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Prediction of Oxygen Mass Transfer Coefficients in Stirred Bioreactor with Rushton Turbine Impeller for Simulated (Non-Microbial) Medias

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Abstract

The study of oxygen mass transfer was conducted in a laboratory scale 5 liter stirred bioreactor equipped with one Rushton turbine impeller. The effects of superficial gas velocity, impeller speed, power input and liquid viscosity on the oxygen mass transfer were considered. Air/ water and air/CMC systems were used as a liquid media for this study. The concentration of CMC was ranging from 0.5 to 3 w/v. The experimental results show that volumetric oxygen mass transfer coefficient increases with the increase in the superficial gas velocity and impeller speed and decreases with increasing liquid viscosity. The experimental results of k_la were correlated with a mathematical correlation describing the influences of the considered factors (the overall power input and the superficial gas velocity) over the studied rages. The predicted k_la values give acceptable results compared with the experimental values. The following correlations were obtained:

Air/water system

$$k_L a = 30.4\left(\frac{P_g}{V_l}\right)^{0.088}\left(V_g\right)^{1.43}$$

Air/CMC system (0.5w/v)

$$k_L a = 522\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (1w/v)

$$k_L a = 811\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (2w/v)

$$k_L a = 1623\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (3w/v)

$$k_L a = 1576\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Keywords: *Stirred bioreactor; oxygen mass transfer coefficient; superficial air velocity; Rushton turbine impeller.*

1. Introduction

In many chemical (e.g. hydrogenation, chlorination) and biochemical industries (e.g. aerobic fermentation), the transfer of gas molecules from swarm of bubbles into turbulent liquid medium play an important role. In fermentation industries, e.g. yogurt, beer, yeast, wine and countless pharmaceutical products are widespread and provide many everyday consumer products. These industries involve the use of microorganism to convert the biomass into a quality product with high yield (Zadghaffari et al, 2009; Najafpour, 2007; MUHD, 2005; Meenal et al., 2005; Galaction et al., 2004). Understanding of all the processes may require basic knowledge of biology, biochemistry, biotechnology, and real knowledge of engineering processes (Cascaval D. et al., 2004; Priede et al., 2002; Vilaça et al., 2000).

In aerobic fermentation, the activities of microorganisms are monitored by the utilization of oxygen from the supplied air and the respiration quotient. The primary and secondary metabolites in a bioprocess can be estimated based on projected pathways for production of intracellular and extracellular by-products (Felix et al., 2009; Ikram-ul, et al., 2005; Le´on et al., 2001). Oxygen transfer is often the limiting step that controls the aerobic system (Felix et al., 2009; Ladislav, 1999). The amount of dissolved oxygen in the reaction medium is limited by the solubility and mass transfer rate, and as well as by its consumption rate on cell metabolic pathways (Davis et al., 2010; Felix et al., 2009; Ghaly et al., 2003).

Transport characteristics are function of many parameters, the most important parameter affecting the design and the operation of the unit is the mass transfer coefficient, k_la. Many factors are known to affect aeration efficiency (k_la), including such parameters as agitation, air flow rate, air pressure, temperature, vessel geometry, fluid characteristics (density, viscosity, surface tension, etc.), presence of antifoam agents, the concentration and physical properties of the immobilizing materials (density, particle size, etc.), etc. (Aoyi et al., 2008; Gimbun et al., 2009; Archis et al., 2002;). The major problem in bioreactor operation and scale–up is the uneven distribution of shear and energy dissipation, which are known to be harmful to the microorganisms in the bioreactors (Davis et al., 2010; Catapano et al., 2009; Scargiali et al., 2007).

In order to meet this demand, an agitation system must provide the required transport characteristics at low possible energy consumption (Davis et al., 2010; Catapano et al., 2009; Aoyi et al., 2008). Stirred tank and bubble column bioreactors are widely used bioprocesses (as aerobic fermentation and biological wastewater treatments, among others). Stirred tank bioreactor provides high values of mass and heat transfer rates and excellent mixing. In this system, a high number of variables affect the mass transfer and mixing, the most important among them are stirrer speed, type and number of stirrers and gas flow rate used. The correct measurement and/or prediction of the volumetric mass transfer coefficient, (k_la), is a crucial step in the design, operation and scale-up of bioreactors (Catapano et al., 2009).

Fermentations are carried out in aqueous medium containing salts and organic substances, and these broths usually are viscous. For low viscosity fluids and for microorganisms and product with low shear sensitivity, almost any type of bioreactors can be used, provided it leads to adequate homogeneity and good mass transfer. However, under highly viscous and non-Newtonian conditions, mixing becomes more difficult, and as a result, poor distribution of oxygen and nutrients inside the bioreactor is obtained (Najafpour , 2007; Muhd, 2005; Hélène, 1998).

The effects of the homogeneity of the fermentation broth, the oxygen mass transfer rate, the shear stress produced by the mixing element and the ease of scale-up are studied on many workplaces all over the world but no unambiguous answer has been found up to these days. Various modifications on operating and geometric parameters were performed to improve the gas-liquid mass transfer.

Many types of agitator have been used in industry to enhance gas-liquid contact operation. Several types of impellers (Rushton turbines, paddle, MIG, hydrofoils. etc.) are used for highly viscous aerated reactors (Paul et al., 2004; Mária et al., 2004; David et al., 2003; Zhen et al., 2003; Tomáš et al., 2003). When viscosity increases, these remote clearance impellers become inefficient because extremely high power must be supplied locally to the fluid by the impeller if enough mixing energy is to reach all parts of the fluid to insure adequate mixing. This problem becomes even more severe if the fluid is non-Newtonian because the viscosity is a function of the shear rate (Archis et al., 2002; Diaz et al., 1999).

Although, there are many studies had been done in this area, but the need for further studies are urgently needed to increase understanding of the bioreactors. The aim of the present work is to examine the volumetric oxygen transfer coefficient k_la in a stirred bioreactor using Rushton turbine impeller, taking into account the effects of viscosity (for Newtonian and non-Newtonian fluid), impeller speed, the superficial gas velocity and the overall power input to medium.

2. Power Consumption

In bioreactors, the energy imparted to the broth by agitator creates uniform distribution of air in the media. The interfacial area increases as a result of reducing air bubble size. Therefore the mass transfer coefficient would be a function of power input per unit volume of fermentation broth, which is also affected by the gas superficial velocity (Najafpour 2007).

2.1. Power Consumption in Ungassed System

The power consumption cannot be predicted theoretically, therefore empirical correlations have been developed to predict the power required. The power consumption in relation to operating variables and geometric parameters data could be grouped to dimensionless groups as power and Reynolds numbers given as follows (Najafpour 2007):

$$N_p = \left(\frac{P_o}{rN^3 D_i^5} \right) \qquad \ldots(1)$$

$$\mathrm{Re} = \left(\frac{rND_i^2}{m} \right) \qquad \ldots(2)$$

where
Po = power in ungassed system (W),
N = impeller speed (rps),
ρ= liquid density (kg/m3),
μ = liquid viscosity (Newton.sec/m2), and
Di = impeller diameter (m)

The power number was correlated with Reynolds number for various impeller geometry and at different regimes. The relation between these two dimensionless groups was presented by log-log figure, (which has been reported by many researchers).

The calculation of power number for non-Newtonian fluids in bioreactors is the same as Newtonian fluids but the viscosity must be correlated with the apparent viscosity. The apparent viscosity for non-Newtonian fluids is not constant varies with the shear rates and velocity gradient in the vessel.

In order to do that, an apparent viscosity (μ app) is defined as follows (Najafpour 2007; Badino et al., 2001; Pouliot et al., 2000):

$$m_{app} = kg^{n} \qquad \ldots(3)$$

where
μapp = shear stress (N/m2)
γ= shear rate (s-1)
k = consistency index (Pa.s)
n = flow behavior index (-)
The value of shear rate in bioreactors was determined using Metzner and Otto equation (Najafpour 2007):

$$g = AN \qquad \ldots(4)$$

where
A = Metzner and Otto constant (depend on impeller type). It was assume to be 11.5, for Rushton turbine.
N = impeller speed (rpm).

2.2. Power Consumption in Gassed System

The power consumption in agitated gassed systems is less than for ungassed systems. The apparent viscosity and density decreases with increasing agitation upon gassing.

Prediction of power consumption (Pg) in a stirred tank is usually based on well known traditional correlation proposed by Michel and Miller (Najafpour 2007; Kumaresan et al., 2006):

$$P_g = m\left(\frac{P_o^2 N D_i^3}{Q^{0.56}} \right)^{0.45} \qquad \ldots(5)$$

where
m= constant depends on impeller type and geometric form (for rushton turbine m=0.832),
Q = volumetric gas flow rate (m3/s)

3. Correlation between Mass Transfer Coefficient and Power Consumption

There are many correlations were proposed that estimate the kla in single and multiple impeller systems for Newtonian and non-Newtonian fluids (Davis et al., 2010; Catapano et al., 2009; Wen et al., 2000). kla was correlated with mechanical agitation power per unit volume (Pg/Vl) and gas sparging rate expressed as the superficial velocity (Vg). The power input per unit volume (Pg/Vl) and, superficial gas velocity Vg are major correlation coefficients for kla. Therefore, the following equation is frequently found which proposed by Cooper and his co-workers (1944) and used in the literature (Davis et al., 2010; Zadghaffari et al., 2009; Felix et al., 2009; Muhd 2005; Cascaval et al., 2004).

$$k_L a = a\left(\frac{P_g}{V_l}\right)^b \left(V_g\right)^g \qquad \ldots(6)$$

where,
Pg = is the mechanical agitation power (W),
Vl = liquid volume (m3)
Vg = gas superficial velocity (m/s),
α,= is a constant,
β, and γ, are exponents

4. Experimental Work

4.1. Materials

Distilled water, carboxymethyl cellulose (CMC) (of analytical grads), and nitrogen gas (99.999%) were used in this study.

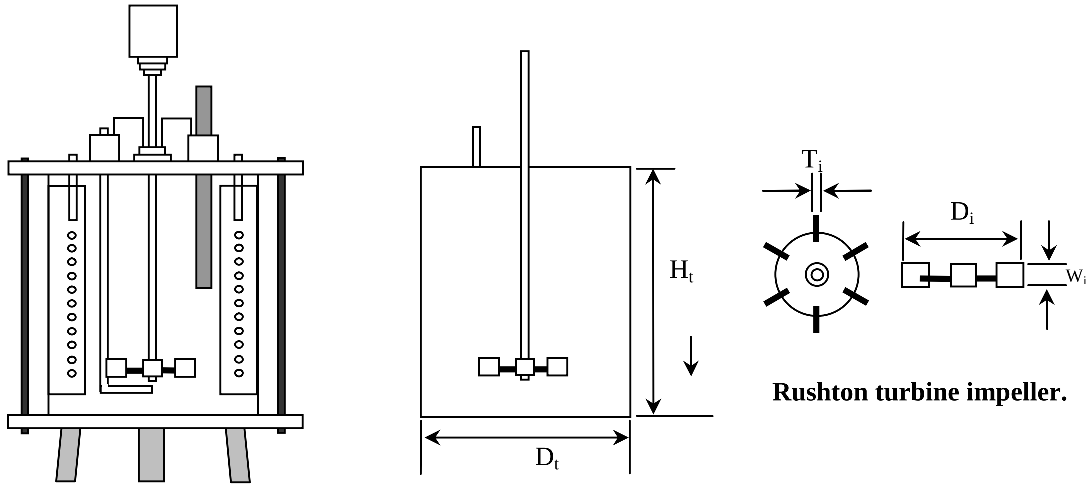
4.2. Bioreactor

A 5 liters bench scale bioreactor was used in this study. The bioreactor was filled with 3.75 l of distilled water to be used as a working volume. The details of the reactor geometry and dimensions are given and illustrated in Table 1 and Fig.1, respectively. Six blades Rushton turbine impeller was conducted to the driven shaft of the agitator and four baffles were provided. The schematic diagram of the experimental setup was shown in Fig.2.

The compressed air or nitrogen, fed at the bottom of the bioreactor was sparged through 4 cm diameter circular sparger, with 12 holes of 1 mm diameter. Air flow rates were measured and controlled by a rotameter (QVF type, 1500 l/h max.). All experimental runs were carried out at atmospheric pressure and a temperature of 33˚C. A series of experiments were performed in the gas flow rate range from 1 to 20 l/min, impeller speed range from 100 to 1200 rpm, the CMC concentration ranging from 0.5 to 3 w/v. The speed of impeller was controlled using voltage regulator and measured using DT-1236L tachometer type Lutron.

Table 1,
Dimensions of Stirred Tank Bioreactor.

Bioreactor total volume, V_t (liter)	5
Bioreactor working volume, V_l (liter)	3.75
Bioreactor vessel height, H_t (cm)	16
Bioreactor vessel diameter, D_t (cm)	20
Impeller type	Rushton turbine
Impeller diameter, (D_i) cm	6
No. of impellers	1
Impeller thickness, (T_i) mm	2
Impeller width, (W_i) (cm)	1.3
Sparger diameter, cm	4
Sparger distance from impeller bottom, cm	2
No. of baffles	4
Width of baffles, cm	2



Rushton turbine impeller.

Fig. 1. Geometry of stirred tank bioreactor.

4.3. Measurement of Volumetric Mass Transfer Coefficient

The determination of the overall volumetric mass transfer coefficient value of a bioreactor is essential in order to establish its aeration efficiency and to quantify the effect of operating variables on the provision of oxygen. The, kla, was determined by the static gassing method (Najafpour, 2010; Bouaifi et al., 2001; Chisti, 1989). The dissolved oxygen concentration in bioreactor liquid phase was measured by means of an oxygen probe inserted vertically and placed at 2 cm under the liquid level, and connected to a dissolved oxygen-meter type Lutron DO-5510. The oxygen probe signals were measured using A/D converter and recorder on a PC. In each experimental run, tap water has been first stripped of oxygen by the static gassing method by bubbling N2 gas through the gas sparger. This step will continue till the probe reading becomes zero. After that the nitrogen gas flow was turned off and the flow switched to the air flow with a specific volumetric flow rate using the rotameter then the dissolved oxygen concentration was recorded with respect to time as air is distributed into the bioreactor and until the water became saturated with oxygen.

The investigations of mass transfer characteristics were restricted to oxygen transfer only, and in all investigations, the bioreactor systems were subject to the following assumptions (Najafpour, 2010; Chisti, 1989):

Gas composition is constant.

The system is isothermal, and the effect of the dynamics of the dissolved oxygen electrode is negligible.

For sparingly soluble gases such as oxygen, the liquid phase volumetric mass transfer coefficient (kla) is nearly equal in value to that of the overall volumetric mass transfer coefficient (Kla).

A material balance on dissolved oxygen according to the above assumption gives the following equation (Najafpour, 2010; Chisti, 1989):

$$\frac{dO}{dt} = k_l a(O^* - O) = K_l a(O^* - O) \qquad \ldots(7)$$

O*: saturation dissolved oxygen concentration.
O: dissolved oxygen concentration in liquid phases.
Integrate Eq. (7) with the limits of O = O° at t = 0 and O = O at t = t results in:

$$\int_{O_0}^{O} \frac{dO}{(O^* - O)} = K_l a \int_0^t dt \qquad \ldots(8)$$

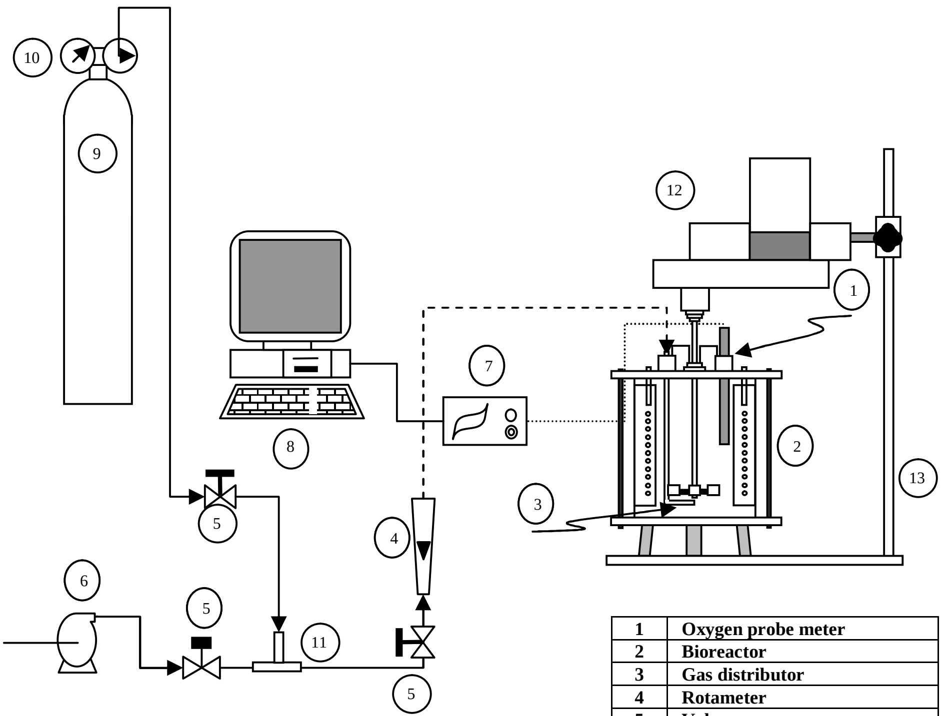
The result of integration is

$$\ln\left[\frac{(O^* - O_0)}{(O^* - O)}\right] = k_l a t \qquad \ldots(9)$$

The value of kla is obtained from the slope of the linear regression with $\ln\left[\frac{(O^* - O_0)}{(O^* - O)}\right]$ with respect to time (t).

4.4. Viscosity Measurement

The actual viscosity of distilled water and water with CMC solutions were measured using viscometer type Brookfield model LVDV (3 - 2000.000 cp).



1	**Oxygen probe meter**
2	**Bioreactor**
3	**Gas distributor**
4	**Rotameter**
5	**Valve**
6	**Air compressor**
7	**Interface**
8	**Computer**
9	**N_2 Cylinder**
10	**N_2 gas pressure regulator**
11	**T-join Connector**
12	**Agitator**
13	**Stand**

Fig. 2. Experimental Setup of Stirred Bioreactor.

5. Results and Discussion

Oxygen transfer in fermentor is the major concern for adjustment in aeration and agitation. In this work a simulation of synthetic fermentation (non- microbial) media was made to approximate the situation. The operating conditions were chosen in order to meet the same situation in fermentor.

5.1. Effect of Superficial Gas Velocity on the k_la Values

The effect of superficial gas velocity Vg on the kla values at different speeds of agitation and liquid viscosities are shown in Fig.3 and 4, respectively. It can be observed that, the value of kla increases with an increase in Vg. Generally, kla values for air/ water system increases from 0.0135 s-1 to 0.048 s-1 when Vg increases from 0.053 cm/s to 1.06 cm/s at 400 rpm.

This is many be attributed to the fact that at high air flow rate, bioreactor gas holdup increases leading to a high a (bubble surface area) which in tern increases the kla values.

The increase in non-Newtonian behavior results in changing the properties of liquid. Consequently, lower Reynolds number in viscous liquid in comparison to Newtonian liquid at the same aeration and agitation was obtained. The kla values decreases from 0.0157 to 0.009 s-1 when the liquid viscosity increases from 0.5 to 3 w/v at constant Vg of 1.06 cm/s and over the same (400) rpm. This can be observed clearly in Fig. 4. Also, it can be seen that the increase of CMC concentration results in an increase in oxygen mass transfer resistance from the air bubble to the liquid.

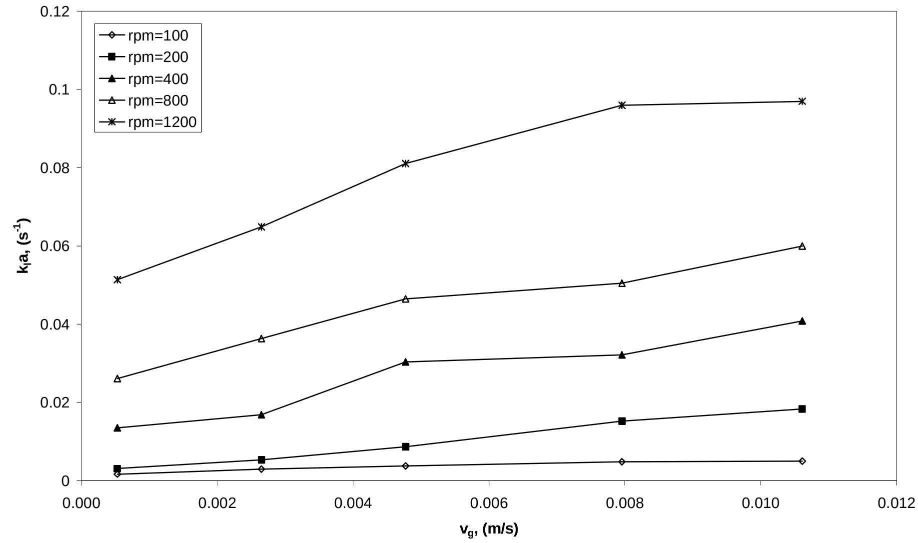


Fig. 3. Effect of superficial gas velocity on k_la for air/water system at different speed of agitation.

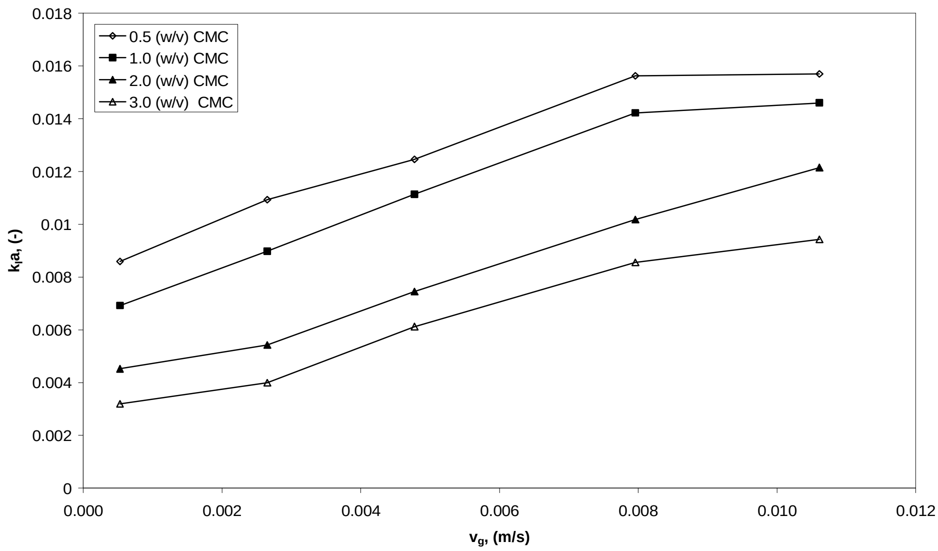


Fig. 4. Effect of superficial gas velocity on k_la for air/CMC system at CMC concentrations and at 400 rpm.

5.2. Effect of Impeller Speed on the kla Values

Impeller speed is one of the most important factor in bioreactor, it decided the overall power dissipation for any specific impeller geometry. Figure 5 and 6 show the relation between impeller speed and kla values for air/water and air/CMC systems. It can be observed that with an increase in the impeller speed, kla values increases from 0.00165 to 0.042s-1, 0.0005 to 0.043s-1, 0.00054 to 0.037s-1, 0.0003 to 0.028s-1, 0.0001 to 0.024s-1, for air/water, 0.5, 1, 2, and 3w/v CMC systems, respectively, and over the same air flow rate of 1l/min. This can be attributed to the rapid breakage of the gas bubbles into smaller size with an increase in the impeller speed and thus enhancing the gas-liquid interfacial area for the mass transfer. This also results in a maximum bioreactor gas holdup and hence high values of kla. The same observations were found in other works (Meenal et al., 2005; Babalona et al., 2005; Muhd, 2005; Galaction et al., 2004).

As the liquid viscosity and impeller speed increases, kla values decreases. This is can be attributed to the same reason that explained in the previous section. Consequently, a drop in oxygen transfer rate occurs. The variation in the kla values attained was consistent with that found in the literature by (Ikram-ul et al., 2005; Cascaval et al., 2004; Badino et al., 2001; Wen et al., 2000).

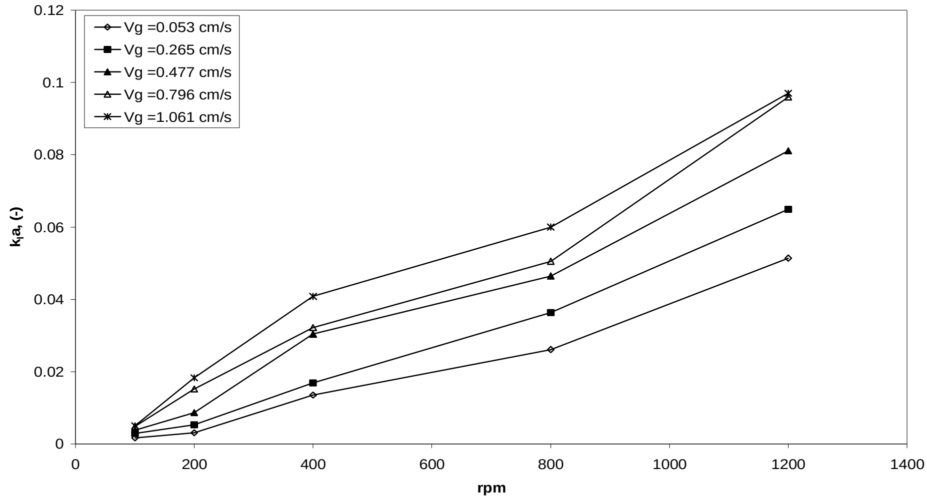


Fig. 5. Effect of impeller speed on $k_l a$ values for air/water system at different air flow rates.

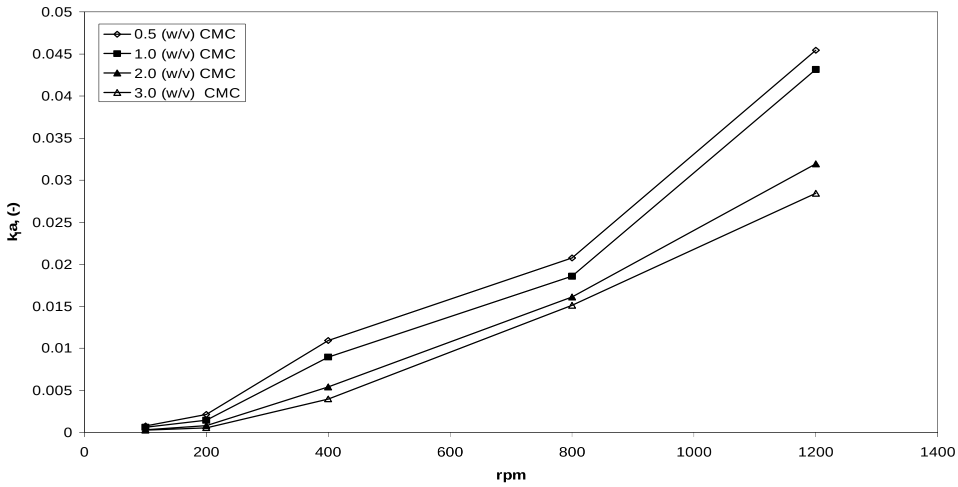


Fig. 6. Effect of impeller speed on $k_l a$ values for air/CMC system at different viscosities and air flow rate of 1 l/min.

5.3. Effect of Impeller Power Input on the kla Values

The effect of the total power input (impeller power and gas expansion) on the volumetric mass transfer coefficient is shown in the Figure 7 and 8 for air/water and air/CMC systems, respectively. The increase of specific power input leads to kla increase. At higher aeration rate, the air dispersion is amplified by combined action of mechanical and pneumatic mixing.

The highest value of kla was observed for air-water system as compared to air/CMC systems. In general, introducing polymer into the liquid will suppress the turbulence and increase the oxygen transfer resistance. On the other hand, the reduction of polymer- law, due to polymer presence, lower the gas hold-up and decreases the interfacial area (Felix et al., 2009; Gimbun et al., 2009; Kumaresan et al., 2006; Galaction et al., 2004, Mária et al., 2004).

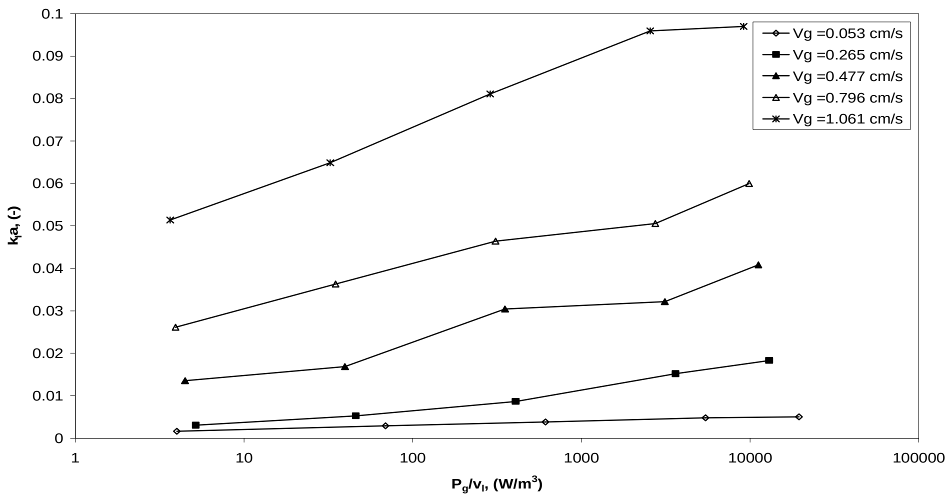


Fig. 7. The effect of specific power input on oxygen mass transfer coefficient for air/water system at different air flow rate.

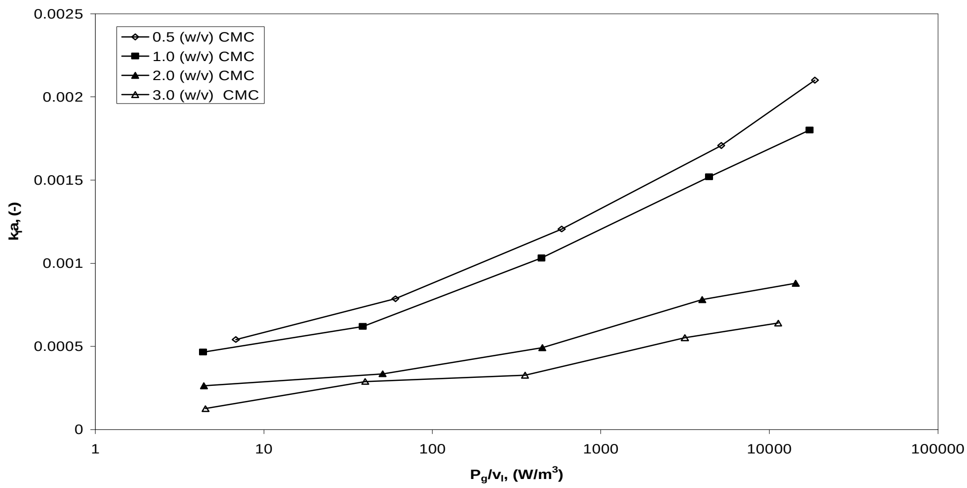


Fig. 8. The effect of specific power input on oxygen mass transfer coefficient for air/CMC system at different viscosities and air flow rate of l/min.

5.4. Correlation for kla at Different Operational Parameters in 5 Liter Bioreactor

The obtained oxygen mass transfer coefficient values with air/water and air/CMC systems were correlated with the impeller speed, liquid viscosity and the superficial gas velocity using Eqn. 6. The analysis was performed using STATISTICA software with non-linear regression. Table 2 summarizes the final results of theses analysis. From this table, it can be observed that there is no significant effect on the exponents of vg and (Pg/Vl) over the studied range of CMC concentration. The exponent of vg for air/water system is lower than that for air/CMC system at different concentrations. This is due to good uniform dispersion and mass transfer rate for air/water than air/CMC systems.

The predicted and experimental data were presented in Fig. 9 to 13. An acceptable result with an average correlation coefficient of 0.95 was obtained. This means that proposed model offers a good agreement with the experimental data.

Table 2,
Correlation constants and nonlinear regression analysis parameters.

		Correlation constants			Standard deviation	Correlation coefficient, R^2
		α	β	γ		
Air/water system		30.4	0.088	1.43	0.01	0.98
Air/CMC system	**(w/v)**					
	0.5	522	0.06	2.3	0.019	0.99
	1	811	0.06	2.3	0.019	0.99
	2	1623	0.06	2.3	0.015	0.99
	3	1576	0.06	2.3	0.014	0.99

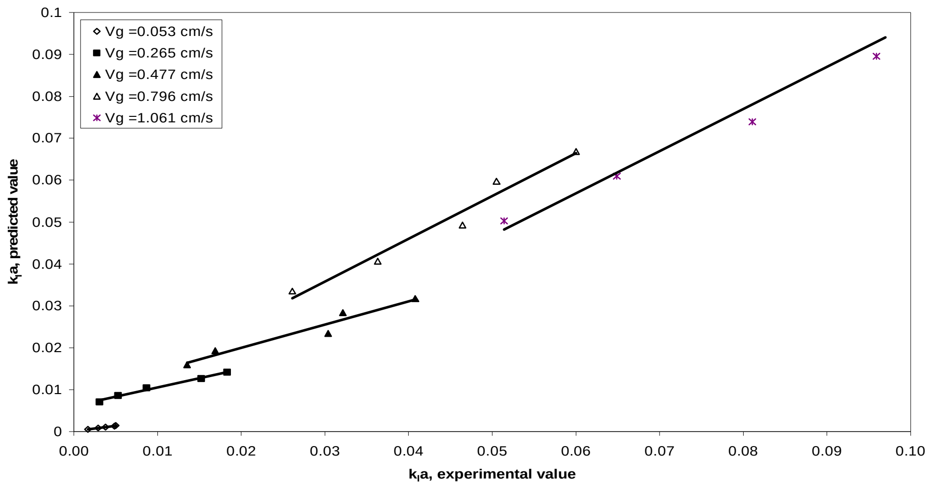


Fig. 9. Comparison between the experimental and predicted data from the proposed model and for air/water systems at different air flow rates.

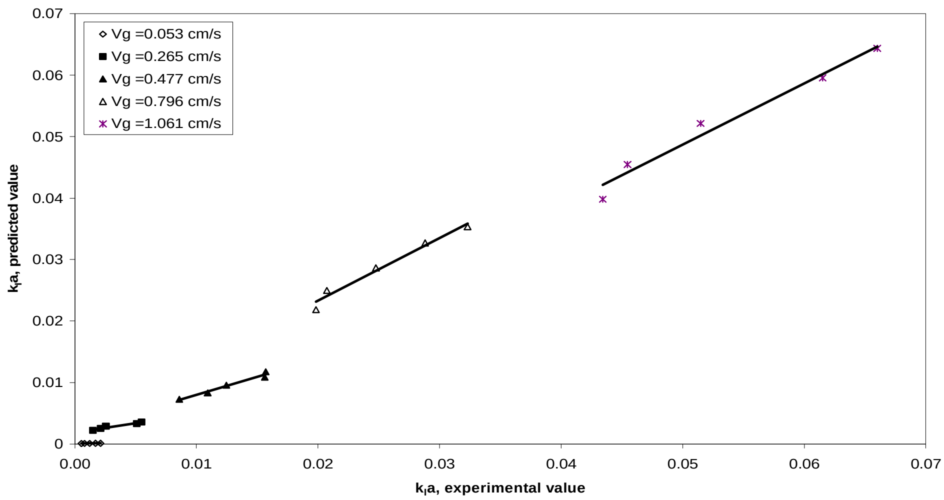


Fig. 10. Comparison between the experimental and predicted data from the proposed model and for air/CMC systems at 0.5w/v concentration and at different air flow rates.

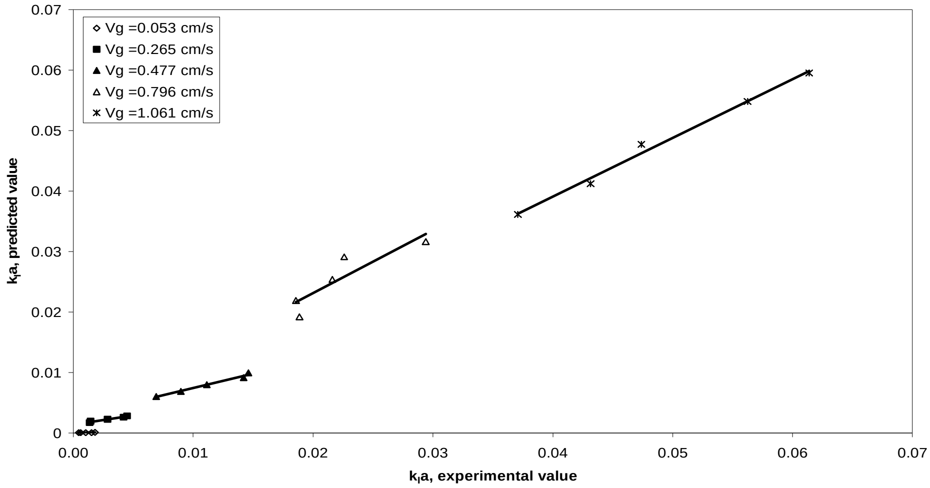


Fig. 11. Comparison between the experimental and predicted data from the proposed model and for air/CMC systems at 1w/v concentration and at different air flow rates.

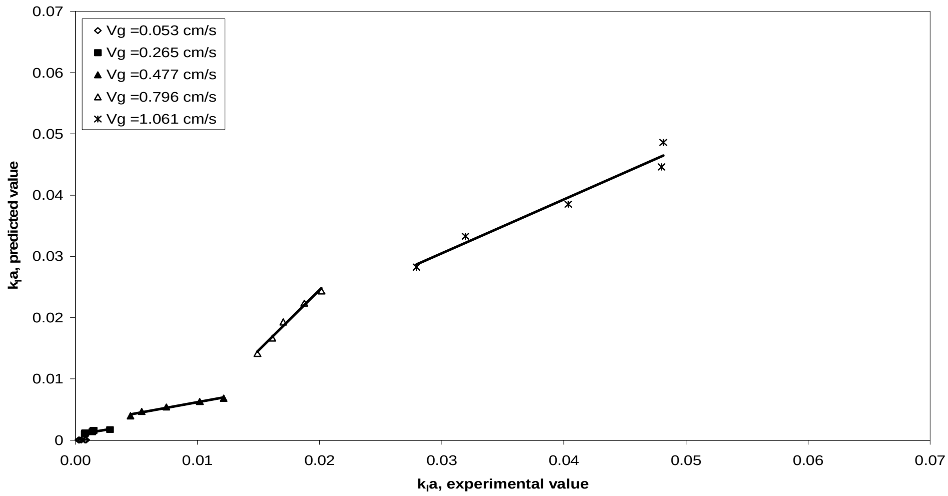


Fig. 12. Comparison between the experimental and predicted data from the proposed model and for air/CMC systems at 2w/v concentration and at different air flow rates.

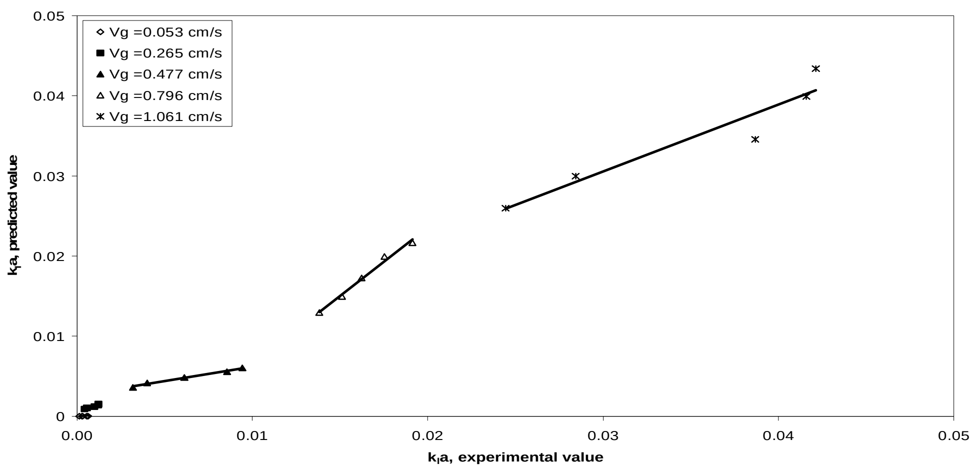


Fig. 13. Comparison between the experimental and predicted data from the proposed model and for air/CMC systems at 3w/v concentration and at different air flow rates.

6. Conclusions

Oxygen mass transfer was evaluated in a 5 liter laboratory bioreactor. Evaluation of the experimental data shows that the kla values are affected by factors, such as impeller speed, the superficial air velocity, total power input to the liquid medium, and media viscosity. The

The correlations developed in this study more accurately model the data and are useful for the design of 5 L bioreactor. These correlations are as follows:

Air/water system

$$k_L a = 30.4\left(\frac{P_g}{V_l}\right)^{0.088}\left(V_g\right)^{1.43}$$

Air/CMC system (0.5w/v)

$$k_L a = 522\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

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Air/CMC system (3w/v)

$$k_L a = 1576\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

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التنبوء بقيم معاملات انتقال الأوكسجين في المفاعلات الحيوية المزودة بزعنفة الخلط من نوع Rushton Turbine في الأوساط المقلدة (غير الميكروبية)

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الخلاصة

اجريت دراسة حول انتقال الاكسجين على نطاق مختبري في مفاعل حيوي سعة ٥ لتر مزود بخلاط يحتوي على زعنفة خلط من نوع Rushton turbine. تمت دراسة تاثير سرعة الغاز الفراغية، سرعة زعنفة الخلط، الطاقة المسلطة ولزوجة السائل على انتقال الاوكسجين. تم استعمال نظام الهواء/ الماء والهواء/ محلول CMC كاوساط سائلة لهذه الدراسة. تراوح تركيز CMC من ٠.٥ الى ٣ وزن/حجم. أظهرت النتائج المختبرية أن معمل انتقال الاوكسجين يزداد بزيادة السرعة الفراغية لغاز الاوكسجين وسرعة زعنفة الخلط، ويقل بزيادة لزوجة السائل. تم ربط النتائج المختبرية لمعاملات انتقال الاوكسجين بعلاقة رياضية التي تصف تأثير العوامل التي تم التطرق اليها (الطاقة الكلية المسلطة على النظام والسرعة الفراغية لغاز الاوكسجين) ضمن المديات اللتي حددت في البحث. اعطت نتائج قيم k_la المستحصلة من الموديلات الرياضية، نتائج مقبولة مقارنتاً مع النتائج المختبرية: تم الحصول على العلاقات الاتية:

نظام الهواء/ الماء:

$$k_L a = 30.4\left(\frac{P_g}{V_l}\right)^{0.088}\left(V_g\right)^{1.43}$$

Air/CMC system (0.5w/v)

$$k_L a = 522\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (1w/v)

$$k_L a = 811\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (2w/v)

$$k_L a = 1623\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$

Air/CMC system (3w/v)

$$k_L a = 1576\left(\frac{P_g}{V_l}\right)^{0.06}\left(V_g\right)^{2.3}$$