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Effect of water conductivity on gas hold-up and oxygen transfer rate in an electroflotation column

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ABSTRACT

This study concerns the investigation of operating conditions and liquid properties effects on the gas hold-up (ε_g) and on volumetric mass transfer coefficient (K_La) during the wastewater treatment by the electro flotation process. The experiments were carried out in a rectangular electro flotation column to study the effects of conductivity (k) and current density (J) on the volumetric oxygen transfer coefficient and on the gas hold-up. Water at different sodium chloride ($NaCl$) concentration was used as model solutions of some effluents. A mathematical model of K_La has been established to show the effect of the current density and conductivity on the oxygen transfer rate.

Keywords: Conductivity; Electro flotation; Gas hold-up; Mass transfer coefficient

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1. Introduction

Demands to the cleaning industrial and domestic wastewater to avoid environmental pollution and especially contamination of pure water resources are becoming national and international issues. Innovative, low-cost and effective methods of purifying and cleaning wastewater like electro coagulation [1], electro flocculation [2], electro deposition, electro oxidation [3], and electro flotation before discharging into any other water systems are needed.

A growing research interest is reported on the treatment of various wastewater types: metal processing wastewaters [4], semiconductor production wastewater, textile dyeing wastewaters [5,6], tannery wastewater pretreatment, oil wastewater [7], arsenic and phosphate removal from wastewater and organics removal from poultry slaughter house wastewaters [8].

However, the addition of electrolyte is inevitable if the wastewater sample is not sufficiently conducting. In many cases, the electrolyte is added to enhance the removal rate process and several studies have employed NaCl as the salt to increase the conductivity [9,10]. But when the addition of NaCl was excessive and uncontrolled it becomes an obstacle for a good treatment [7].

Electro flotation process is the electrochemically version of the traditional flotation process. It has been successfully used in the treatment of various emissions: water washing, wastewater rich on surfactants [11], wastewater resulting from tannery textile processing, oil in water emulsion, etc. [12]. Electro flotation process was first proposed by Elmore in 1904 [13]. It has been recognized as an economically and technically significant alternative with simple design and construction, high efficiency of homogenization and intense mixing for heat and mass transfer, low power consumption, and shear stresses [14]. In electro flotation process, the oxygen and hydrogen bubbles are generated at insoluble titanium coated with ruthenium oxide anode and a stainless steel cathode respectively, as below:

Anode oxidation: $2H_2O \rightarrow 4H^+ + O_2^{\uparrow} + 4e-$ (1)

Cathode reduction: $4H_2O + 4e- \rightarrow 2H_2^{\uparrow} + 4OH^-$ (2)

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The most important parameters which govern the performance of electro flotation column are the overall gas hold-up (ε_g), volumetric oxygen transfer coefficient (k_La), interfacial area (a), and liquid-side oxygen transfer coefficient (K_L).

Salinity which is related to the conductivity is known to affect the wastewater process treatment, for instance it affect significantly the bubble diameter (d_B) and the inter facial area (a) [15]**.** Moreover, water conductivity has a notable influence on the volumetric mass transfer coefficient [16]**.**

This work is focused on the quantitative analysis of water conductivity and current density effects on the gas hold-up and on the oxygen transfer rate in a rectangular electro flotation column.

One of the most important parameters defining the hydrodynamics of electro flotation column is the gas hold-up (ε_g) [17]. It defines the gas-phase volume fraction present in the column. Gas hold-up (ε_g) lead to determine the inter facial area (a) [18].

The volumetric mass transfer coefficient of dissolved oxygen can be derived from the two-film theory [19]. Assume that the diffusion rate of oxygen through gas film is much higher than the diffusion rate through liquid film so the resistance of gas film can be neglected [20]. The mass balance of oxygen in the liquid phase is given in Eq. (3):

$$\frac{dC}{dt} = K_L a\left(C^* - C\right) \tag{3}$$

where dC/dt is the rate of oxygen concentration variation with time.

The volumetric oxygen transfer coefficient must be corrected to a standard reference temperature (T) of 20°C by using the Arrhenius relationship [20].

Although the specific inter facial area (**a**) is the key parameter in the study of the gas–liquid mass transfer [21]. Generally, the inter facial area depends on the unit's geometrical size, the operating parameters and the physical and chemical properties of the liquid phase [22].

In addition, the liquid-side oxygen transfer coefficient (K_L) represents an essential part as enhancement factor for the mass transfer rate. Commonly reported as a function of liquid properties and bubble diameter [23], it depends also on the diffusivity coefficient and on the flow pattern around the bubbles (local hydrodynamics).

2. Materials and methods

2.1. Models solutions preparation

The model solutions used in this experimental study were prepared with adding sodium chloride (NaCl) to osmosis water at a concentration varying from 2.5 g/L to 10 g/L, so water conductivity has been varied between 0.6 mS/cm and 15.5 mS/cm. Experiments were conducted for different water conductivity. The current density has been varied from 60 A/m² to 300 A/m².

All experiments were conducted at ambient pressure and temperature conditions, and in a batch mode operation.

2.2. Experimental unit

The experiments were carried out using a rectangular electro flotation column in batch mode, which was made of Plexiglas material to enable visual observations. It has dimensions of 5.8 × 6.7 × 71.5 cm as detailed in Fig. 1.

The electro flotation column was equipped with insoluble anode and stainless cathode placed in the bottom of the column. The electrical current was applied using a stabilized power supply which is a DC rectifier (DC Power GPC-M Series GW-INSTEK-TAIWAN) equipped with a digital ammeter and voltmeter. The amount of gas bubbles produced per unit time is directly related to the cur-

Table 1
Model solutions conductivity

Liquid phase	Conductivity "ƙ" (mS/cm)
Osmosis water	0.6
Saline water (2.5 g/l)	4.3
Saline water (5 g/l)	7.6
Saline water (7.5 g/l)	9.9
Saline water (10 g/l)	15.5

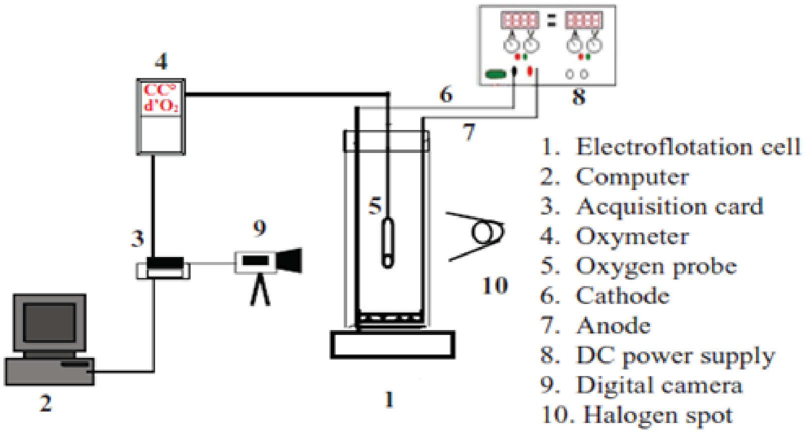

Fig. 1. Experimental setup.

rent flowing through the electro flotation column. The gap between anode and cathode was maintained at *5 mm* to minimize the ohmic loss. The cathode compared to the anode was perforated and occupied the top opposition. This perforation allows the evacuation of bubbles produced at the anode. The dissolved oxygen concentration was measured using an oxygen probe (Consort C 863) placed mid-way in the electro flotation column.

2.3. Determination of the gas hold-up

Gas hold-up is needed to estimate inter facial area (*a*) and liquid-side oxygen transfer coefficient, K_L [24]. It is usually expressed as the volume fraction of gas phase occupied by the gas bubbles [25]. In our study the gas hold-up was determinate using image treatment system [26].

2.4. Determination of volumetric oxygen transfer coefficient, K_La

The volumetric oxygen transfer coefficient ($K_L\,a$) was determinate using the unsteady state method with an oxygen probe (Consort 863) placed mid-way in the electro flotation column.

The oxygen concentration was reduced to zero by adding 150 mg/L of sodium sulphite (Na_2SO_3) and 3 mg/L of cobalt ions was added as catalyst.

$$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4 \tag{4}$$

The re-oxygenation experiments were conducted with different models saline water solutions at current density ranging from 60 A/m² to 300 A/m².

2.5. Determination of the specific inter facial area (a) and bubble diameter (d_B)

Knowing the bubble diameter and gas hold-up, it is possible to evaluate the specific inter facial area using the following equation [27]:

$$a = \frac{\left(6\varepsilon_g\right)}{\left(d_B\left(1-\varepsilon_g\right)\right)} \tag{5}$$

where a is specific inter facial area, ε_g is gas hold-up, d_B is bubble diameter

Bubble flow images were taken by an analog Video camera in each experimental condition to determinate the bubble diameter. A wire of known diameter (0.149 mm) was also recorded to be used as a calibration factor of the bubbles diameter. A sufficiently representative bubble diameter usually diameters of at least 100 bubbles were determined in each experimental condition [28].

2.6. Determination of liquid-side oxygen transfer coefficient, K_L

The product of the liquid-side oxygen transfer coefficient and the inter facial area is known as the volumetric oxygen transfer coefficient.

Thus, the liquid-side oxygen transfer coefficient can be determined by:

$$K_L = \frac{\left(K_L\,a\right)}{a} \tag{6}$$

3. Results and discussion

3.1. Effect of conductivity on bubble diameter and gas hold-up

It has been observed that the addition of NaCl as a strong electrolyte to water inhibits bubble coalescence. As a result there is a decrease of bubbles diameter as shown in Fig. 2.

It was reported that the effect of the electrolyte solution on bubble size is directly related to the ionic strength of the electrolyte solution, the bubble size decreases with increasing ionic strength of the electrolyte solution. Some authors did not find any effect of current density on bubble size [29]. Indeed, in our case, the current density acts directly on number and shape of the gas bubbles. In fact, the number of bubbles increases when current density increases. So the probability of bubbles coalescence increases. As a result the bubbles diameter increase also.

The gas hold-up, which is one of the most important parameters characterizing the hydrodynamics of electro flotation column, depends mainly on the solution conductivity. When the solution conductivity enhanced, the bubbles were efficiently dispersed and the gas hold-up increase also. This is well explained by Fig. 3.

For high current density gas hold-up begin also higher. These results show also that when the value of conductivity becomes higher than 9.9 mS/cm, the bubble diameter tends to become stable and the enhancement of gas hold-up becomes weak.

3.2. Effect of conductivity on volumetric oxygen transfer coefficient, K_La

In order to calculate the volumetric oxygen transfer coefficients using the integral of Eq. (3) [30], a series of unsteady states re-oxygenation tests at different current densities and concentrations of sodium chloride (NaCl) were conducted. The oxygen concentration increases at the beginning of the electrolysis process than stabilizes when

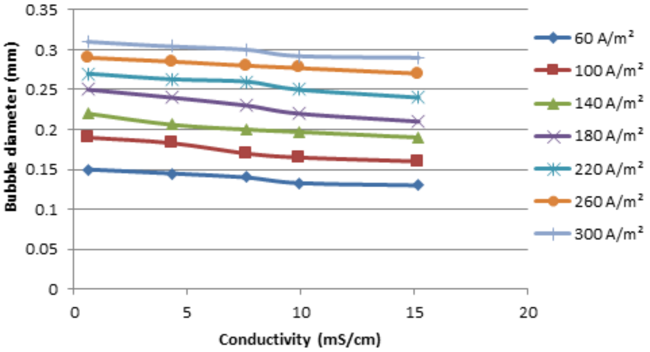

Fig. 2. Effect of conductivity on bubble diameters for different current density.

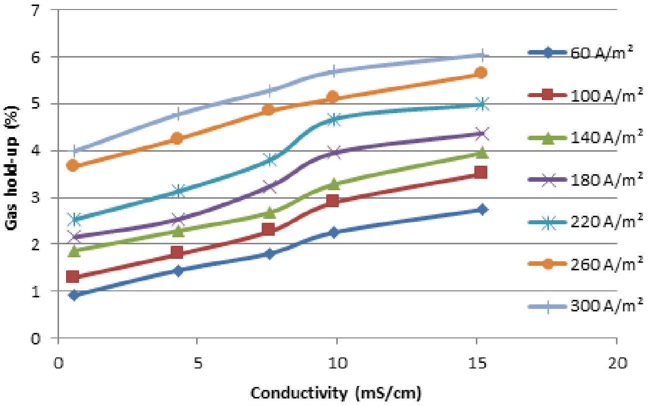

Fig. 3. Effect of conductivity on gas hold-up for different current density.

it reaches the equilibrium concentration. All the data are exploited by a specific data processing program which is (Data Fit version 8.1.69). The principle of this method is to make a non-linear regression of the integral of Eq. (3).

The volumetric oxygen transfer coefficient K_La was measured under the same conditions as gas hold-up. The effect of different conductivity levels on the volumetric oxygen transfer coefficient at different current density is shown in Fig. 4. From this figure, it can be seen that increase in conductivity highly enhances the volumetric oxygen transfer coefficient.

Also when the current density increases the number of oxygen bubbles increases too. So the enhancement of the bubbles number generates an intense agitation which decreases the transfer resistance at the liquid side. As a result the volumetric oxygen transfer coefficient $K_L a$ increases.

3.3. Effect of the conductivity on the specific inter facial area (a)

As discussed earlier, the bubble diameter in saline water was small and more than that in the osmosis water. Electrolyte concentrations have a noticeable effect on the specific inter facial area. It was enhanced due to the gas hold-up increasing and bubble diameter reducing.

Therefore, the specific inter facial area obtained in the systems at all salinity levels was greatly enhanced for different current density as shown in Fig. 5. The specific inter facial area ranges between 371.82 m²/m³ and 1400 m²/m³ for a current density between 60 A/m² and 300 A/m². Fig. 5 shows that the specific inter facial area increases significantly with current density.

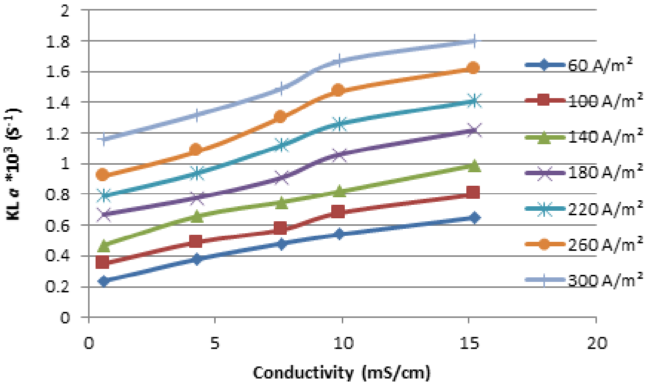

Fig. 4. Effect of conductivity on volumetric oxygen transfer coefficient for different current density.

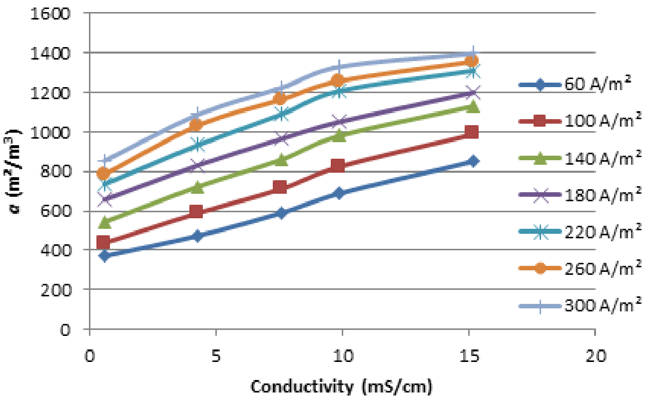

Fig. 5. Effect of conductivity on the specific inter facial area for different current density.

3.4. Effect of conductivity in Liquid-side oxygen transfer coefficient, K_L

The mass transfer rate depends not only on the gas hold-up and bubble size but also on the value of liquid-side oxygen transfer coefficient K_L. The relationship between liquid-side oxygen transfer coefficient and different conductivity levels of saline samples for different current density is presented in Fig. 6.

It was noticed that the liquid-side oxygen transfer coefficient decreases with the increasing of conductivity. These results clearly indicate that the presence of salt at the bubble interface disturbs the mass transfer, certainly by modifying the composition or the thickness of liquid film around the bubbles [31]. It has been also shown that K_L increases with increasing current density. At higher current densities, a large amount of oxygen was induced into the liquid phase, resulting in more gas bubbles. Consequently, turbulence created in the liquid phase was more intense due to the higher shear force. This is similar to previous studies of other types of gas-inducing contactor [32,33].

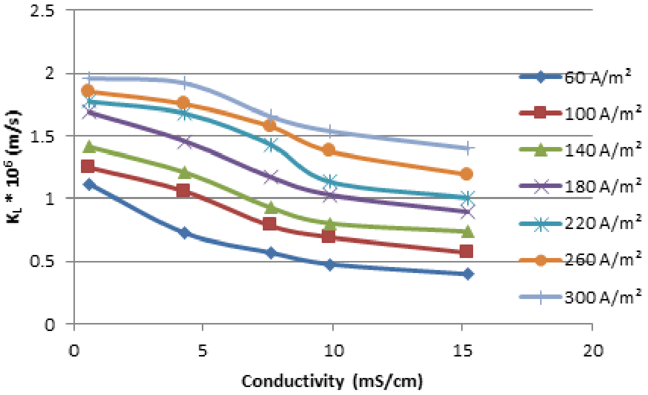

Fig. 6. Effect of conductivity on liquid-side oxygen transfer coefficient for different current density.

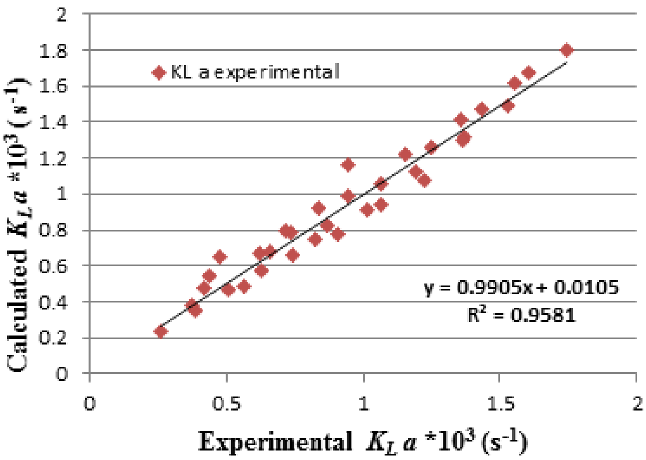

Fig. 7. Experimental and calculated volumetric oxygen transfer coefficient at different conductivity.

3.5. Mathematical study

A mathematical equation that permits to express the volumetric oxygen transfer coefficient according to the water conductivity and current density was established by nonlinear regression. For this, an appropriate mathematical program Data Fit (version 8.1.69) was selected and the following relationship was obtained.

$$K_L a = 1.052 * 10^{-5} * J^{0.8} * \kappa^{0.19} \tag{7}$$

where J is the current density and κ is the water conductivity.

This relation indicates clearly that the volumetric oxygen transfer coefficient $K_L a$ increases with increasing of booth current density and conductivity.

Fig. 7 shows the comparison between the experimental and the calculated values of volumetric oxygen transfer coefficient. The average difference is considered satisfactory since the regression coefficient is about $R^2 = 0.958$.

4. Conclusions

The effects of solution conductivity and current density on the oxygen transfer were experimentally investigated in a rectangular electro flotation column function in batch mode. A satisfactory result for a wide range of bubbles characteristics has been obtained by using the video image processing technique. It is clear that the presence of a strong electrolyte as NaCl in water has a significant effect on the gas hold-up, the bubble diameter and on the inter facial area, consequently on the volumetric oxygen transfer coefficient during the wastewater treatment for different current density. The addition of NaCl in wastewater lead to an increase of the values of gas hold-up, inter facial area and the volumetric oxygen transfer coefficient but to decrease of the bubble diameter and liquid-side oxygen transfer coefficient A mathematical equation allows the determination of volumetric oxygen transfer coefficient as a function of the conductivity and current density was developed.

Symbols

a — Inter facial area, m^2/m^3;
C — Dissolved oxygen concentration in liquid phase, kg/m^3;
C^* — Equilibrium oxygen concentration in liquid phase, kg/m^3;
d_B — Bubble diameter, mm;
J — Current density, A/m^2;
$K_L a$ — Volumetric mass transfer coefficient, s^{-1};
K_L — Liquid-side oxygen transfer coefficient, m/s;
T — Temperature, °C;

Greek

ε_g — Gas hold-up, %;
κ — Conductivity, mS/cm;

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