Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.874136

52 (2014) 1693–1698
February

Taylor & Francis
Taylor & Francis Group

Impact of hydrodynamic regime on the capacity of oxygen transfer in a stirred electroflotation column

M. Kotti, I. Ksentini, L. Ben Mansour*

Laboratory of Applied Fluid Mechanics, Process Engineering and Environment, Sciences Faculty of Sfax, B.P.1171, 3000 Sfax, Tunisia
Tel. +216 98657 061; Fax: +216 74666 479; email: lassaadbenmansour@yahoo.fr

Received 14 December 2011; Accepted 14 November 2013

ABSTRACT

Electroflotation (EF) is a relatively new technology for industrial wastewater treatment. It is considered as the electrochemical version of the traditional flotation. It is distinguished by the mechanism of bubbles production. In this context, we studied oxygen transfer in an agitated EF column by Rushton turbine (TR). The capacity of oxygen transfer is controlled by the volumetric mass transfer coefficient (K_La). This coefficient was experimentally evaluated for different hydrodynamic regimes. The hydrodynamic regimes are associated with the variation of Reynolds number relative to the agitation movement and to the movement of gas bubble in the liquid phase. Model of K_La was established in order to describe the effect of the operating parameters and the Reynolds number on the oxygen transfer rate. Such model allows the prediction of optimal treatment regime when EF is used as an industrial process to treat wastewaters.

Keywords: Electroflotation (EF); Coefficient of oxygen transfer; Agitation; Reynolds number

1. Introduction

For a long time, the mechanically agitated and aerated type of vessels is among the most common reactors used almost universally for gas dispersion and reactions in biochemical, fermentation, and wastewater treatment industries [1–3]. It is the objective of such processes to agitate the gas–liquid mixture in order to generate a dispersion of gas bubbles in a continuous liquid phase. Mass transfer then takes place across the created gas–liquid interface.

In the Electroflotation (EF) process, bubbles are generated by water electrolysis [4,5] to produce hydrogen and oxygen at the cathode and the anode, respectively.

Anodic oxidation:

$$2H_2O \rightarrow O_2^{\uparrow} + 4H^+ + 4e^- \tag{1}$$

Cathodic reduction:

$$4H_2O + 4e^- \rightarrow 2H_2^{\uparrow} + 4OH^- \tag{2}$$

---

*Corresponding author.

Presented at the Third Maghreb Conference on Desalination and Water Treatment (CMTDE 2011) Hammamet, Tunisia, 18–22 December 2011

Compared with conventional flotation, EF has many advantages. Firstly, it is characterized by a fast rate of pollutant particles removal. Secondly, it is able to achieve, simultaneously, the flotation and coagulation processes with less produced sludge. Thirdly, the EF equipment is very compact and thus suitable for installation where the available space is rather limited. Furthermore, this process can be adjusted by mainly controlling the current density applied which makes quite easy the automation operation. This offers simplicity and low operating costs [6,7].

The objective of the present study is to investigate the effect of the mechanical agitation using Rushton turbine (TR) impeller on oxygen transfer rate in the EF cell.

2. Theory

In the absence of chemical reaction and for a low bubble solubility, gas–liquid mass transfer is controlled by molecular diffusion in the liquid phase [8]. Lewis and Whitman assumed that the gas side resistance is negligible and that the gas transfer may be determined from considering the liquid-side resistance only [9]:

$$\frac{dC}{dt} = K_L\, a(C^* - C) \quad (3)$$

where dC/dt is the rate of oxygen concentration change with time, $(K_L\, a)$ is the volumetric mass transfer coefficient (s^{-1}), C^* is the equilibrium oxygen concentration in liquid phase (kg/m^3), and C is the dissolved oxygen concentration in liquid phase (kg/m^3).

Eq. (3) can be readily integrated to yield the following expression for C as a function of time:

$$C = C^* - (C^* - C_0)\ \exp(-K_L a\, t) \quad (4)$$

where C_0 is the initial dissolved oxygen concentration at $t = 0$. A non-linear regression analysis based on the Gauss–Newton method is recommended by American Society of Civil Engineers to fit Eq. (4) to experimental data using $K_L\, a$, C^* and C_0 as three adjustable model parameters [10].

The volumetric mass transfer coefficient must be corrected to a standard reference temperature of 20℃ by using the Arrhenius relationship [8]:

$$K_L a_{(20^\circ C)} \ = \ K_L\, a_{(T)}\ \theta^{(20-T)} \quad (5)$$

Generally, the accepted value of the temperature correction's factor θ is 1.024.

3. Experimental setup and measuring techniques

3.1. EF cell

The EF cell, shown in Fig. 1, is used for batch mode. It is a cylindrical Plexiglas vessel with a diameter of 9.50 cm and a height of 71.5 cm. It is provided with two electrodes: titanium coated with ruthenium oxide anode and a stainless steel cathode. These two electrodes are supplied by a generator of DC current which enables the variation of current density. It is also noticed that the gap between anode and cathode was maintained at 5 mm to minimize the ohmic loss. The cathode, compared to the anode, is perforated and occupies the top position. This perforation allows the evacuation of bubbles produced at the anode. This EF column is occupied with radial impellers Rushton turbine.

3.2. Volumetric mass transfer coefficient

The volumetric mass transfer coefficient ($K_L a$) was measured using the unsteady state method with an oxygen probe (Consort C932) placed midway in the EF cell. The oxygen concentration was reduced to zero by adding 150 mg/L of sodium sulphite (Na_2SO_3) and 2 mg/L of cobalt ions [11].

$$2\, Na_2SO_3 + O_2 \rightarrow 2\, Na_2SO_4 \quad (7)$$

3.3. Reynolds number relative to the agitation movement

Processing with mechanical mixers occurs under either laminar or turbulent flow conditions, depending on the impeller Reynolds number, defined as:

$$Re = \frac{\rho N D^2}{\mu} \quad (8)$$

where Re is the impeller Reynolds number, ρ is the volume mass ($kg\, m^{-3}$), N is the impeller rotational speed (rps), D is the impeller diameter (m), and μ is the dynamic viscosity ($kg\, m^{-1}\, s^{-1}$).

For Reynolds numbers below about 10, the process is laminar, also called creeping flow. Fully turbulent conditions are achieved at Reynolds numbers higher than about 10^4, and the flow is considered transitional between these two regimes [12].

Experiments were conducted with stirred EF column by RT of 3.2 and 4.2 cm diameter and for current density ranging from 60 to 260 A/m.

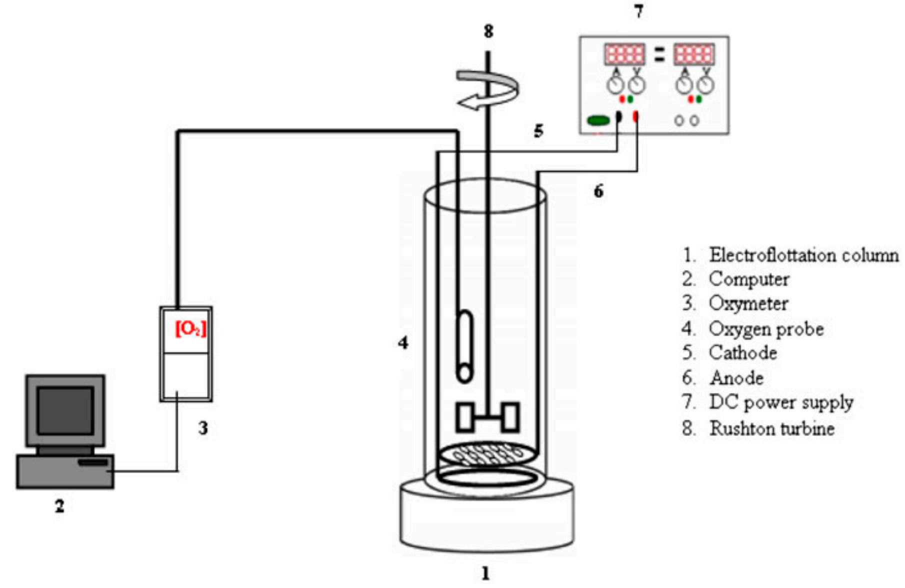

Fig. 1. Experimental setup.

4. Results and discussion

Fig. 2 presents the effect of Reynolds number relative to the agitation movement on K_La for current density of 60 A/m. This density corresponds to laminar regime relative to the ascensional movement of the gas bubble in the liquid phase [13].

According to Fig. 2, K_La increases with the Reynolds number relative to agitation movement and once the turbulent regime established ($Re > 10^4$) K_La is stabilized.

Physically, the energy dissipated by the Rushton turbine is used for breakage of the larger bubbles into smaller ones; hence, the contact area available for mass transfer between the two phases increases [14], thus increasing the interface area (a). The agitation enhances also the turbulence effects at the proximity of the gas–liquid interface, which increases K_L. Of course, there is a limit where an increase in gassed impeller power consumption will no longer affect the K_La [15].

Fig. 3 presents the effect of Reynolds number relative to the agitation movement on K_La for current density of 140 A/m. This density corresponds to transitional regime relative to the ascensional movement of the gas bubble in the liquid phase [13].

As shown in Fig. 3, K_La increases with the agitation Reynolds number whatever the hydrodynamic regime of the bubbles.

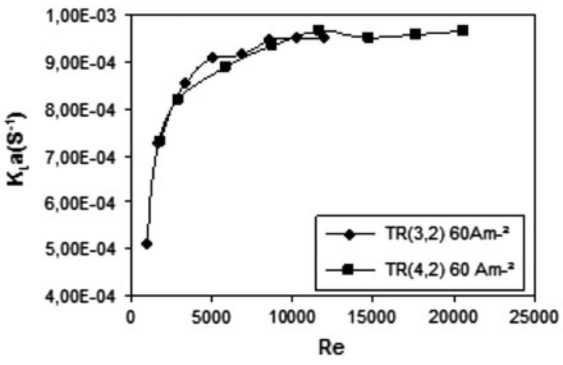

Fig. 2. Variation of the volumetric mass transfer coefficient as a function of Reynolds number relative to the agitation movement for 60 A/m^2.

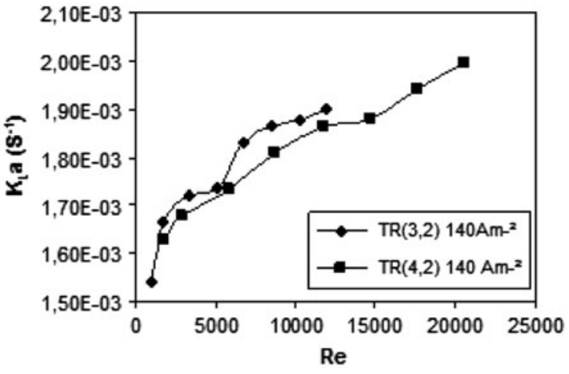

Fig. 3. Variation of the volumetric mass transfer coefficient as a function of Reynolds number relative to the agitation movement for 140 A/m^2.

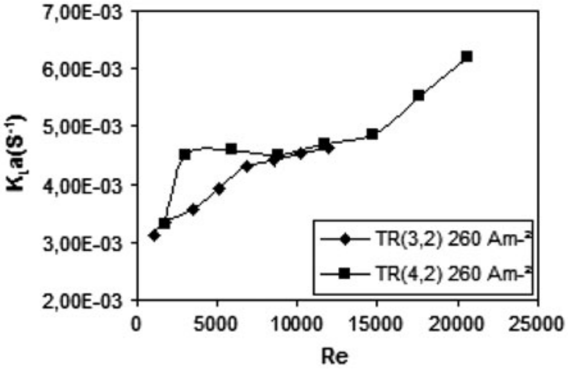

Fig. 4. Variation of the volumetric mass transfer coefficient as a function of Reynolds number relative to the agitation movement for 260 A/m^2.

Fig. 4 presents the effect of Reynolds number relative to the agitation movement on K_La for current density of 260 A/m. This density corresponds to turbulent regime relative to the ascensional movement of the gas bubble in the liquid phase [13].

It is shown in Fig. 4 that K_La increases with increasing agitation Reynolds number. A notable exchange of the curve around $Re = 10^4$ was observed; this exchange corresponds to the occurrence of turbulent regime of the liquid phase.

The results of Fig. 5 show that the K_La value increases with increasing agitation speed. According to the two-film theory, the film thickness decreases with increasing agitation speed due to the higher shear force. The mass transfer resistance decreases, and therefore higher mass transfer rate can be obtained. Nevertheless, the value will reach a limiting value. This is similar to previous studies of other types of gas-inducing contactor [16–18].

We noticed also that the diameter of agitator has a positive effect on K_La; this effect is remarkable for a turbulent bubble flow. In fact, if the diameter of impeller increases, the flow of pumping increases. Thus, the circulation of the liquid is increased [19].

5. Modeling of data

In order to explain the results of the present studies, we have to puzzle out the mathematical model that permits to express the volumetric mass transfer coefficient according to operation condition. For this objective, an appropriate mathematical program DataFit (version 8.1.69) [20] was used and permitted to find the following model:

$$K_La = 6.6910^{-7} J^{1.29} Re^{0.18} \tag{9}$$

where K_La is the volumetric mass transfer coefficient (s^{-1}), J is the current density (A/m^2), and Re is the impeller Reynolds number.

The comparison between the experimental values of the K_La and the values predicted by the model (Eq. (9)) was presented in Fig. 6. As shown in this figure, the obtained model fits the experimental data very well.

The effect of current density on K_La is more important than Reynolds number relative to agitation movement.

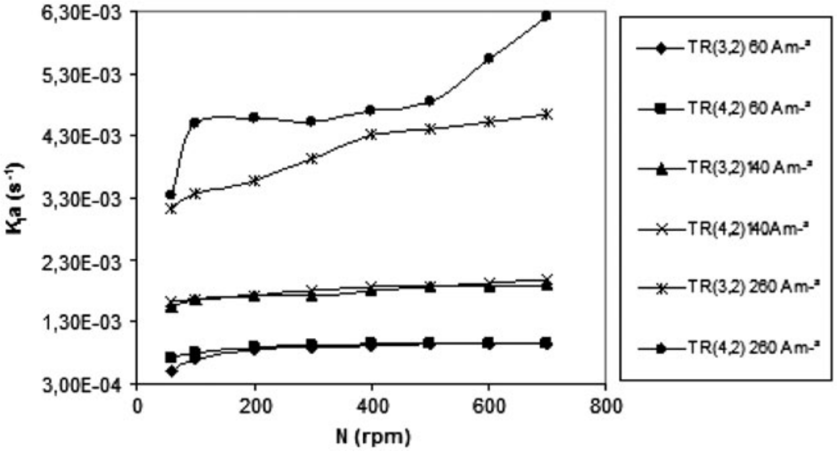

Fig. 5. K_La values in case of Rushton turbine agitation speed variation.

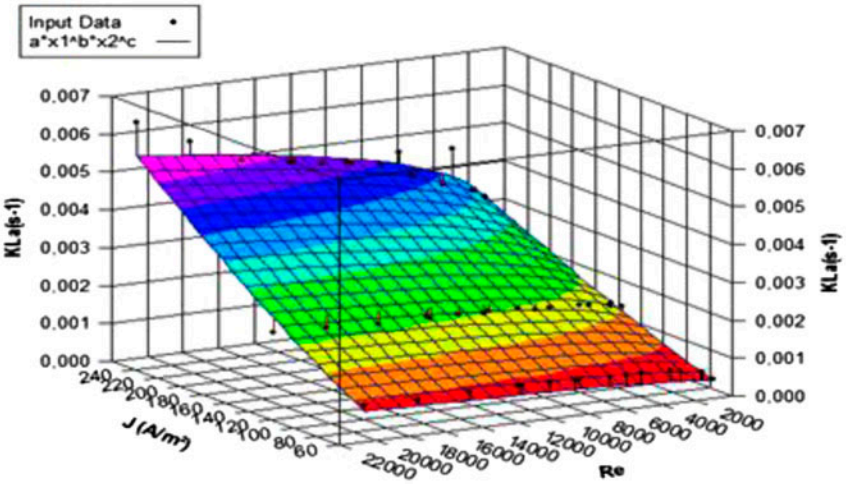

Fig. 6. Experimental values of K_La in comparison with the values considered by the model.

6. Conclusion

It is clearly that agitation affects oxygen transfer rate when different bubble hydrodynamic regime is considered. In this study, we noted that:

- The agitation speed of 400 rpm represents the transition point in the behavior of K_La. This speed corresponds to the transition between laminar and turbulent liquid phase hydrodynamic regime.
- The use of Rushton turbine is more efficient in terms of transfer when the hydrodynamic regime relative to the rise bubble movement is turbulent.
- K_La increases with increasing speed and diameter of Rushton turbine.

Symbols

a — specific interfacial 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 — impeller diameter (m)
J — current density (A/m^2)
K_L — liquid-side mass transfer coefficient (m/s)
K_La — volumetric mass transfer coefficient (s^{-1})
N — impeller rotational speed (rpm)
T — temperature (°C)
t — time (s)

Greek

θ — thêta factor
ρ — density (kg/m^3)
μ — dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)

Subscripts

g — gas
L — liquid

References

[1] T. Moucha, V. Linek, E. Prokopová, Gas hold-up, mixing time and gas–liquid volumetric mass transfer coefficient of various multiple-impeller configurations: Rushton turbine, pitched blade and techmix impeller and their combinations, Chem. Eng. Sci. 2 (2003) 1839–1846.

[2] AW. Nienow, Hydrodynamics of stirred bioreactors, App. Mech. Rev. 51 (1998) 1–32.

[3] B. Özbek, S. Gayik, The studies on the oxygen mass transfer coefficient in a bioreactor, Process. Biochem. 36 (2001) 729–741.

[4] X. Chen, G. Chen, and P.L. Yue, Investigation on the electrolysis voltage of electrocoagulation, Chem. Eng. Sci. 57 (2002) 2449–2455.

[5] L. Ben Mansour, S. Chalbi, Removal of oil from oil/water emulsions using electroflotation process, J. Appl. Electrochem. 36 (2006) 577–581

[6] A.Y. Hosny, Separation of oil from oil/water emulsions using an electroflotation cell with insoluble electrodes, Filtr. Sep. 29(5) (1992) 419–423.

[7] P.C.P. Calvin, Electroflotation for groundwater decontamination, J. Hazard. Mater. 55 (1997) 150–170.

[8] 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.

[9] W.K. Lewis, W.G. Whitman, Principles of gas absorption, Ind. Eng. Chem. 16 (1924) 1215–1220.

[10] ASCE, Standard measurement of oxygen transfer in clean water, American Society of Civil Engineers, New York, NY, 1984.

[11] L. Ben Mansour, K. Kolsi, I. Ksentini, Influence of current density on oxygen transfer in an electroflotation cell, J. Appl. Electrochem. 37 (2007) 887–892.

[12] E.L. Paul, V.A. Atiemo-Obeng, S.M. Kresta, Handbook of industrial mixing: science and practice, Wiley, San Francisco, CA, 2004.

[13] I. Ksentini, M. Kotti, L. Ben Mansour, Effect of liquid phase physicochemical characteristics on hydrody-

namics of an electroflotation column, Desalin. Water Treat. 51 (2013) 1–8.

[14] D. Devakumar, K. Saravanan, T. Kannadasan, B. Meenakshipriya, Mass transfer coefficient studies in bubble column reactor, Mod. Appl. Sci. 4(7) July 2010.

[15] R. Sardeing, J. Aubin, C. Xuereb, Gas–liquid mass transfer, Chem. Eng. Res. Des. 82(12) (2004) 1589–1596.

[16] J.-H. Chen, Y.-C. Hsu, Y.-F. Chen, C.-C. Lin, Application of gas-inducing reactor to obtain high oxygen dissolution in aeration process, Water. Res. 37 (2003) 2919–2928.

[17] R.S. Albal, Y.T. Shah, A. Schumpe, Mass transfer in multiphase agitated contactors, Chem. Eng. J. Biochem. Eng. J. 27(2) (1983) 61–80.

[18] A. Deimling, B.M. Karandikar, Y.T. Shah, N.L. Carr, Solubility and mass transfer of CO and H_2 in Fischer– Tropsch liquids and slurries, Chem. Eng. J. Biochem. Eng. J. 29(3) (1984) 127–140.

[19] M. Roustan, J. Pharamond, A. Line, Agitation. Mélange – Concepts théoriques de base, Techniques de l'ingénieur J3800 (1999).

[20] M. Kotti, I. Ksentini, L. Ben Mansour, Impact of anionic surfactants on oxygen transfer rate in the electroflotation process, Desalin. Wat. Treat. 36 (2011)1–7.