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Study of oxygen mass transfer coefficient and oxygen uptake rate in a stirred tank reactor for uranium ore bioleaching

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ABSTRACT

In this work, the volumetric oxygen mass transfer coefficient and the oxygen uptake rate (*OUR*) were studied for uranium ore bioleaching process by Acidthiobacillus ferrooxidans in a stirred tank reactor. The Box-Bohnken design method was used to study the effect of operating parameters on the oxygen mass transfer coefficient. The investigated factors were agitation speed (rpm), aeration rate (vvm) and pulp density (% weight/volume) of the stirred tank reactor. Analysis of experimental results showed that the oxygen mass transfer coefficient had low dependence on biomass concentration but had higher dependence on the agitation speed, aeration rate and pulp density.

The obtained biological enhancement factors were equal to ones in experiments. On the other hand, the obtained values for Damkohler number ($Da < 0.468$) indicated that the process was limited by the biochemical reaction rate. Experimental results obtained for oxygen mass transfer coefficient were correlated with the empirical relations proposed by Garcia-Ochoa and Gomez (2009) and Neale and Pinches (1994). Due to the high relative error in the correlation of Neale and Pinches, that correlation was corrected and the coefficient of determination was calculated to be 89%. The modified correlation has been obtained based on a wide range of operating conditions, which can be used to determine the mass transfer coefficient in a bioreactor.

1. Introduction

In recent decades, processes for the bioleaching of the sulfide ores have received considerable attention such as copper, zinc and nickel, either from concentrate or from whole ore materials (Jin et al., 2010). The rate of leaching in a bioleaching process was determined by the rates of a large number of sub-processes, with the slowest being rate limiting (Petersen and Dixon, 2006).

Oxygen is the primary reactant in the oxidative dissolution of sulfide minerals as it occurs in bioleaching (Petersen, 2010) and also it is a key substrate in most microbial processes of industrial relevance, where it can be required for growth, maintenance or production of metabolites (Garcia-Ochoa and Gomez, 2009; Buchs, 2001). These processes were typically performed in an aqueous environment but oxygen is sparingly soluble in water, roughly 0.272 mmol L^{-1}, at 25 °C and 101 kPa air pressure, and even lower in culture media, depending on the composition, thus often becomes the limiting substrate (Marques et al., 2010). In order to supply oxygen to the culture at a non-limiting rate and to facilitate scale-up it is therefore essential to have knowledge of the oxygen uptake rate (*OUR*) and the volumetric oxygen mass transfer coefficient, (k_La) of a process (Ruffieux et al., 1998; Lopez et al., 2006).

The k_La values were affected by many factors, such as geometrical characteristics of the vessels, operating parameter, media composition, type, concentration, and microorganism morphology, etc. (Galaction et al., 2004).

It is possible to assess the mass transfer limitation by use of a modified Damkohler number (*Da*), which was calculated as the ratio between the maximum oxygen uptake and transfer rates (Calik et al., 2004).

$$Da = OUR_{\max}/OTR_{\max} \quad (1)$$

A large consumption rate or low diffusivity leads to $Da > 1$, hence the process is mass transfer limited; oppositely, small consumption rate or high diffusivity results in $Da \leqslant 1$, thus the process is limited by the biochemical reaction rate (Gomez et al., 2006).

Although oxygen is transferred from the bulk gas phase to the bulk liquid phase, it is assumed that the gas phase resistance to mass transfer is negligible. Oxygen consumption through the process due to biochemical reactions can be considered using a biological enhancement factor, *E*, (Gomez et al., 2006) leading to a volumetric mass transfer coefficient k_La given by:

$$K_La = E \cdot K_L^{/}a \quad (2)$$

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Nomenclature

Da	Damkohler number (–)
OTR	oxygen transfer rate (mmol l^{-1} h^{-1})
OTR_{max}	maximum oxygen transfer rate (mmol l^{-1} h^{-1})
OUR	oxygen uptake rate (mmol l^{-1} h^{-1})
OUR_{max}	maximum oxygen uptake rate (mmol l^{-1} h^{-1})
E	biological enhancement factor (–)
a	specific interfacial area (m^2 m^{-3})
K_L	overall mass transfer coefficient in liquid phase (m s^{-1})
K_La	gas–liquid overall volumetric oxygen mass transfer coefficient (h^{-1})
k_La	gas–liquid volumetric oxygen mass transfer coefficient (h^{-1})
k_La'	gas–liquid volumetric oxygen mass transfer coefficient without consumption term (h^{-1})
Sh	Sherwood number (–)
Re	Reynolds number (–)
Sc	Schmidt number (–)
P_a/V	specific mechanical power input (w m^{-3})
v_s	superficial air velocity (m s^{-1})
C^*	equilibrium oxygen concentration (mmol l^{-1})
C_L	oxygen concentration in bulk of liquid (mmol l^{-1})
$F_{O_2}^{in}$	molar flow rate in air input (mmol.h^{-1})
$F_{O_2}^{out}$	molar flow rate in air output (mmol h^{-1})
V	bioreactor working volume (l)
t	Time (h)
OUR_{en}	endogenous oxygen uptake rate (mmol l^{-1} h^{-1})
OUR_{de}	exogenous oxygen uptake rate (mmol l^{-1} h^{-1})
P_{O2}	oxygen partial pressure in the gas phase (atm)
k	Henry constant (–)
T	temperature (k)
C_i	salt i concentration (molality)
T_D	Tank diameter (m)
D	Impeller diameter (m)
g	Gravitational acceleration (ms^{-2})
N_P	Power number (-)
N	Stirrer speed (s^{-1})
Q	Aeration rate (l.h^{-1})
W	Width of turbine blades (m)

Greek symbols

φ	Constant Henry law correction factor (–)
ρ	Slurry density (kg.m^{-3})
Φ	Solid hold-up (–)

where E incorporates the transport enhancement due to the oxygen uptake by microorganisms, alongside with opposing mass transfer resistances caused by layers of materials placed between the gas bubble and the bulk liquid phase, namely adsorbed surfactant and cells, and stagnant liquid film (Gomez et al., 2006; Ju and Sundarajan, 1992). The E has been shown experimentally to change with the concentration of biomass, typically increasing with increased cell concentration, but with varying patterns, according to different strains and incubation media. In these dedicated experiments, E was within 0.8–1.3, although values as high as 5 were also reported (Garcia-Ochoa and Gomez, 2009; Gomez et al., 2006; Ju and Sundarajan, 1992). Nonetheless, and for most cases, the biochemical rate is not significantly higher than the mass transfer rate, hence it was usually assumed that $E = 1$.

For oxygen mass transfer coefficients, numerous mathematical correlations have been proposed as follows:

$$Sh = f(\mathrm{Re}, Sc, \ldots) \quad (3)$$

$$k_La = f\left(\frac{P_a}{V}, V_S, \ldots\right) \quad (4)$$

Eq. (4) was preferred, being more useful in practical applications or for fermentation scale-up using oxygen mass transfer efficiency criteria (Galaction et al., 2004).

Response surface methodology (RSM), which is a collection of statistical techniques for designing experiments, building models, evaluating the effects of factors and searching for the optimum conditions, has successfully been used in the optimization of bioprocesses (Muthuvelayudham and Viruthagiri, 2010).

The aim of this study was to determine the oxygen mass transfer coefficient and the oxygen uptake rate in uranium bioleaching process in a stirred tank bioreactor. The volumetric oxygen mass transfer coefficient (k_La) and the oxygen uptake rate (OUR) have been determined in different operating parameters (agitation velocity; aeration rate and pulp density). The obtained results have been used to establish some mathematical correlation for the oxygen mass transfer coefficient. The proposed equations could be useful for optimization or scaling-up the fermentation. In this work, Box-Behnken based response surface methodology (RSM) has been used for analyzing the effects of the operating parameters and for determination of optimal values of oxygen mass transfer coefficient.

2. Materials and methods

2.1. Microorganism and cultivation conditions

The strain of *Acidthiobacillus ferrooxidans*, isolated from the uranium mine of Bandar-Abbas in Iran, was grown on the mineral salts medium was a mixture of mineral salts ($(NH_4)_2SO_4$ 2.0 g/l, K_2HPO_4 0.5 g/l, $MgSO_4{\cdot}7H_2O$ 0.5 g/l, KCl 0.1 g/l, $Ca(NO_3)_2$ 0.01 g/l (Atlas, 2005). $FeSO_4{\cdot}7H_2O$ (20 g/l) was added as an energy source. The inoculum was cultivated in a shaking flask at 30 °C for 3 days. The initial pH was adjusted to 2 using 10 N H_2SO_4.

2.2. Ore

The samples of uranium ore were obtained from the anomaly II of the Saghand mine of Yazd in Iran. The ore composition is shown

Table 1
The ore compositions according to XRF analysis result.

Composition	Content (%)
SiO_2	24.83
Al_2O_3	1.49
Fe_2O_3	49.67
CaO	1.03
Na_2O	0.18
MgO	19.03
K_2O	0.34
TiO_2	0.08
MnO	0.02
P_2O_5	0.23
Cl	0.0601
S	0.7527
Co	0.0158
Cr	0.0341
Ni	0.0357
V	0.3547
Mo	0.0221
U	0.065

in Table 1 according to XRF analysis result. The mean particle size was 80 μm (d_{80}).

2.3. The used apparatus characteristics

A stirred tank was used for the determination of the k_La and the *OUR* values. The main characteristics of reactor are shown in Table 2.

2.4. Measurement of oxygen concentrations

The dissolved oxygen in liquid phase and oxygen concentration in the outlet gas phase were measured using Polarographic Mettler Toledo Electrodes InPro 6850i and 6850iG Series types, respectively. As was outlined in the literature, because the k_La values were in all cases less than 0.3 s^{-1}, it was assumed that the response of the oxygen electrode to the change in the oxygen concentration was sufficiently fast and does not affect the determination accuracy (Galaction et al., 2004; Ozbek and Gayik, 2001; Montes et al., 1999).

2.5. Determination of aerated consumption power (P_a)

The following relationship suggested for estimating the aerated consumption power (Hughmark, 1980; Marques et al., 2010):

$$\frac{P_a}{P_0} = 0.1\left(\frac{N^2T^4}{gWV^{\frac{2}{3}}}\right)^{\frac{1}{6}}\left(\frac{Q}{NV}\right)^{\frac{1}{4}} \quad (5)$$

where P_a is the aerated consumption power, P_0 is the non-aerated consumption power, T is the impeller diameter, N is the agitation velocity, W is the width of turbine blades, g is gravity constant (9.806 m s^{-2}), V is reactor volume and Q is the volumetric gas flow rate.

The consumption power for a non-aerated mixture, P_0, and the density of the pulp, ρ_{pulp}, can be determined with the following relationships (Rushton et al., 1950; Bircumshaw et al., 2006):

$$P_0 = N_P\rho N^3T^5 \quad (6)$$

$$\rho_{pulp} = \frac{\rho_{solid}\rho_{liq}}{\rho_{solid} - X(\rho_{solid-\rho_{liq}})} \quad (7)$$

where N_P is the power number, ρ_{solid} is solid density, ρ_{liq} is liquid density and X is solid fraction in the pulp.

Table 2
The main characteristics of the reactor.

Characterizes	Size
Total volume	8.5 l
Working volume	6 l
Height to diameter ratio	2
Internal diameter	16.5 cm
Total height	43 cm
Number of baffles	4
Baffles height	30 cm
Impeller to tank diameter ratio	0.33
Number of impellers	2
Distance of first impeller from bottom	4 cm
Distance of impellers	16 cm
Type of impeller	Rushton disk turbine
Diameter of impeller disk	3.7 cm
Impeller blade width	1.8 cm
Impeller blade height	2 cm
Number of blades	6
Material of reactor body	Glass
Material of the stirred and the baffles	Stainless steel 304

2.6. Experimental design

In this research, we used an experimental design method. According to the Box-Behnken total 13 experiments were generated. These 13 experiments were performed with different combinations of the three independent variables.

The behavior of each variable, their interactions, and statistical analysis to obtain predicted responses was explained by the following quadratic equation:

$$y = b_0 + \sum b_ix_i + \sum b_{ij}x_ix_j + \sum b_{ii}x_i^2 + \varepsilon \quad (8)$$

where y is the predicted response; b_0 is constant; b_i is the linear coefficient, b_{ij} is interaction coefficient, and b_{ii} is squared coefficient (Guo et al., 2009). Thirteen experiments were elected (12 experiments at boundaries and 1 experiment at center point) for the oxygen mass transfer coefficient, oxygen uptake rate and analysis of variance (ANOVA) were done to find out the amounts of each factor's effect, squared effect and interaction between them. The Minitab® 16 statistical software was used for experimental design, data analysis, and model construction.

2.7. Bioleaching experiments

In this study, Response Surface Methodology (Box–Behnken design) was used to evaluate the effect of some variables on the oxygen mass transfer coefficient and uptake rate. Agitation velocity, aeration rate, and pulp density were chosen as three factors and each factor's level varied according to Table 3.

The dissolved oxygen concentration was lowered by passing nitrogen gas through the system for about 5 min. The nitrogen gas flow stopped when oxygen concentration is nearly zero and it followed by aeration at certain operating conditions.

The volumetric mass transfer coefficient, k_La, and oxygen uptake rate (*OUR*) has been determined in a wide range of operating conditions. The measurements have been carried out by changing the superficial gas velocity, the agitation velocity, the pulp density. The k_La and *OUR* values have been determined continuously during bioleaching process until extraction become higher than 95%.

The experimental were carried out in constant temperature (T = 25 °C) and pH (pH = 2). pH of the each medium was measured by pH meter (Metrohm, model 827). In addition, reactor temperature was measured by oxygen sensor.

3. Theory

Different methods can be used for measuring the volumetric mass transfer coefficient k_La (Boon et al., 1992). In fermentation systems, the overall volumetric oxygen mass transfer coefficient (K_La) can be determined by measuring the total airflow and the oxygen concentration difference between the inflow and outflow air and dissolved oxygen concentration, C_L, during operation. Now, K_La versus time can be derived:

$$K_La = \frac{F_{O_2}^{in} - F_{O_2}^{out}(t)}{V(C^* - C_L(t))} \quad (9)$$

Table 3
Levels and codes of variables for Box–Behnken design.

Factors	Unit	Levels		
		−1	0	+1
Agitation velocity	rpm	400	500	600
Aeration rate	vvm	0.2	0.6	1
Pulp density	% weight/volume	5	10	15

where C_L is the oxygen concentration in the liquid phase, C^* is the equilibrium or saturation concentration of the oxygen in the liquid under the temperature and pressure conditions, $F_{O_2}^{in}$ and $F_{O_2}^{out}$ are the molar flow rates measured at bioreactor inlet and outlet and V is the bioreactor volume. Taking into account that oxygen is only slightly soluble in water, it was commonly accepted that the greatest resistance for mass transfer is on the liquid side of the interface and the gas phase resistance can usually be neglected and thus the mass transport coefficient is equal to the local coefficient: $K_L = k_L$.

Simultaneously with determination of the k_La, the *OUR* can be calculated from oxygen mass balance (Ruffieux et al., 1998).

$$\frac{dC_L}{dt} = k_La(C^* - C_L) - OUR \tag{10}$$

The first and second terms on the right hand side of Eq. (6) represent the oxygen transfer rate (*OTR*) and the oxygen uptake rate (*OUR*), respectively. The *OUR* may be written as:

$$OUR = OUR_{en} + OUR_{de} \tag{11}$$

The oxygen consumption is due to the microbial oxygen uptake for both the endogenous and exogenous respiration (Mineta et al., 2011).

Tromans (2000) offers a comprehensive formula for the calculation of oxygen solubility in pure water as follows:

$$C^* = P_{O_2} \cdot k \tag{12}$$

where:

$$k = \exp\{(0.046T^2 + 203.35T \times \ln\left(\tfrac{T}{298}\right) - (299.378 + 0.092 \times T) \times (T - 298) - 2.0591 \times 10^4)/(8.3144T)\} \tag{13}$$

where P_{O2} is the oxygen partial pressure in the gas phase in atm, T is the temperature in solution.

For aqueous solutions, Tromans (2000) proposes a coefficient as follows:

$$C^* = P_{O_2} \cdot k \cdot \phi = P_{O_2} \cdot k \cdot [1 + \kappa(C_i)^{\gamma}]^{-h} \tag{14}$$

where C_i refers to the molality of the salt i in solution. The parameters κ, γ and h are empirically determined for different types of dissolved salts. For some salts values of they were listed by Tromans.

It is also critical to consider the effect of humidity in a stirred tank situation. Due to the low gas velocities, passing air is likely to become saturated with water vapor at the given temperature. At saturation, the partial pressure of water vapor in the gas phase corresponds to the water vapor pressure at that temperature. It is calculated as follows (Perry and Green, 1984):

$$p_{vap} = \exp(-57.154 + 0.3538 \cdot T - 7.617 \times 10^{-4} \cdot T^2 + 6.0 \times 10^{-7} \cdot T^3) \tag{15}$$

The presence of water vapor effectively depresses the partial pressure of oxygen in the gas phase. Hence, the oxygen partial pressure was calculated as follows (Petersen, 2010):

$$p_{O_2} = 0.2095(P - p_{vap}) \tag{16}$$

4. Results and discussion

4.1. Overall volumetric oxygen mass transfer coefficient

4.1.1. Mass transfer coefficient without biological consumption of oxygen

In first instance, the *OUR* value was neglected in Eq. (6) for each experiment, because it was neglect bacteria growth and activity. Therefore, the mass transfer coefficient was obtained with *OUR* term removal from Eq. (6) in this stage with dynamic method. The operating conditions and the k_La values for each experiment was shown in Table 4. The values of volumetric oxygen mass transfer were in the range of 11.57–54.87 h^{-1}.

The analysis of variance (ANOVA) was carried out and the results were shown in Table 5. To predict the regression coefficient of the model the ANOVA of the regression model was performed on the experimental data. Whereas the *P*-values of interaction of agitation velocity and aeration rate (X_1, X_2), square of agitation velocity (X_1^2) were much higher than significant α-level of 5%, this terms was eliminated. Eq. (17) shows the model for this system (the factors are the coded):

$$K_La = 39.38 + 10.39X_1 + 5.53X_2 - 5.56X_3 - 10.87X_2^2 - 4.14X_3^2 - 3.23X_1X_3 + 2.76X_2 \tag{17}$$

where X_1 is agitation velocity; X_2 is aeration rate; X_3 is pulp density. The ANOVA of the regression model demonstrated that the determination coefficient (R^2) was 0.931, thus indicating that 93.1% of the variability in the response could be explained by the model. The value of the adjusted R^2 is 0.893, which shows that the model affords a better precision and reliability for the experiments. The model *F*-value of 42.33 implies that the model is highly significant ($P < 0.0001$), and there is only a 0.01% chance that it could occur as the result of noise. Positive coefficient of X_1, X_2 and X_2X_3 indicated increasing effect and negative coefficient of X_3, X_2^2, X_3^2 and X_1X_3 had decreasing effect on mass transfer coefficient.

By solving the Eq. (17), the optimal uncoded values for agitation velocity (X_1), aeration rate (X_2), and pulp density (X_3) were estimated to be 600 (rpm), 0.653 (vvm), and 5 (%w/v), respectively which yield the maximum mass transfer coefficient.

4.1.2. Mass transfer coefficient with biological consumption of oxygen

The bacterial growth and activity were be the noticeable value after 1 to 2 days, so, the *OUR* value cannot be neglected in K_La value calculation. The mass transfer coefficient and oxygen uptake rate were determined simultaneously. The obtained results were shown in Figs. 1–13.

The results showed the mass transfer coefficient was approximately constant during the bioleaching process for constant temperature of 25 °C and pH = 2, moreover the mass transfer coefficient had few dependency to biomass concentration (oxygen uptake rate) and biological enhancement factor was equal to one. In addition, more research on the effect of biomass concentration on mass transfer coefficient in uranium bioleaching showed that the biomass concentration had no effect on mass transfer coefficient (Zokaei-Kadijani et al., 2012; 2011a).

The comparison of obtained values in Section 4.1.1 (*OUR* = 0) and this section for mass transfer coefficient show that recent values are 2% to 7% higher than Section 4.1.1 in same operating conditions. The consumption term could make the difference.

The ANOVA of the regression model was performed on the experimental data to predict the regression coefficient of the model. So the interactions of agitation velocity and aeration rate (X_1X_2), agitation velocity and pulp density (X_1X_3), aeration rate and pulp density (X_2X_3) and squares of agitation velocity (X_1^2), pulp density (X_3^2) were eliminated, because the *P*-values of them are much higher than significant α-level of 5%. The signification model was shown in the following equation:

$$k_La = 40.25 + 12.21X_1 + 4.67X_2 - 5.74X_3 - 11.55X_2^2 \tag{18}$$

where X_1 is agitation velocity; X_2 is aeration rate; X_3 is pulp density. The model *F*-value of 10.72 implies the model is significant. Also the value of the determination coefficient R^2 (0.842) suggested the model could explain 89.09% of the total variation. The ANOVA

Table 4
Values of the volumetric oxygen mass transfer coefficient with non-consumption term.

Run no.	Agitation velocity (rpm)	Aeration rate (vvm)	Pulp density (% weight/volume)	Overall volumetric oxygen mass transfer coefficient (h^{-1})
1	500	0.6	10	40.00
2	500	0.2	5	33.12
3	500	1	5	29.41
4	600	0.6	15	45.47
5	400	0.6	5	26.795
6	400	0.6	15	24.05
7	600	0.6	5	60.03
8	600	0.2	10	30.56
9	400	0.2	10	13.76
10	400	1	10	27.94
11	600	1	10	50.64
12	500	0.2	15	12.19
13	500	1	15	25.3

Table 5
Results of variance analysis.

Source	*F*	*P*
Regression	20.48	0.015
Linear	47.25	0.005
Square	11.64	0.037
Interaction	2.53	0.233

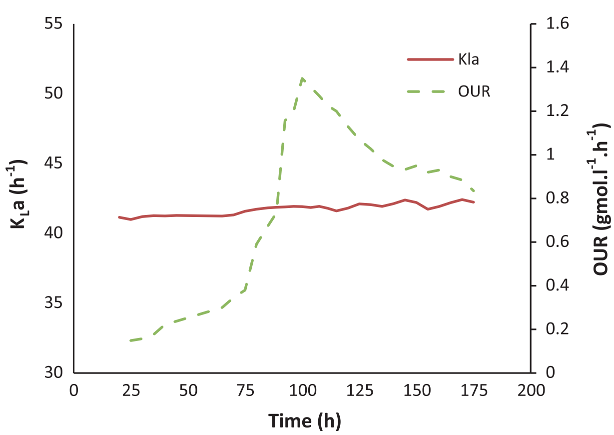

Fig. 1. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 500 rpm; aeration rate of 0.6 vvm; and pulp density 10% conditions.

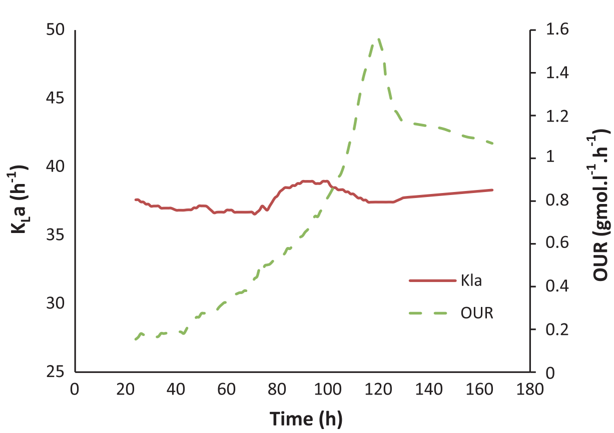

Fig. 2. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 500 rpm; aeration rate of 0.2 vvm; and pulp density 5% conditions.

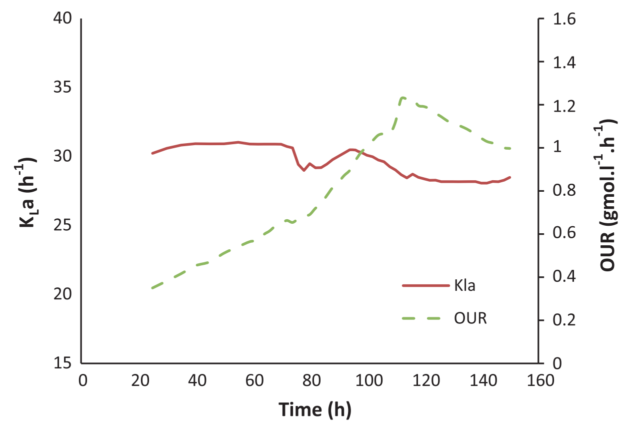

Fig. 3. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 500 rpm; aeration rate of 1 vvm; and pulp density 5% conditions.

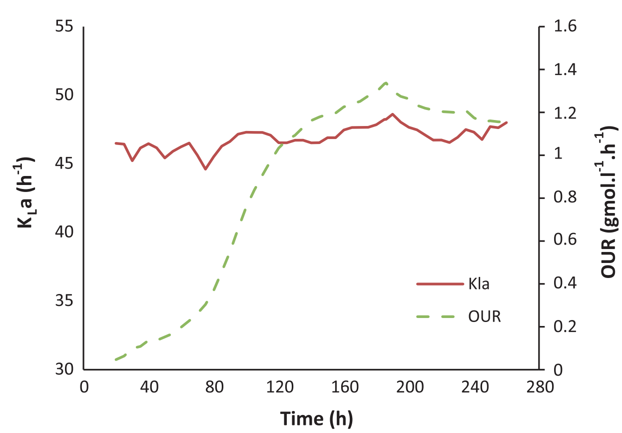

Fig. 4. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 600 rpm; aeration rate of 0.6 vvm; and pulp density 15% conditions.

analysis indicates a linear relationship between the main effects of the agitation velocity, is aeration rate, and pulp density; the quadratic relationship with aeration rate. The X_1, X_2 and X_2X_3 factors with positive coefficient increase mass transfer coefficient X_3, and X_2^2 with negative coefficient decrease it. Conducted research on the presence of solid particles in same reactor (glass + water) showed that the presence of solid particles reduce mass transfer coefficient (Zokaei-Kadijani et al., 2011b).

By solving the Eq. (18), the optimal values for agitation speed (X_1), aeration rate (X_2), and pulp density (X_3) were estimated to

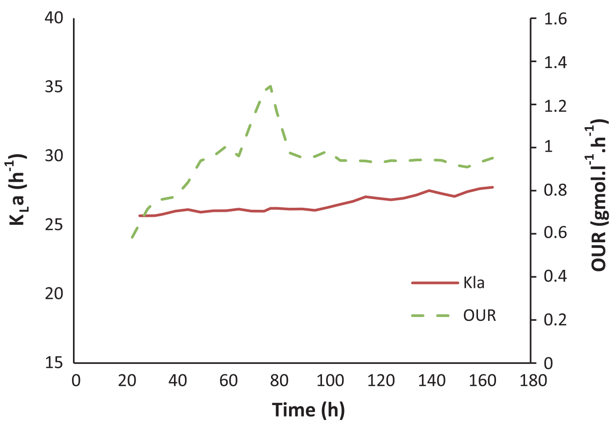

Fig. 5. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 400 rpm; aeration rate of 0.6 vvm; and pulp density 5% conditions.

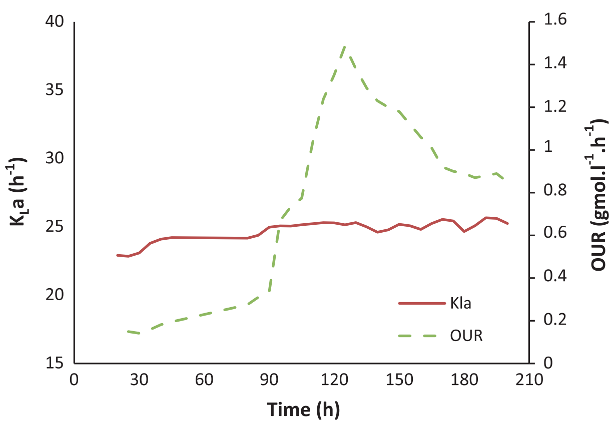

Fig. 6. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 400 rpm; aeration rate of 0.6 vvm; and pulp density 15% conditions.

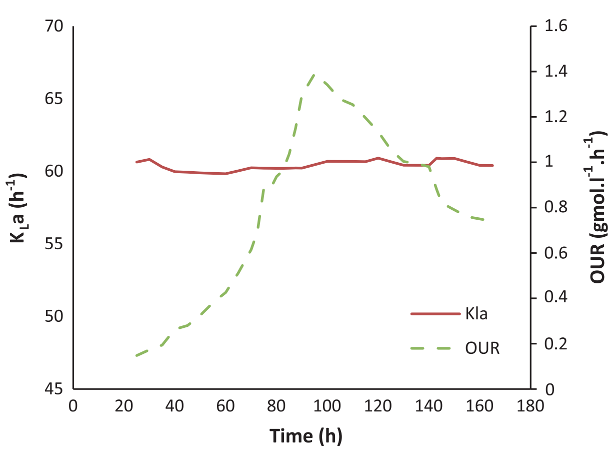

Fig. 7. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 600 rpm; aeration rate of 0.6 vvm; and pulp density 5% conditions.

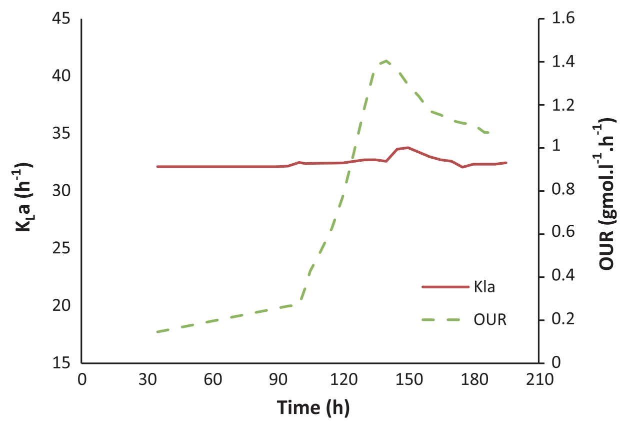

Fig. 8. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 600 rpm; aeration rate of 0.2 vvm; and pulp density 10% conditions.

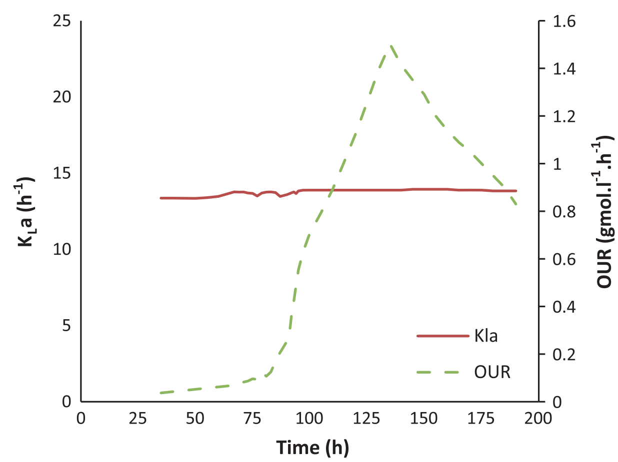

Fig. 9. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 400 rpm; aeration rate of 0.2 vvm; and pulp density 10% conditions.

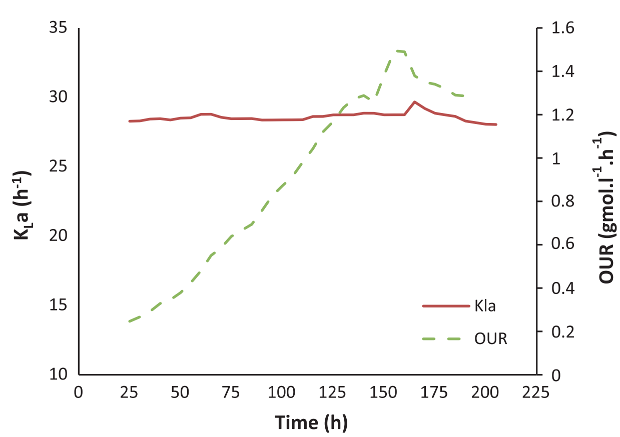

Fig. 10. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 400 rpm; aeration rate of 1 vvm; and pulp density 10% conditions.

be 600 (rpm), 0.681 (vvm), and 5 (%w/v), respectively which yield the maximum mass transfer coefficient.

The optimizing result showed that the volumetric oxygen mass transfer coefficient does not always increase with increasing of aeration rate. It could be due to decreasing of specified interfacial area after maximum point. In this case, the size of bubbles grows because of coalescence behavior and it can cause the mass transfer coefficient decreasing.

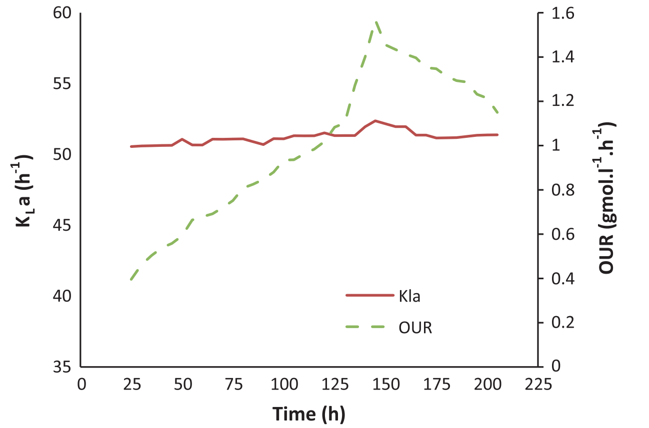

Fig. 11. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 600 rpm; aeration rate of 1 vvm; and pulp density 10% conditions.

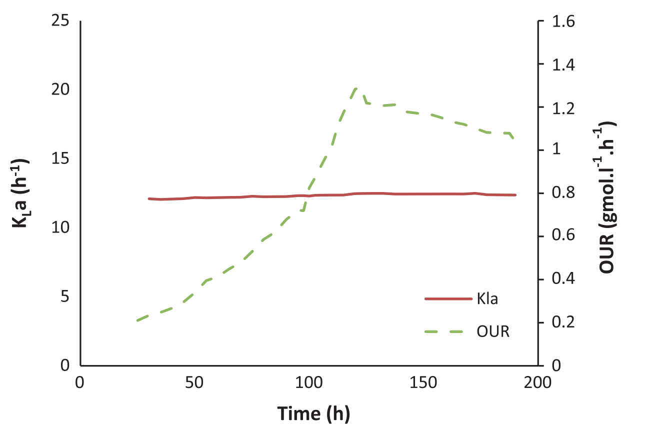

Fig. 12. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 500 rpm; aeration rate of 0.2 vvm; and pulp density 15% conditions.

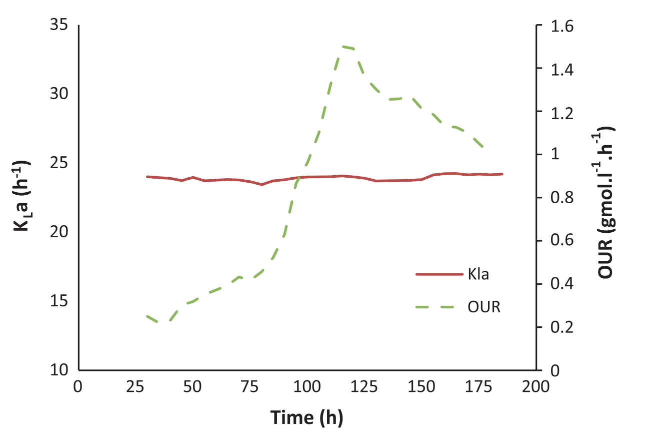

Fig. 13. Measured volumetric oxygen mass transfer coefficient and oxygen uptake rate for agitation velocity of 500 rpm; aeration rate of 1 vvm; and pulp density 15% conditions.

4.2. Correlations for oxygen mass transfer coefficients

The values of the oxygen mass transfer coefficients have been correlated using an empirical model with operating parameters (Garcia-Ochoa and Gomez, 2009; Neale and Pinches, 1994). The expressions that found for the k_La were:

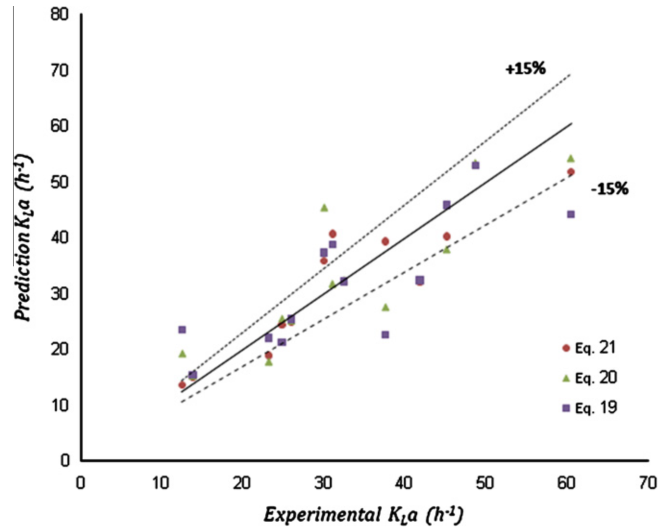

Fig. 14. Comparison between the experimental results and its correlations.

$$k_La(h^{-1}) = 26.73\left(\frac{P_a}{V_t}\right)^{0.618}(V_s)^{0.461} \quad (19)$$

$$k_La(h^{-1}) = 19.09(1-\Phi)^{13.53}\left(\frac{P_a}{V_t}\right)^{0.636}(V_s)^{0.465} \quad (20)$$

where V_s is the superficial air velocity, $\frac{P_a}{V_t}$ is the specific input power and Φ is the solid hold up. R-square values are 62.1% and 74.5%, respectively. Since R-square values were small, Eqs. (19) and (20) were corrected. The modified empirical correlation for k_La was obtained as follows:

$$k_La(h^{-1}) = 0.258(1-\Phi)^{-134.5}\left(\frac{P_a}{V_t}\right)^{0.636}(V_s)^{-0.263+25.48\Phi} \quad (21)$$

where R-square values were 88.95%. Fig. 14 shows the k_La plot of experimental versus predicted values from the correlation using calculated parameters (Eq. (21)). Most of the predicted values appeared to be well distributed about the experimental data, which indicates a good approximation between experimental k_La values and the values calculated by the correlation.

4.3. Oxygen uptake rate (OUR)

The oxygen uptake rate varied from an initial value of zero to approximate 1.6 mmol L^{-1} h^{-1}.The results showed that after an initial lag of about 2–3 days, the oxygen uptake rate rises to its maximum rapidly and then decreases gradually. In all experiments, Damkohler number was less than 0.468, so process was limited by the biochemical reaction rate.

The oxygen uptake rate (*OUR*) is a good indicator for the bacterial activity, and even under some conditions, a good indicator for the number of viable cells. The variance analysis of the operating parameters was carried out on the time which oxygen uptake rate was maximum (maximum bacterial activity) in order to find variables effects on maximum *OUR* time. The result of analysis showed that the pulp density was the only significant factor.

5. Conclusions

Based on the results obtained from the effect of operating parameters on the oxygen mass transfer coefficient and the uptake rate for the bioleaching of uranium by AF bacteria in a stirred tank bioreactor the main conclusions are:

a. The aeration rate at first had a positive effect and then the negative effect on the mass transfer coefficient. Mass transfer coefficient does not depend on biomass concentration. The pulp density has a negative effect on mass transfer coefficient and is the unique factor affecting the maximum *OUR*.
b. In this study as Damkohler number is smaller than 0.468, biochemical reaction is a limiting factor in the uranium bioleaching process.
c. Experimental results obtained for oxygen mass transfer coefficient were correlated with the empirical relations proposed by Garcia-Ochoa and Neale. Due to their relative high error, the correlation proposed by Neale was corrected and the coefficient of determination was calculated 89%. The modified relationship has been obtained in a wide range of operating conditions which can be used to determine the mass transfer coefficient in a bioreactor.

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