pinnacle systems in order to calculate bubble diameter and bubble velocity. We used image software (Mesurim-Pro version 6.0, virtual dub 1.6.11 and photo filter (8.0) to calculate the characteristics of bubbles. Knowing the reference wire diameter (0.149 mm), we determine the bubble's diameter then we can determine bubble raise velocity values using the equation below:

$$U_B = \frac{l}{t} \quad (3)$$

where l (mm) is the lap course at time t (s).

The gas holdup is an important and dimensionless key for the design of bubble column; it is defined by the volume fraction occupied by the gas phase. It is calculated by using image software by means of equation below [11]:

$$\varepsilon_g = \frac{H_d - H_s}{H_d} \quad (4)$$

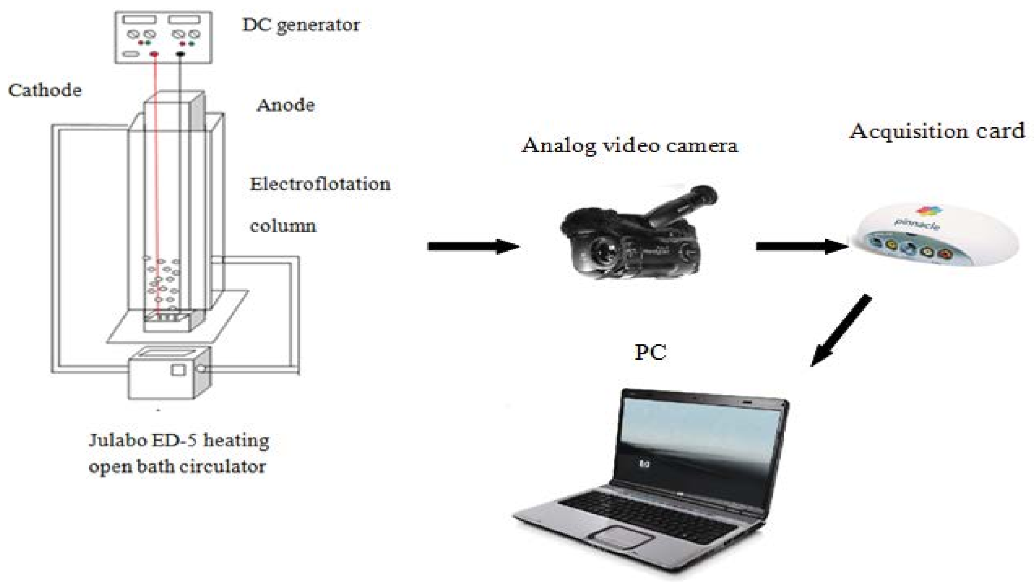

Fig. 1. Schematic diagram of the electroflotation column and equipment used.

H_d: The dispersion height in the column (m); H_s: The liquid height in the column (m); The Reynolds number expression is as follows [12]:

$$Re = \frac{\rho \times d_B \times U_B}{\mu} \quad (5)$$

where ρ: liquid density (kg/m³), d_B: bubble diameter (m), U_B: bubble velocity (m/s), μ: liquid viscosity (kg/m/s).

It characterizes the bubble flow regime which can be laminar, transitional or turbulent regime. The values of Re = 1 delimit this zone [13].

The characteristics of the obtained oil-water emulsion are given in the following Table 1:

3. Results and discussions

3.1. Effect of operating parameters on bubble diameter and bubble velocity

3.1.1. Effect of current density and viscosity on bubble diameter and bubble velocity

The variation of bubble diameter and bubble rise velocity as a function of current density for different oil concentrations was presented in the following figures:

Bubble properties can be affected by many factors such as liquid phase properties. Based on these results it is found that the increase of oil concentration leads to obtaining large bubbles. As shown in Fig. 2, the addition of oil has a significant effect, leading to higher viscous emulsion, which leads to the reduction of liquid phase turbulence. Hence, the energy of eddies is reduced and the bubble breakup is suppressed which in turn favors the coalescence rate. This is explained by the fact that two bubbles approach and collide with each other, therefore giving rise to the formation of a large bubble and the evolution of numerous bubbles characterized by large size. However, as shown in Fig. 3 the upward movement of bubbles increases as a function of current densities, it is also affected by viscosity. In fact, the increase of the latter leads to high rise velocity due to upward forces effects [14,15]. Hence, the trend of bubble interactions increases, resulting in forced coalescence. Moreover Li et al [16] and Joshi et al. [17] have shown that the increase of viscosity leads to the increase of coalescence thus giving rise to large bubbles, which further increases the rate of bubble rise velocity.

Current density has an effect on bubbles sizes [18, 19], it has a major role regarding the generation of bubbles. These bubbles are generated at both electrodes. Moreover, the increase of current density leads to an important dispersion of bubbles. Consequently some of the bubbles may coalesce due to the increase of viscosity by the formation of large bubbles.

3.1.2. Determination of bubble flow regime

The evaluation of the bubble flow regime is performed through the determination of liquid phase characteristics and current density impacts on the Reynolds number.

In bubble column there are 3 bubble flow regimes which are as follows: Laminar regime, transitional regime and turbulent bubble flow regime. Each regime has its own properties. According to Fig. 4 current density leads to the increase of values pertaining to Reynolds number for the different emulsions. The increase of oil concentration gives rise to the increase of viscosity which induces the coalescence, thus resulting in the formation of a large bubble with high rise velocity. Therefore, there is a transition of flow regime from laminar to turbulent regime.

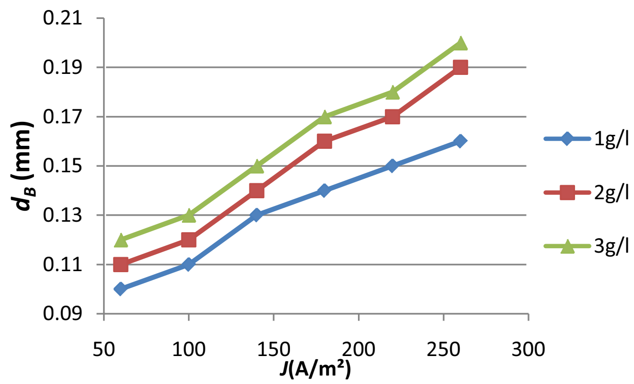

Fig. 2. Effect of current density and oil concentration on bubble diameter.

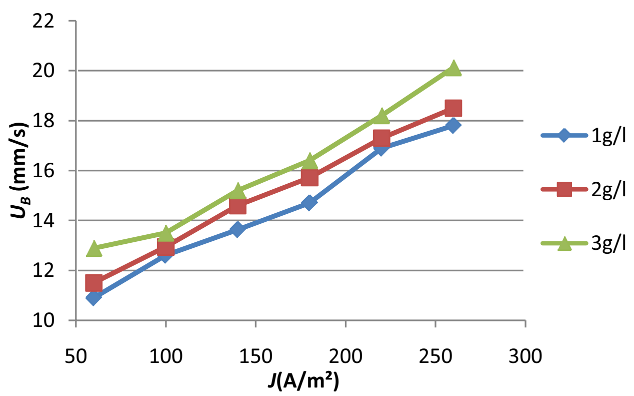

Fig. 3. Effect of current density and oil concentration on bubble velocity.

Table 1
Physicochemical characteristics of model solution at 25°C

Characteristics	1 g/L	2 g/L	3 g/L
Density (kg/m³)	999.8	998.06	997.003
Dynamic viscosity (kg/m/s)	1.42×10^{-3}	1.44×10^{-3}	1.47×10^{-3}

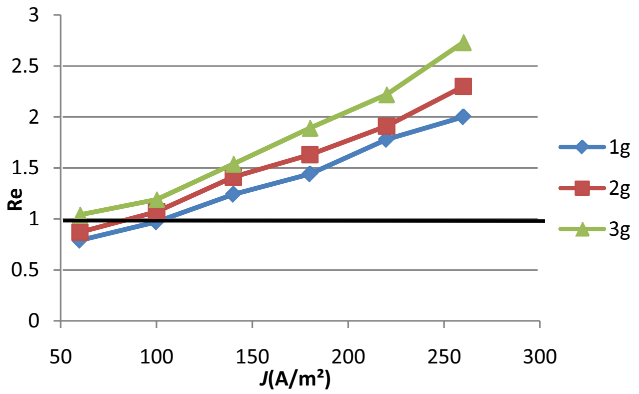

Fig. 4. Effect of current density and oil concentration on Reynolds number.

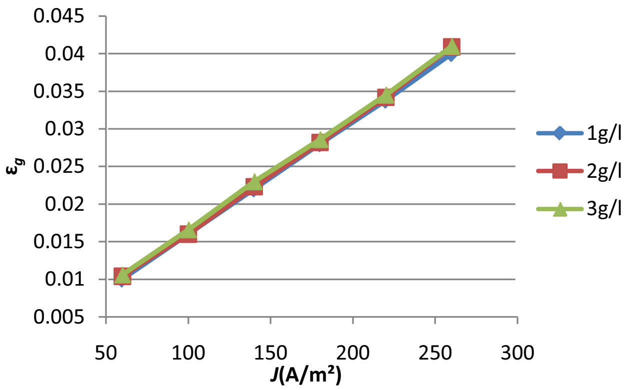

Fig. 5. Effect of current density and oil concentration on gas holdup.

The laminar bubble flow regime is observed at current density lower than 100 A/m², corresponding to Re lower than 1 [13]. It is characterized by an even distribution of small bubbles with low velocities [20] and no bubble coalescence is observed. The turbulent regime occurs at Re > 1 with current density greater than 100 A/m². It is characterized by the formation of large size bubbles that move in a disordered manner, thus creating turbulence and unfavorable regime for separation [21].

The variation of gas holdup as a function of current density for different oil/water emulsions is presented in Fig. 5:

The factors affecting gas holdup there are as follows: liquid phase properties, superficial gas velocity, column dimensions, etc, as shown in Fig. 5:

When the current density increases the values of gas holdup increases due to important gas dispersion; the increase of oil concentration has no significant effect on gas holdup which is also found by Sherif et al. [22]. Besides the addition of oil to water ratio has no effect on gas holdup.

3.1.3. Modeling of the hydrodynamic parameters

Due to the dependence of bubble diameter, bubble velocity and Reynolds number on current density and liquid viscosity at fixed temperature, we attempted to express them as a function of those operation conditions using Data fit program version (8.1.69). Hence we obtained the following equations:

$$d_B = -19{,}11 + 3{,}73.10^{-4} J + \frac{5{,}65.10^{-2}}{\mu} - \frac{4{,}16.10^{-5}}{\mu^2} \tag{6}$$

Fig. 6 displays the difference between the experimental results of bubble diameter and the values predicted calculated by Eq. (6) where J is current density and μ is liquid viscosity. The error bars represent the average deviation from the average of the replicates. In fact the average difference error between experimental and predicted results is ±5% which is considered satisfactory. The equation shows a good agreement with the experiment data. This correlation justify

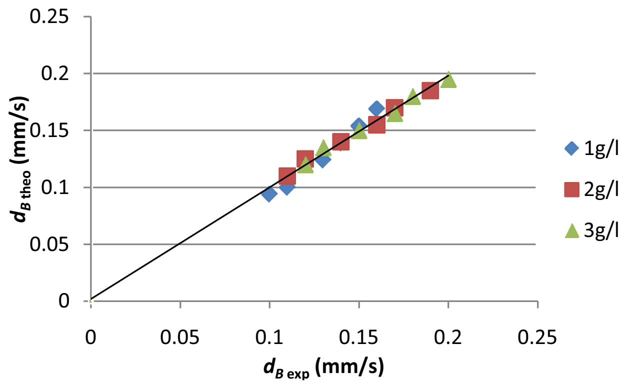

Fig. 6. Comparison between predicted values and experimental values of bubble diameter.

that bubble diameter tend to increase when current density and viscosity increases due to increasing coalescence.

$$U_B = 725{,}57 \times 10^6 \times J^{0{,}33} \times \mu^{2{,}95} \tag{7}$$

According to Fig. 7 predicted model fits the experimental data very well with regression coefficient R^2 = 0,96. From Eq. (7) the dependence of bubble velocity on operating parameters were found. Thus this correlation shows that bubble velocity increases as a function of current density and viscosity for different oil/water emulsion.

$$\mathrm{Re} = 12{,}05 + 3{,}8 \times 10^{-3} J + 1{,}07 \times 10^{-5} J^2 - \frac{1{,}64 \times 10^{-2}}{\mu} \tag{8}$$

As shown in Fig. 8, the predicted values found by the empirical equation of Reynolds number agrees very well with the experimental values with regression coefficient R^2 = 0.97. Eq. (8) shows a good agreement with the experimental data. As results this equation confirm that Reynolds number increases when current density and viscosity increases. This can be attributed to the fact that increasing Reynolds

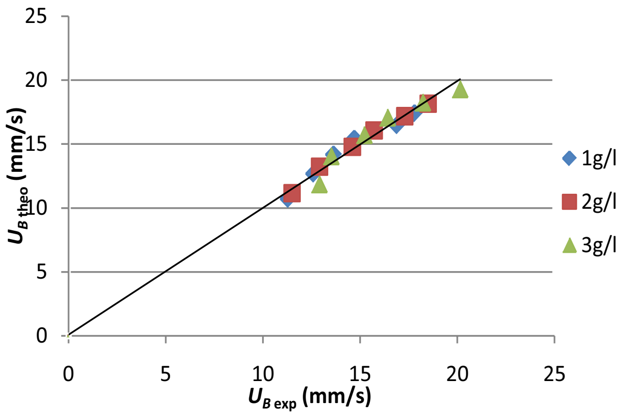

Fig. 7. Comparison of experimental values and predicted values of bubble velocity.

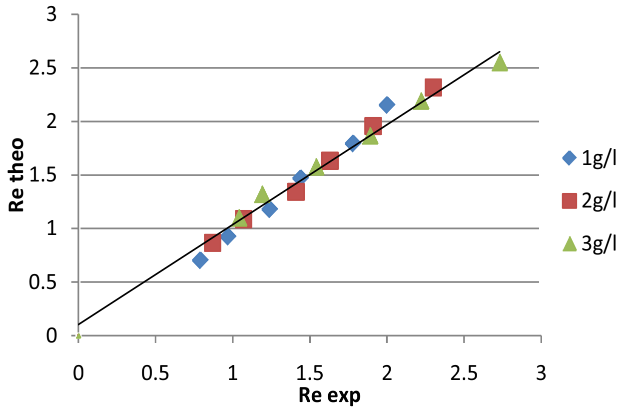

Fig. 8. Comparison of experimental data and predicted values of Reynolds number.

number leads to increasing of liquid turbulence and favors the appearance of turbulent regime

3.2. Effect of temperature on bubble characteristics

Similar to the previous methods, to investigate the impact of temperature on physicochemical properties and bubble characteristics experiments were carried out by using the same model solution of oil/water emulsion with concentration 2 g/L. A JULABO Ed-5 related to outer column was employed to fix the temperature of the solution in the inner column. The chosen range of temperature was between (30°C–60°C) for current densities ranging from 60 to 260 A/m².

The obtained values of physicochemical properties were presented in following Table 2:

According to the above Table 2, it is noted that temperature has an effect on the physicochemical properties: the density and the viscosity. When the liquid is heated the viscosity of the liquids is reduced. Besides, the increase of temperature leads to a decrease in the liquid phase density.

Table 2
Physicochemical characteristics of model solution (oil/water emulsion 2 g/L) for different temperatures

	30°C	40°C	50°C	60°C
ρ (kg/m³)	997	996.3	995	993.1
μ (kg/m/s)	0.0014	0.00138	0.0013	0.00124

3.3. Effect of temperature on bubble diameter and bubble velocity

After the video recording and image processing, different parameters as well as their effects on the bubble's characteristics were taken in consideration. Furthermore, the values of the diameter and the velocity of bubbles were calculated. The results are presented in the following figures:

According to Fig. 9, bubble diameter increases when current density increases for different emulsions however increasing temperature leads to the decrease of bubble diameter. On the other hand, Drogaris and Weiland [23] reported an exponential decrease in coalescence time with an increase in temperature from 10°C to 60°C. Pounder [24] found that the decrease in temperature causes a reduction of bubble size. The increase of temperature reduces the values of viscosity which in turn reduces coalescence and leads to the decrease of bubble diameter.

Based on Fig. 10, increasing temperature leads to a slight increase of bubble rise velocity. Several authors revealed that the variation of bubble velocity is dependent on temperature while others reported that bubble's velocity increases to maximum values at certain values of temperatures then it decreases, Zhang et al. [25] found that bubble's velocity in water increases when temperature increases, however, the time to reach constant velocity decreases.

3.4. Effect of temperature on bubble flow regime

According to Fig. 11, increasing temperature leads to the increase of Reynolds number which causes an increasing of liquid turbulence. Besides, the increase of current density in obtaining higher values of Reynolds number which causes the appearance of turbulent regime which is obtained

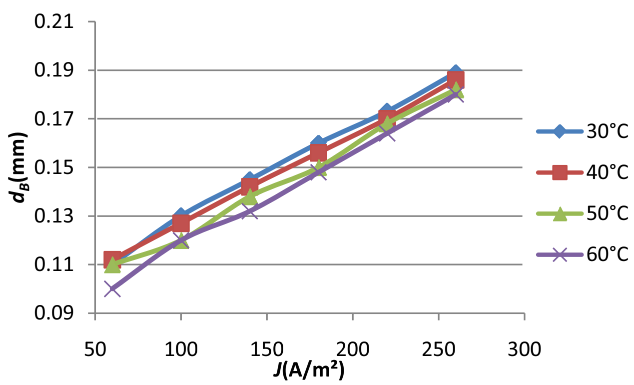

Fig. 9. Effect of temperature on bubble diameter for different oil/water emulsions.

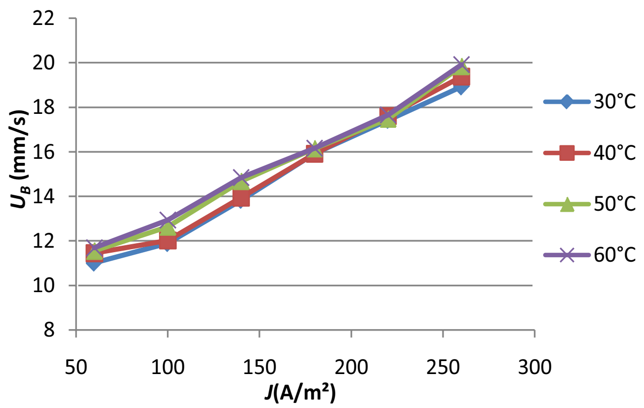

Fig. 10. Effect of temperature on bubble velocity for different oil/water emulsions.

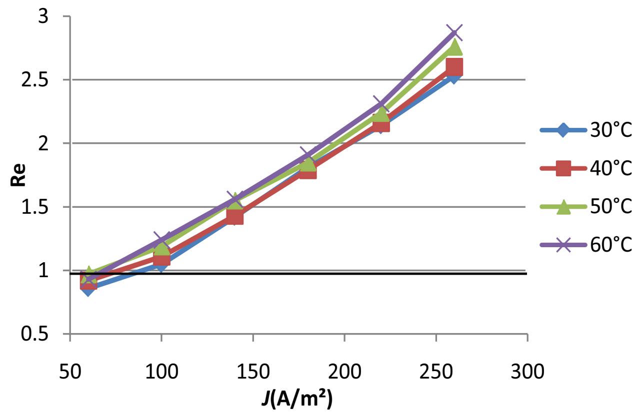

Fig. 11. Effect of temperature on Reynolds number for different oil/water emulsions.

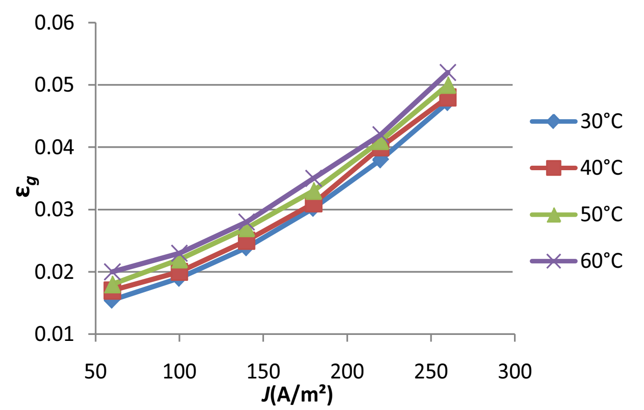

Fig. 12. Effect of temperature on gas holdup for different oil/water emulsions.

at current density greater than 60 A/m² corresponding to Re > 1. Accordingly, bubble velocity has a dominant effect on Reynolds number because; despite the decrease of bubble diameter, liquid density and liquid viscosity the values of Reynolds number increase.

3.5. Effect of temperature on gas holdup

Temperature can be a factor affecting gas holdup. Indeed Saxena et al. [26] observed an increase of gas holdup and a decrease in bubble diameter while increasing temperature. Lin et al. [27] and Shafer et al. [28] found that the increase in temperature leads to higher values of gas holdup. As illustrated in the figure below (Fig. 12) temperature has a significant impact on gas holdup, which increases as temperature increases. This is ascribed to the reduction of liquid viscosity which causes the reduction of coalescence rate and smaller bubble size, thus leading to the increase of gas holdup.

4. Conclusion

Based on the results of the experimental studies on electroflotation columns the following conclusions can be drawn:

- The increase of current density leads to obtaining large bubbles diameter with high rise velocity.
- Current density also has an effect on Reynolds number. Its increase leads to the transition of regime from laminar to turbulent regime. Furthermore the increase of oil concentration results in obtaining higher viscous emulsion and creating turbulent regime.
- The transition from laminar regime to turbulent regime was obtained at a current density higher than 100 Am² with Re > 1.
- The study of the effect of temperature demonstrates that this factor has an effect on physicochemical properties In fact; its increase leads to the decrease of liquid phase viscosity and liquid phase density.
- The augmentation of temperature also has a significant effect on bubble characteristics especially on bubble diameter.
- Reynolds number depends on temperature and there is transition of bubble regime from laminar to turbulent regime at current density 60 A/m².
- Temperature has an impact on gas holdup. Its increase leads to obtaining higher values of gas holdup

Symbols

μ	—	Liquid phase viscosity, kg/m/s
d_B	—	Bubble diameter, m
ε_g	—	Gas holdup
H_d	—	Dispersion height in column, m
H_s	—	Initial height in column, m
J	—	Current density, A/m²
l	—	Lap course of bubble, m
Re	—	Reynolds number
t	—	Time, s
U_B	—	Bubble rise velocity, m/s
ρ	—	Liquid phase density, kg/m³

References

[1] Y. Li, M. Han, H. Fang, A review of treating oily wastewater, Arabian J. Chem., 10 (2017) 1–10.

[2] S. Degaleesan, M. Dudukovic, Y. Pan, Experimental study of gas-induced liquid-flow structures in bubble columns, AIChE J., 7 (2001) 1913–1931.

[3] S. Walke, S. Vivek, Review of gas holdup characteristics of bubble column reactors, Int. J. Chem. Eng. Res., 3 (2011) 71–80.
[4] B. Khadem-Hamedani, S. Yaghmaei, M. Fattahi, S. Mashayekhan, S.M. Hosseini-Ardali, Mathematical modeling of a slurry bubble column reactor for hydrodesulfurization of diesel fuel: single- and two-bubble configurations, Chem. Eng. Res. Des., 100 (2016) 362–376.
[5] S. Papari, M. Kazemeini, M. Fattahi, M. Fatahi, DME direct synthesis from syngas in a large-scale three-phase slurry bubble column reactor: transient modeling, Chem. Eng. Commun., 201 (2014) 612–634.
[6] G. Chen, Electrochemical technologies in wastewater treatment, Sep. Purif. Technol., 38 (2004) 11–41.
[7] M. Kotti, I. Ksentini, L. Ben Mansour, Impact of anionic surfactants on oxygen transfer rate in the electroflotation process, Desal. Wat. Treat., 36 (2011) 1–7.
[8] C.C. Ho, C.Y. Chan, The application of lead dioxide-coated titanium anode in the electroflotation of palm oil mill effluent, Water Res., 20 (1986) 1523–1527.
[9] X. Chen, G. Chen, P.L. Yue, Novel electrode system for electroflotation of wastewater, Environ. Sci. Technol., 36 (2002) 778–783.
[10] M. Murugananthan, G. Bhaskar Raju, S. Prabhakar, Separation of pollutants from tannery effluents by electro flotation, Sep. Purif. Technol., 40 (2004) 69–75.
[11] J.M.T. Vasconcelos, J.M.L. Rodrigues, S.C.P. Orvalho, S.S. Alves, R.L. Mendes, A. Reis, Effect of contaminants on mass transfer coefficients in bubble column and airlift contactors, Chem. Eng. Sci., 58 (2003) 1431–1440.
[12] I. Parashivoilu, M. Prud'homme, L. Rabillard, Mécanique des fluides, Press Inter Polytechnique, Montereal, Canada, 2003.
[13] A.A. Kendoush, T.J. Mohammed, B.A. Abid, M.S. Hameed, Experimental investigation of the hydrodynamic interaction in bubbly two-phase flow, Chem. Eng. Process., 43 (2004) 23–33.
[14] A. Esmaeili, C. Guy and J. Chaouki, Local hydrodynamic parameters of bubble column reactors operating with non-Newtonian liquids: experiments and models development, AIChE J., 62 (2016) 1382–1396.
[15] A.A. Kulkarni, J.B. Joshi, Bubble formation and bubble rise velocity in gas–liquid system: a review, Ind. Eng. Chem. Res., 44 (2005) 5873–5931.
[16] H. Li, A. Prakash, Heat transfer and hydrodynamics in a three-phase slurry bubble column, Ind. Eng. Chem. Res., 36 (1997) 4688–4694.
[17] J.B. Joshi, V.S. Vitankar, A.A. Kulkarni, M.T. Dhotre, K. Ekambara, Coherent flow structures in bubble column reactors, Chem. Eng. Sci., 57 (2002) 3157–3183.
[18] V.A. Kolesnikov, S.O. Varaksin, V.I. Ilyin, An electroflotation method for purifying effluents from ions of metals and organic pollutants and its equipment, Russ. Chem. Ind., 26 (1994) 38–46.
[19] S.C. Saxena, N.S. Rao, A.C. Saxena, Heat-transfer and gas-holdup studies in a bubble column: air–water–glass bead system, Chem. Eng. Commun., 96 (1990) 31–55.
[20] J.Y. Kim, B. Kim, N.-S. Nho, K.-S. Go, W.H. Kim, J.W. Bae, S.W. Jeong, N. Epstein, D.H. Lee, Gas holdup and hydrodynamic flow regime transition in bubble columns, J. Ind. Eng. Chem., 56 (2017) 450–462.
[21] R. Issaoui, I. Ksentini, M. Kotti, L. Ben Mansour, Effect of current density and oil concentration on hydrodynamic aspects in electroflotation column during oil/water emulsion treatment, J. Water Chem. Technol., 39 (2017) 166–170.
[22] S.H. Eissa, K. Schügerl, Holdup and backmixing investigations in cocurrent and countercurrent bubble columns, Chem. Eng. Sci., 30 (1975) 1251–1256.
[23] G. Drogaris, P. Weiland, Coalescence behavior of gas bubbles in aqueous solutions of *n*-alcohols and fatty acids, Chem. Eng. Sci., 38 (1983) 1501–1506.
[24] C. Pounder, Sodium Chloride and Water Temperature Effects on Bubbles, Oceanic White Caps, Oceanographic Sciences Library, Dordrecht, 1986.
[25] Y. Zhang, A. Sam, J.A. Finch, Temperature effect on single bubble velocity profile in water and surfactant solution, Colloids Surf., A, 223 (2003) 45–54.
[26] S.C. Saxena, N.S. Rao, P.R. Thimmapuram, Gas phase holdup in slurry bubble columns for two- and three-phase systems, Chem. Eng. J., 49 (1992) 151–159.
[27] T.-J. Lin, K. Tsuchiya, L.-S. Fan, Bubble flow characteristics in bubble columns at elevated pressure and temperature, AIChE J., 44 (1998) 545–560.
[28] R. Schäfer, C. Merten, G. Eigenberger, Bubble size distributions in a bubble column reactor under industrial conditions, Exp. Therm Fluid Sci., 26 (2002) 595–604.