

# The studies on the oxygen mass transfer coefficient in a bioreactor

Belma Özbek \*, Sevgi Gayik

*Department of Chemical Engineering, Yıldız Technical University, Davutpaşa Campus, 34210, Esenler, İstanbul, Turkey*

Received 16 May 2000; received in revised form 18 July 2000; accepted 15 November 2000

## Abstract

The effects of process variables on the volumetric liquid phase mass transfer coefficient of oxygen,  $k_La$ , in a stirred bioreactor were investigated by the static gassing-out method. The process variables chosen were impeller speed, air flow rate, temperature, viscosity and loading (%) of biomass support particles (BSP). The  $k_La$  value was obtained as  $2.766 \text{ min}^{-1}$  in distilled water at process variables such as stirrer speed 300 rpm, air flow rate  $0.3 \text{ l min}^{-1}$ , temperature  $37^\circ\text{C}$  and pH 7. By using the same process conditions,  $k_La$  values obtained in glycerol (50%) + distilled water, distilled water containing BSP (loading 25%, particle volume  $0.1625 \text{ cm}^3$ ) and glycerol (50%) + distilled water containing BSP (loading 25%, particle volume  $0.1625 \text{ cm}^3$ ) were 1.383, 0.933 and  $0.450 \text{ min}^{-1}$ , respectively. The exponents representing dependence of  $k_La$  on the process variables were also obtained by using oxygen absorption data, then these values were compared with literature values. © 2001 Elsevier Science Ltd. All rights reserved.

**Keywords:** Oxygen mass transfer coefficient; Process variables; Correlation studies; Biomass support particles (BSP); Viscosity; Bioreactor

## 1. Introduction

Mechanically agitated vessels are widely used for various gas–liquid reactions, aerobic fermentation and waste treatment. These provide high values of mass and heat transfer coefficients and excellent mixing. The agitated vessels are useful for cases where the liquid contains suspended solids or in the fermentation industries where the provision of oxygen (air) to the fluid is a most important factor. Sparged or stirred vessels are used to diffuse substance to the surfaces of microbial cells. Similar principles and requirements apply to waste disposal by aerobic fermentation in sewage works and process waste disposal plants.

The most important parameter effecting 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 immobilising materials (density, particle size, etc.), etc.

Oxygen transfer is the key to aerobic biological processes, both natural and industrial. Therefore a considerable amount of work has been done for the purpose of mass transfer from gas phase and different types of gas liquid contacting devices, such as bubble columns, tray towers, wetted wall towers, packed towers and agitated vessels have been used in the studies. Bubble columns and agitated vessels are ideal equipment for processes where the fraction of gas absorbed does not have to be high, and the liquid is required to be well mixed. Many investigators have studied mass transfer in the gas liquid contacting systems in agitated vessels [1–17].

The present study was undertaken to determine the influence of process variables such as impeller speed, air flow rate, temperature, viscosity and loading (%) of biomass support particles (BSP) on the gas–liquid mass transfer of oxygen. Using a modular bioreactor system (laboratory-scale), with a single impeller and a capacity of approximately 1 l (total volume), the effects of process variables on the  $k_La$  was investigated. The effect of the viscosity was investigated on  $k_La$  by increasing the viscosity of the process fluid with glycerol. Scotch-Brite pieces [18] (green pads were cut into pieces) were chosen as biomass support particles to investigate their effects on the  $k_La$  values at various

\* Corresponding author. Fax: +90-212-4491895.

E-mail address: bozbek@yildiz.edu.tr (B. Özbek).

loadings and sizes. Later,  $k_La$  values obtained from the data on oxygen absorption were used to establish correlations as a function of the process variables. Thus, the exponents obtained from the correlations, representing the dependence of the  $k_La$  on the process variables, were compared with the literature values.

## 2. Materials and methods

### 2.1. Determination of the $k_La$ values

The static gassing-out method was used for the determination of  $k_La$  values. This method has advantages over chemical methods in that it can be carried out in many different media and does not involve a chemical reaction which could affect the liquid film resistance [19]. The limitations of the gassing-out method lie in the facts that a non-respiring system is involved, which may differ from the actual fermentation conditions. With a fast responding oxygen electrode (Galvanic type, Model No: FER454-050A, manufactured by Sanyo Gallenkamp PLC), the oxygen solution rate was determined by direct measurement of the rate of increase in dissolved oxygen concentration after it was lowered by passing nitrogen gas (oxygen free),  $0.6 \text{ l min}^{-1}$ , through the system for 30 min. The nitrogen gas flow was stopped and this was followed by passing various rates of dry air as a source of oxygen (obtained from a pressurized gas cylinder) through the air sparger at the bottom of the agitated bioreactor.  $k_La$  values were obtained from the data using Eq. (1).

$$\frac{d[V_L \cdot c_L]}{dt} = k_La(c^* - c_L) V_L \quad (1)$$

where  $k_La$  is the volumetric mass transfer coefficient ( $\text{min}^{-1}$ ),  $(c^* - c_L)$  is the driving force causing the mass transfer,  $c^*$  and  $c_L$  refer to the liquid phase oxygen concentration at saturation and at any time, respectively.

It is assumed that the response of the oxygen electrode to a change in the dissolved oxygen concentration is sufficiently fast in the analyzer. Most investigators [20–22] did not take the response time of the electrode into account. As a result, the  $k_La$  value was evaluated from the slope of the straight portion of the curve between  $\ln(c^* - c_L)$  vs. without worrying about the time constant of the measuring device. (Since in all the runs in this work  $k_La$  was less than  $0.1 \text{ s}^{-1}$ , this assumption was made.)

### 2.2. Bioreactor

Experiments were performed with various aeration rates, impeller speeds and with or without addition of biomass support particles and glycerol, into the distilled

water. The Gallenkamp Modular Bioreactor system (Model No: FER-195-010, manufactured by Sanyo Gallenkamp PLC) was used for the determination of the  $k_La$  values. The controls of various parameters such as impeller speed, temperature, dissolved oxygen were performed by its modules. The 1.0 l vessel (round bottom) was constructed of glass and stainless steel with an aspect ratio (height/diameter) of 1.545. The important design details were as follows: operating volume, 0.6 l; internal diameter, 11 cm; height, 17 cm; number of baffles, 4; baffle height, 13.5 cm; baffle width, 1.5 cm, number of impellers, 1; location of impeller from top plate, 14 cm; location of impeller from bottom plate, 3 cm; type of impeller, Rushton disc turbine; impeller diameter of disc, 4.8 cm; impeller blade width, 1.4 cm; impeller blade length, 1.9 cm; number of blades, 6. The proportionality of diameter of impeller to diameter of tank ( $D/T$ ) is 0.436.

### 2.3. Biomass support material

In various loadings and sizes of Scotch-Brite particles (green pad pieces) are used to investigate the effect on the  $k_La$ . These porous biomass support particles are also used for the application of a passive cell immobilization technique in an earlier study. Preliminary experiments [18] showed that they were inert, sterilizable, and did not deform or decolourize during sterilization or fermentation, and they allowed a higher degree of immobilization. These support particles have an open network structure with a high degree of interconnection between the voids and resemble a non-woven support material. Due to the complex nature of their three dimensional network, it was not possible to determine the void volume or the pore density of the BSP used. The 0.65 cm thick support material used in this present study were cut into various pieces such as sizes of  $0.65 \text{ cm} \times 0.5 \text{ cm} \times 0.5 \text{ cm}$  (particle volume of  $0.1625 \text{ cm}^3$ ),  $0.65 \text{ cm} \times 1 \text{ cm} \times 1 \text{ cm}$  (particle volume of  $0.65 \text{ cm}^3$ ) and  $0.65 \text{ cm} \times 1.5 \text{ cm} \times 1.5 \text{ cm}$  (particle volume of  $1.4625 \text{ cm}^3$ ). After putting the support particles in a beaker, distilled water was added to cover them. These biomass support particles, submerged in distilled water, were autoclaved for 15 min at  $121^\circ\text{C}$  prior to use to remove any chemicals, contaminants.

### 2.4. Correlation studies

Predictions about the rate of absorption of a gaseous species in a stirred tank are usually based on correlations of overall volumetric mass transfer coefficient ( $k_La$ ) with mechanical agitation power per unit volume ( $P/V_L$ ) and gas sparging rate expressed as the superficial velocity ( $V_s$ ). The power input per unit volume ( $P/V_L$ ) and, superficial gas velocity  $V_s$  are major correlation coefficients for  $k_La$ . Therefore, equations of the

following type are frequently found in the literature [7–10,15,22–29].

$$k_L a = A \left[ \frac{P}{V_L} \right]^\alpha [V_s]^\beta, \quad (2)$$

where,  $P$ , is the mechanical agitation power in gas liquid dispersion (W);  $V_L$ , liquid volume ( $\text{m}^3$ );  $V_s$ , gas superficial velocity ( $\text{m s}^{-1}$ );  $A$ , constant;  $\alpha$  and  $\beta$  are exponents. When  $P$  is omitted an equation like the one following can usually adapted.

$$k_L a = A N D^{\alpha_1, \alpha_2} [V_s]^\beta, \quad (3)$$

where,  $D$  is the impeller diameter (m) and  $N$  is the impeller speed.

However, since the accurate measurement of the actual power input into the system may be quite cumbersome many investigators [22–25] have chosen to use the Power Number, i.e.  $N^3 D^2$  to represent the power input per volume.

In this present work,  $k_L a$  values obtained from the experimental data were plotted against the operating variables. For the correlation studies, to obtain the exponential relationship between the  $k_L a$  and the operating variable chosen, other variables being at constant values, logarithmic coordinates were used. In the absence of a power input measuring apparatus,  $\log k_L a$  values were plotted against  $\log N^3 D^2$  values. Also, previous investigators have used linear relationships on the log–log basis by using the least squares technique to express these effects [3,6,22–29].

### 3. Results and discussion

#### 3.1. The effect of impeller speed on the $k_L a$ values

The effects of various impeller speeds on the  $k_L a$  were investigated using the impeller speeds in the range of 100–500 rpm at constant values such as working volume of 0.6 l, aeration rate of  $0.3 \text{ l min}^{-1}$ , temperature of  $37^\circ\text{C}$  and pH of 7.0.

#### 3.2. Distilled water

The values of  $k_L a$  for distilled water versus impeller speeds are plotted in Fig. 1a. The oxygen transfer coefficient,  $k_L a$ , increased from  $0.132$  to  $5.274 \text{ min}^{-1}$  when the impeller speed was increased from 100 to 500 rpm. It can be also seen from Fig. 1a that the impeller speed versus  $k_L a$  plot could be considered in two regions. In the first region, below 300 rpm, the slope is much lower. In the second region, above 300 rpm,  $k_L a$  increases linearly with an increase in the speed of the impeller. Westerterp et al. [2] and Sandall [6] observed similar results in their studies. They suggested that there is a critical impeller speed,  $N_C$ , above which a linear

function of impeller speed only occurs. They found that different critical speeds ranged from 200 to 650 rpm depending on the geometry used.

The exponential relationship between the  $k_L a$  and the power number ( $N^3 D^2$ ) for this study (impeller speed  $\geq 300$  rpm) is given in Eq. (4). The values of  $k_L a$  for distilled water versus power number on the log–log basis are plotted in Fig. 1b. The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data were 0.9999 and 0.00016, respectively.

$$k_L a \propto (N^3 D^2)^{0.42}. \quad (4)$$

For gas sparged agitated vessels the literature indicates a large variation in the exponent of  $P/V_L$  (0.4–1.0) for geometrically different vessels. In the absence of power measurement equipment, the exponents of  $N^3 D^2$  were obtained for the power number. The exponents representing the dependence of the  $k_L a$  on  $N^3 D^2$  and  $P/V_L$  found in the literature are given in Table 1. The exponents of  $P/V_L$  and  $N^3 D^2$  are similar and (the relationship [22] that can be written between them is  $P/V_L = C N^3 D^2$ . The constant,  $C$ , could be different for different gas loadings in the vessel, therefore, the exponent of  $P/V_L$  may be different than the exponent of  $N^3 D^2$ . The exponent of  $N^3 D^2$  obtained from this study ( $\alpha = 0.42$ ), is in the range obtained from the literature (0.16–0.68). This is because of the fact that, the geometry of the vessel (the proportionality of impeller diameter to vessel diameter, tank bottom geometry, tank liquid height, etc.) is different from the others.

#### 3.3. Glycerol + distilled water

The values of  $k_L a$  for glycerol + distilled water (10, 20, 30, 40 and 50% glycerol solutions, w/w) were plotted in Fig. 2a. The  $k_L a$ , for 10 and 50% glycerol solutions increased from  $0.126 \text{ min}^{-1}$  and  $0.067 \text{ min}^{-1}$  to  $4.983 \text{ min}^{-1}$  and  $2.583 \text{ min}^{-1}$  when the impeller speed was increased from 100 rpm to 500 rpm. As can be seen in Fig. 2a, above 300 rpm,  $k_L a$  increase linearly with an increase in the speed of the impeller.

The values of  $k_L a$  for oxygen absorbed into distilled water containing glycerol (in Fig. 2a) were lower than those for absorption into distilled water (in Fig. 1a) under the experimental conditions employed in this study, depending on the impeller speeds.

The exponential relationship between the  $k_L a$  and the power number ( $N^3 D^2$ ) for this study (impeller speed  $\geq 300$  rpm) is given in Eq. (5). The values of  $k_L a$  for distilled water versus power number on the log–log basis are plotted in Fig. 2b. The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data are given in Table A1 in the Appendix A.

$$k_L a \propto (N^3 D^2)^{0.41}. \quad (5)$$

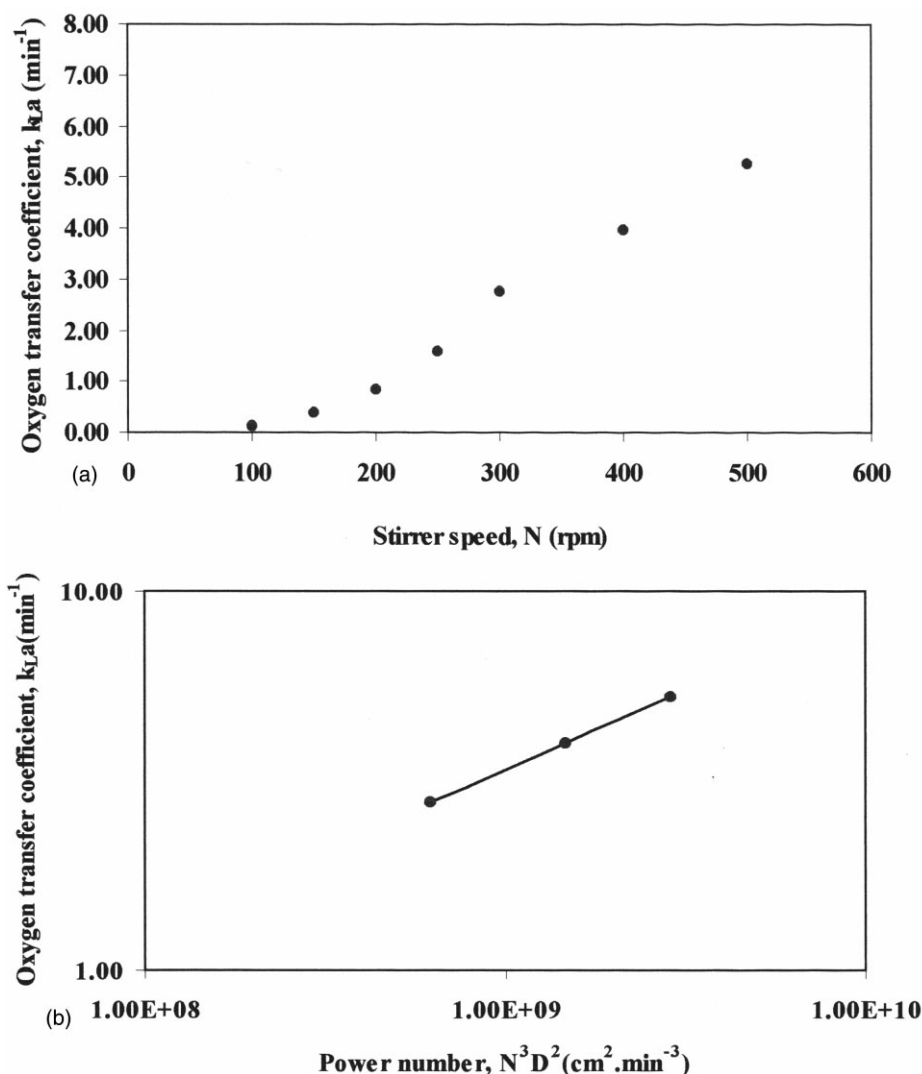


Fig. 1. (a) The  $k_La$  values versus impeller speeds in distilled water; (b) The  $k_La$  values versus power numbers in distilled water.

In this study, the exponent ( $\alpha = 0.41$ ) representing the dependence of the  $k_La$  for oxygen absorbed into distilled water containing glycerol is nearly the same that obtained for absorption into distilled water ( $\alpha = 0.42$ ).

### 3.4. Biomass support particles + distilled water

The values of  $k_La$  for biomass support particles + distilled water (loading of 25%, volume of biomass support particles/volume of solution) are plotted in Fig. 3. The particle volumes used in this study were 0.1625, 0.65 and 1.4625  $\text{cm}^3$ , respectively. The oxygen transfer coefficients,  $k_La$ , for 0.1625 and 1.4625  $\text{cm}^3$  particle volumes were increased from 0.051 and 0.061  $\text{min}^{-1}$  to 1.473 and 1.780  $\text{min}^{-1}$  when impeller speed was increased from 100 to 500 rpm, respectively. As can be seen in Fig. 3, above 300 rpm,  $k_La$  increases linearly with an increase in the speed of the impeller.

The values of  $k_La$  for oxygen absorbed into distilled

Table 1  
The exponents of  $N^3D^2$  and  $P/V_L$  for distilled water

Data from literature	The exponent of $N^3D^2$ , ( $\alpha$ )	The exponent of $P/V_L$ , ( $\alpha$ )
Yoshida et al. [23]	0.43–0.68	–
Yagi and Yoshida [8]	0.74	–
Van't Riet [9]	–	0.4
Hortaçsu [24]	0.37	–
Robinson and Wilke [7]	–	(0.35–0.5)
Hassan and Robinson [10]	–	–
Chandrasekharan and Calderbank [15]	–	0.57
Richards [25]	–	0.4
Wu [26]	–	0.67
Aksak [22]	0.16–0.37	$0.4 < \alpha < 1.0$
Present study	0.42	–

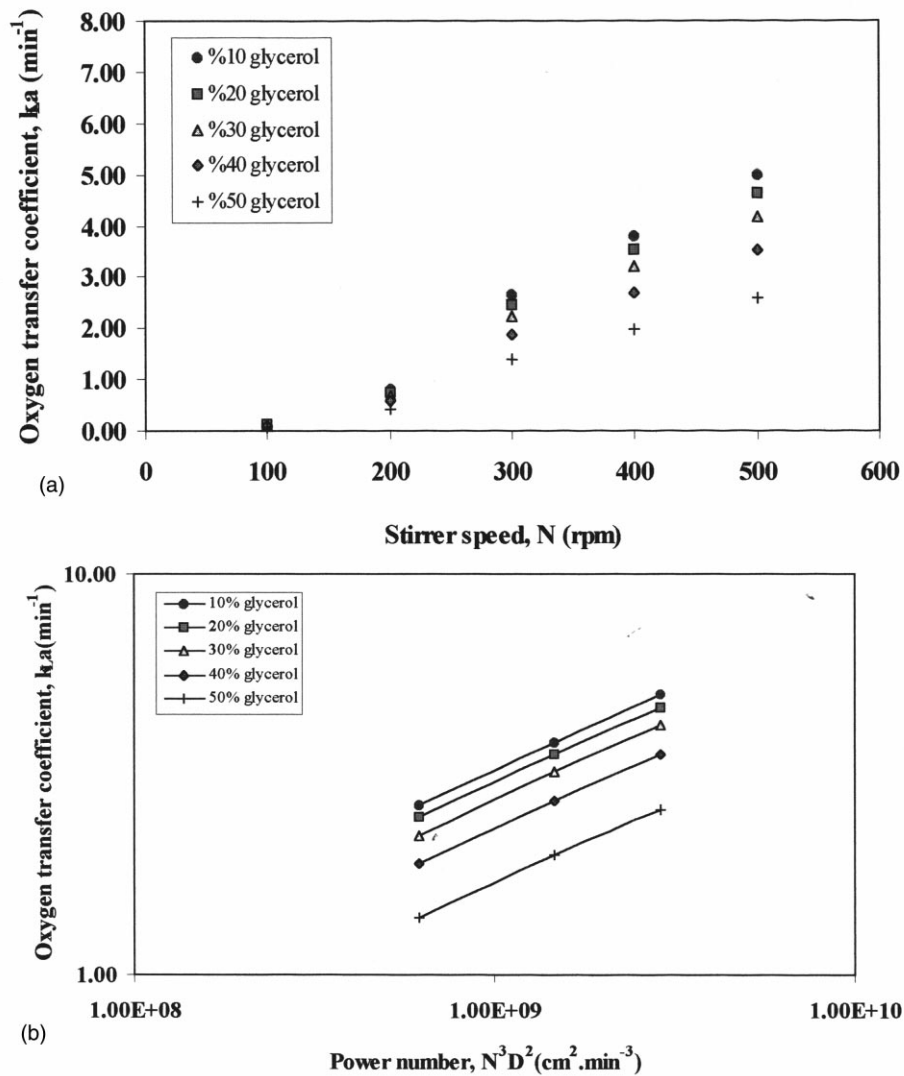


Fig. 2. (a) The  $k_La$  values versus impeller speeds in glycerol + distilled water; (b) The  $k_La$  values power numbers in glycerol + distilled water.

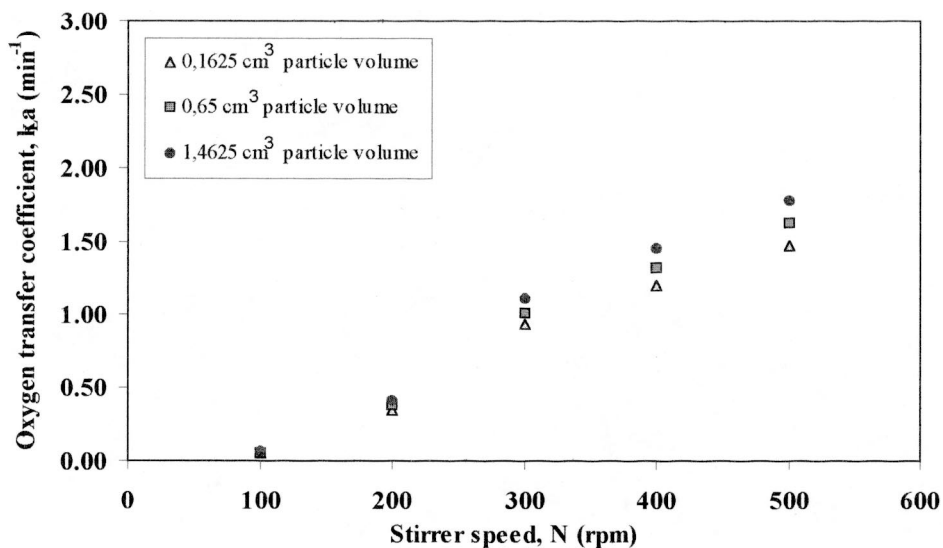


Fig. 3. The  $k_La$  values versus impeller speeds in distilled water containing biomass support particles, loading of 25%.

water containing suspended biomass support particles (in Fig. 3) were lower than that for absorption into distilled water (in Fig. 1a) under the experimental conditions employed in this study, depending on the impeller speeds. The presence of biomass support particles negatively influenced aeration due to a reduction in the gas–liquid interfacial area ( $a$ ) as a result of the coalescence process [30–34].

On the other hand, at the same impeller speed (at constant loading of 25% biomass support particles), the values of  $k_L a$  with the larger size particles were higher than those for smaller particles. It was concluded that the reduction of the effective interfacial area due to the occupation of the liquid volume by the biomass support particles, was probably one of the plausible explanations. One of the probable reasons for the increase in  $k_L a$  values with particle size could be turbulence in the liquid film for larger particles. This is in agreement with the previously reported data for solid particles [30,34].

The exponential relation between the  $k_L a$  and the power number ( $N^3 D^2$ ) for this study (impeller speed  $\geq 300$  rpm) is given in Eq. (6). The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data are given in Table A2 in the Appendix A.

$$k_L a \propto (N^3 D^2)^{0.31}. \quad (6)$$

The exponent ( $\alpha = 0.31$ ) representing the dependence of the  $k_L a$  for oxygen absorbed into distilled water containing biomass support particles was lower than that obtained for absorption into distilled water ( $\alpha = 0.42$ ) for this study.

### 3.5. Biomass support particles + glycerol + distilled water

The values of  $k_L a$  for biomass support particles +

glycerol + distilled water (loading of 25%, volume of biomass support particles/volume of solution) are plotted in Fig. 4. The glycerol concentration in distilled water was kept constant as 50% (w/w). The particle volumes used in this study were 0.1625, 0.65 and 1.4625  $\text{cm}^3$ , respectively. The oxygen transfer coefficients,  $k_L a$ , for 0.1625 and 1.4625  $\text{cm}^3$  particle volumes increased from 0.025 and 0.030  $\text{min}^{-1}$  to 0.716 and 0.865  $\text{min}^{-1}$  when the impeller speed was increased from 100 to 500 rpm, respectively. As can be seen in Fig. 4, above 300 rpm,  $k_L a$  increase linearly with an increase in the speed of the impeller.

The values of  $k_L a$  for oxygen absorbed into distilled water containing suspended biomass support particles and glycerol (in Fig. 4) were lower than that for absorption into distilled water containing biomass support particles (in Fig. 3) under the experimental conditions employed in this study, depending on the impeller speeds. As mentioned before, the reduction in  $k_L a$  was probably due in large measure to a reduction in the specific interfacial area ( $a$ ) caused by the presence of biomass support particles and the viscous forces generated in the fluid by addition of glycerol [30,34].

The exponential relationship between the  $k_L a$  and the power number ( $N^3 D^2$ ) for this study (impeller speed  $\geq 300$  rpm), was given in Eq. (7). The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data are given in Table A3 in the Appendix A.

$$k_L a \propto (N^3 D^2)^{0.30}. \quad (7)$$

Again, the exponent ( $\alpha = 0.30$ ) representing the dependence of the  $k_L a$  for oxygen absorbed into distilled water containing biomass support particles is lower than that for absorption into distilled water ( $\alpha = 0.42$ ) under the experimental conditions employed in this study.

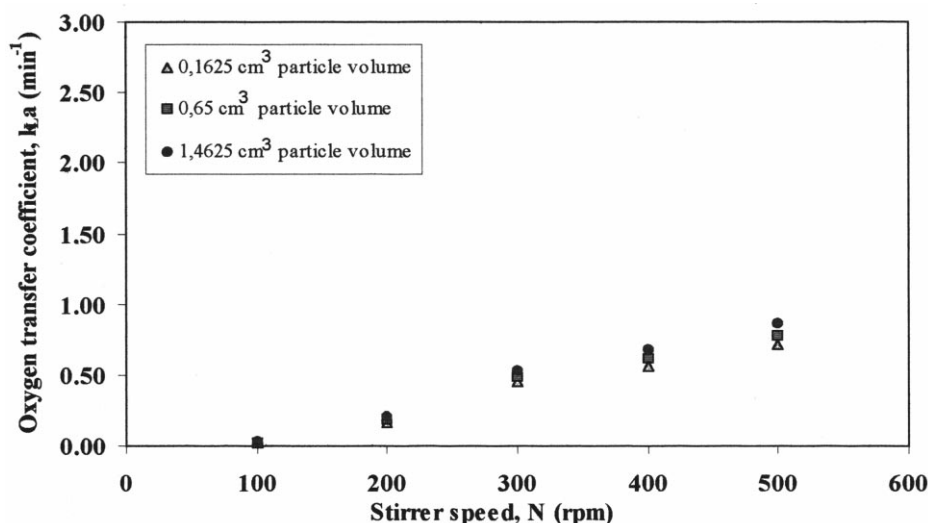


Fig. 4. The  $k_L a$  values versus impeller speeds in glycerol + distilled water containing biomass support particles, loading of 25%.

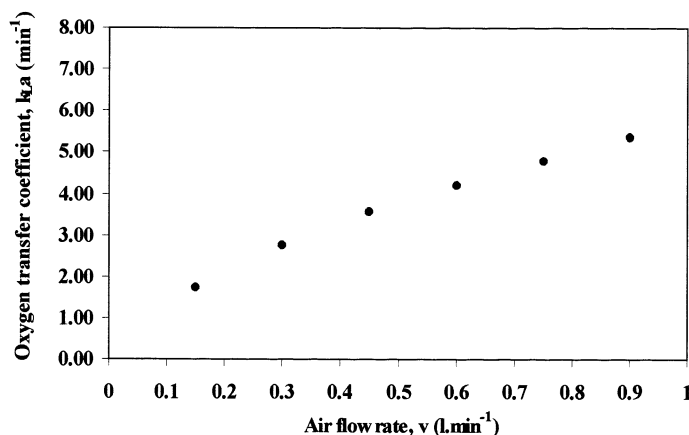


Fig. 5. The  $k_La$  values versus air flow rates in distilled water.

Table 2  
The exponents of  $V_s$  for distilled water

Data from literature	The exponent of $V_s$ ( $\beta$ )
Van't Riet [9]	0.5
Robinson and Wilke [7], Hassan and Robinson [10]	(0.3–0.6)
Hortaçsu [24]	0.67
Hyman and Van Der Bogaerde [35]	0.17
Cooper et al. [28]	0.67
Chandrasekharan and Calderbank [15]	0.63
Gibilaro et al. [36]	0.45
Aksak [22]	(0.3–0.48)
Present study	0.60

### 3.6. The effect of aeration rate on the $k_La$ values

In this study, experiments were performed at aeration rates at 0.3 and 0.6 l min<sup>-1</sup> at a working volume of 0.6 l, impeller speed 300 rpm, temperature of 37°C and pH of 7.0. For distilled water, the effects of aeration rates on the  $k_La$  were investigated using the aeration rates in the range of 0.15–0.9 l min<sup>-1</sup>. It is appreciated that two points are necessary but not sufficient to obtain the parameter values for a straight line relationship. However, this was done in an effort to obtain a quick check on the dependency rather than to arrive at a strict conclusion.

### 3.7. Distilled water

The values of  $k_La$  for distilled water are plotted in Fig. 5. The oxygen transfer coefficient,  $k_La$ , increased from 1.728 min<sup>-1</sup> to 5.35 min<sup>-1</sup> when the aeration rate was increased from 0.15 to 0.9 l min<sup>-1</sup>, respectively.

The exponential relationship between the  $k_La$  and the superficial gas velocity ( $V_s$ ) for this study is given in Eq. (8). The statistical values of  $R^2$  and standard error ( $\sigma$ )

obtained using the data were 0.9995 and 0.00075, respectively.

$$k_La \propto (V_s)^{0.62}. \quad (8)$$

The exponent ( $\beta = 0.62$ ) representing the dependence of  $k_La$  on the superficial gas velocity ( $V_s$ ) was compared with the literature values (Table 2). Previous investigators obtained the values of the exponent on the superficial gas velocity ranged from 0.17 to 0.67, depending on the agitator speed and the geometry of the equipment. The exponent obtained from this study is in the range obtained from the literature.

### 3.8. Glycerol + distilled water

The values of  $k_La$  for glycerol + distilled water (10, 20, 30, 40 and 50% glycerol solutions, w/w) are plotted in Fig. 6. 0.3 and 0.6 l min<sup>-1</sup> were chosen as aeration rate for glycerol + distilled water. The oxygen transfer coefficients,  $k_La$ , for 10 and 50% glycerol solutions were increased from 2.65 and 1.383 min<sup>-1</sup> to 4.016 and 2.078 min<sup>-1</sup> when the aeration rate was increased from 0.3 to 0.6 l min<sup>-1</sup>, respectively.

From the results shown in Fig. 6, the values of  $k_La$  for oxygen absorbed into distilled water containing glycerol are lower than that for absorption into distilled water (Fig. 5), depending on the aeration rates.

The exponential relationship between the  $k_La$  and the superficial gas velocity for this study is given in Eq. (9).

$$k_La \propto (V_s)^{0.59}. \quad (9)$$

For this study, The exponent ( $\beta = 0.59$ ) representing the dependence of the  $k_La$  for oxygen absorbed into distilled water containing glycerol was lower than that for absorption into distilled water ( $\beta = 0.62$ ).

### 3.9. Biomass support particles + distilled water

The values of  $k_La$  for biomass support particles + distilled water (loading of 25%, volume of particles/volume of solution) were plotted in Fig. 7. The particle volumes used in this study were 0.1625, 0.65 and 1.4625 cm<sup>3</sup>, respectively. The oxygen transfer coefficients,  $k_La$ , for 0.1625 and 1.4625 cm<sup>3</sup> particle volumes increased from 0.933 and 1.116 min<sup>-1</sup> to 1.216 and 1.467 min<sup>-1</sup> when the aeration rate was increased from 0.3 to 0.6 l min<sup>-1</sup>, respectively.

From the results shown in Fig. 7, the values of  $k_La$  for oxygen absorbed into distilled water containing suspended biomass support particles were lower than those for absorption into distilled water (in Fig. 5) depending on the aeration rates.

The exponential relationship between the  $k_La$  and the superficial gas velocity is given in Eq. (10).

$$k_La \propto (V_s)^{0.39}. \quad (10)$$

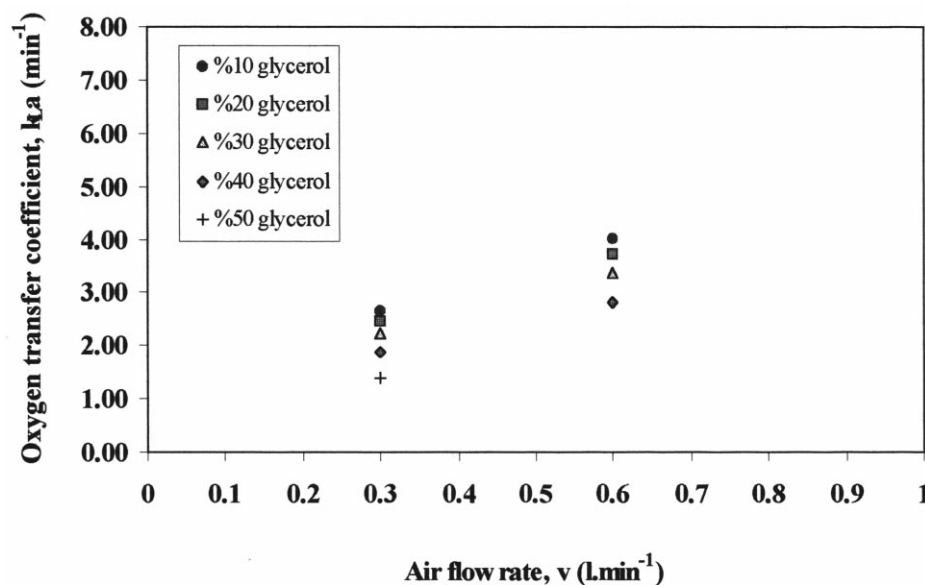


Fig. 6. The  $k_La$  values versus air flow rates in glycerol + distilled water.

The exponent ( $\beta = 0.39$ ) representing the dependence of the  $k_La$  for oxygen absorbed into distilled water containing biomass support particles, was lower than that obtained for absorption into distilled water ( $\beta = 0.62$ ) for this study.

### 3.10. Biomass support particles + glycerol + distilled water

The values of  $k_La$  for biomass support particles + glycerol + distilled water (loading of 25%, volume of particles/volume of solution) were plotted in Fig. 8. The glycerol concentration in distilled water was kept constant as 50% (w/w). The particle volumes used in this study were 0.1625, 0.65 and 1.4625 cm<sup>3</sup>, respectively. The oxygen transfer coefficients,  $k_La$ , for 0.1625 and 1.4625 cm<sup>3</sup> particle volumes increased from 0.45 and 0.533 min<sup>-1</sup> to 0.583 and 0.7 min<sup>-1</sup> when the aeration rate was increased from 0.3 to 0.6 l min<sup>-1</sup>, respectively.

From the results shown in Fig. 8, the values of  $k_La$  for oxygen absorbed into distilled water containing suspended biomass support particles and glycerol were lower than those for absorption into distilled water containing biomass support particles (in Fig. 7) under the experimental conditions employed in this study, depending on the aeration rates.

The exponential relationship between the  $k_La$  and the superficial gas velocity for this study is given in Eq. (11).

$$k_La \propto (v_s)^{0.38}. \quad (11)$$

Again in this study, the exponent ( $\beta = 0.38$ ) representing the dependence of the  $k_La$  for oxygen absorbed into distilled water containing biomass support particles

was lower than that for absorption into distilled water ( $\beta = 0.62$ ) under the experimental conditions employed.

### 3.11. The effect of viscosity on the $k_La$ values

Another factor known to effect the mass transfer in a bioreactor is the viscosity of the process fluid. Glycerol solutions at 10, 20, 30, 40, 50 and 100% were prepared in distilled water at pH 7.0. These gave viscosities [37] of 0.935–566.04 cpoise. The effect of viscosity on the  $k_La$  was investigated using all aeration rate of 0.3 l min<sup>-1</sup>, with a working volume of 0.6 l, impeller speed 300 rpm and temperature of 37°C. The data up to 50% glycerol concentration (viscosity of 6.948 cpoise) are plotted in Fig. 9. The oxygen transfer coefficients,  $k_La$ , for 10 and 100% glycerol solutions decreased from 2.65 to 0.083 min<sup>-1</sup> when the viscosity was increased from 0.935 to 566.04 cpoise.

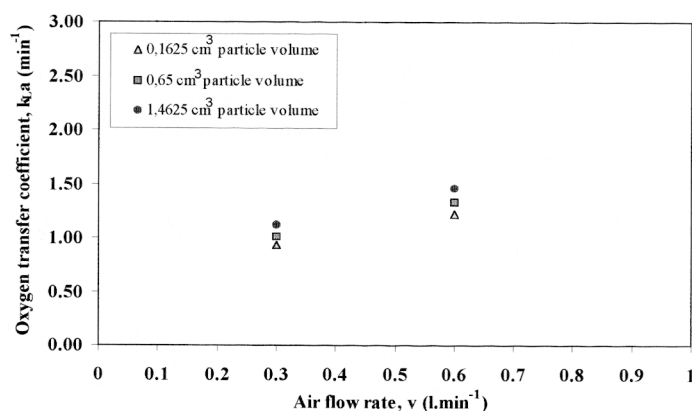


Fig. 7. The  $k_La$  values versus air flow rates in distilled water containing biomass support particles, loading of 25%.



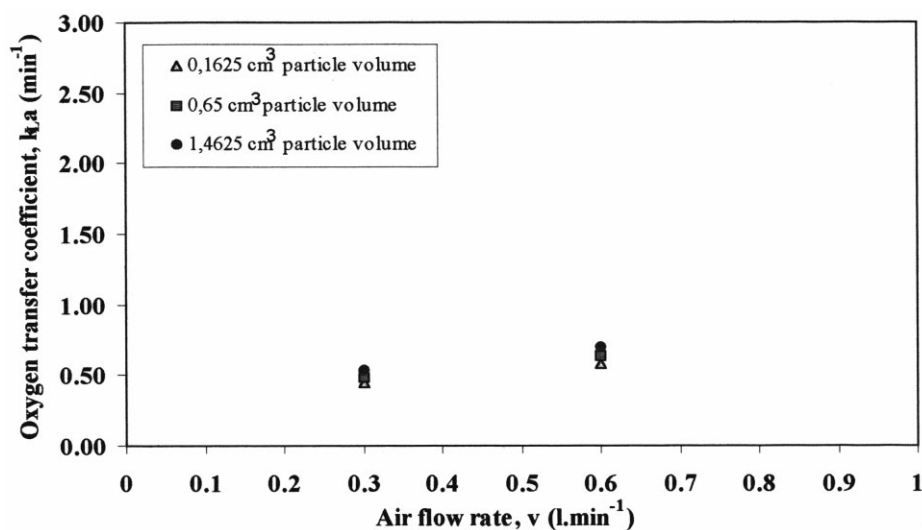


Fig. 8. The  $k_{La}$  values versus air flow rates in glycerol + distilled water containing biomass support particles, loading of 25%.

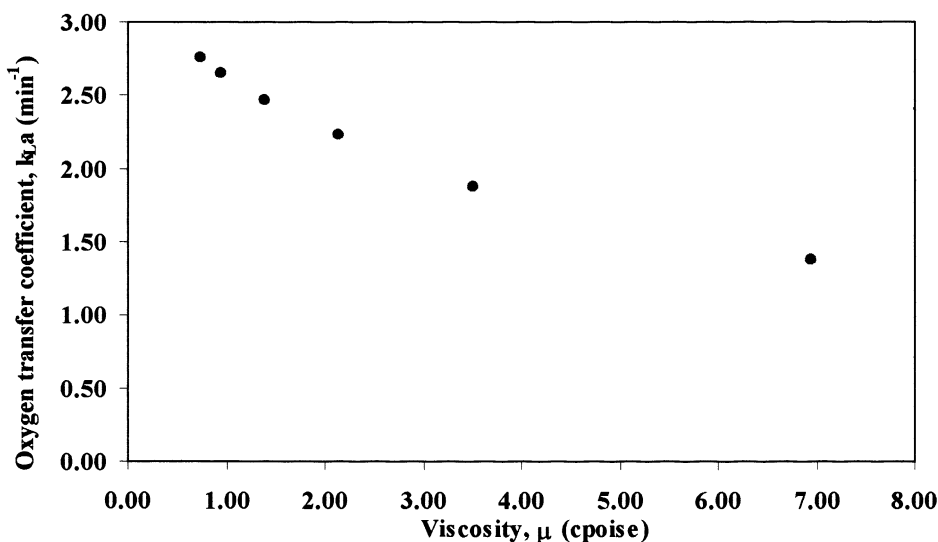


Fig. 9. The  $k_{La}$  values versus viscosities of the process fluid.

The exponential relationship between the  $k_{La}$  and the viscosity for this study is given in Eq. (12). The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data were 0.9813 and 0.00187, respectively.

$$k_{La} \propto (\mu)^{-0.30}. \quad (12)$$

The exponent ( $\delta = -0.30$ ) representing the dependence of the  $k_{La}$  on the viscosity was compared with the literature values. Previous investigators, Yagi and Yoshida [8], Albal et al. [16] and Andrew [31] found the exponents by using the glycerol + water mixtures as  $-0.4$ ,  $-0.17$  and  $-0.5$ , respectively, depending on the agitator speed and the geometry of the equipment, etc. The exponent of viscosity obtained from this study is in the range obtained from the literature.

### 3.12. The effect loading (%) of biomass support particles on the $k_{La}$ values

The effects of loading of biomass support particles on the  $k_{La}$  were investigated using loadings in the range of 5–25% (volume of particle/volume of solution) and particle volumes in the range of 0.1625–1.4625 cm<sup>3</sup> at constant values of working volume of 0.6 l, impeller speed 300 rpm, aeration rate 0.3 l min<sup>-1</sup>, temperature of 37°C and pH of 7.0.

### 3.13. Biomass support particles + distilled water

The values of  $k_{La}$  for biomass support particles + distilled water at various loadings, 5, 11, 18 and 25%,

are plotted in Fig. 10. In the literature [16,30–34] many results have been reported on the influence of the particles on aeration and agreement exists on the mechanism responsible for the change in  $k_La$ . The presence of the solid phase negatively influences aeration. It is proposed that higher concentrations increase the viscosity of the slurry thereby increasing coalescence as a result of which  $k_La$  decreases. The reduction in  $k_La$  is probably due to a larger extent to a reduction in the specific area (a) as a result of the coalescence process. When solid particles were added,  $k_La$  began to decline at a concentration which depended on solids type and their particle size.

In this study, at the same loading (%) of biomass support particles, the values of  $k_La$  with the larger size particles were higher than those for smaller particles. It was concluded that the reduction of the effective interfacial area due to the occupation of the liquid volume by the biomass support particles is probably the plausible explanation. One of the probable reasons for the increase in  $k_La$  values with particle size could be that turbulence in the liquid film for larger particles may be more violent than for smaller particles. This is in agreement with previously reported data for solid particles [30,34].

The exponential relationship between  $k_La$  and the loading (%) of biomass support particles for this study is given in Eq. (13). The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data are given in Table A4 in the Appendix A.

$$k_La \propto (\text{Loading } \%)^{-0.52} \quad (13)$$

### 3.14. Biomass support particles + glycerol + distilled water

The values of  $k_La$  for biomass support particles + glycerol + distilled water at various loadings, 5, 11, 18 and

25%, are plotted in Fig. 11. The glycerol concentration in distilled water was kept constant as 50% (w/w). The oxygen transfer coefficients,  $k_La$ , for 0.1625 and 1.4625  $\text{cm}^3$  particle volumes increased from 1.056 and 1.233  $\text{min}^{-1}$  to 0.45 and 0.533  $\text{min}^{-1}$  when the loading was increased from 5 to 25%, respectively.

The exponential relationship between  $k_La$  and the loading (%) of biomass support particles for this study is given in Eq. (14). The statistical values of  $R^2$  and standard error ( $\sigma$ ) obtained by using the data are given in Table A5 in the Appendix A.

$$k_La \propto (\text{Loading } \%)^{-0.51} \quad (14)$$

The exponent ( $-0.51$ ) representing the dependence of the  $k_La$  for oxygen absorbed into distilled water containing biomass support particles and glycerol was nearly the same as that obtained for absorption into distilled water containing biomass support particles ( $-0.52$ ) under the experimental conditions employed in this study.

## 4. Conclusions

Evaluation of the experimental data shows that  $k_La$  values are effected by process variables such as impeller speed, aeration rate, viscosity of the fluid and presence of biomass support particles (loading % and particle size).

A  $k_La$  value was obtained as 2.766  $\text{min}^{-1}$  in distilled water by using an impeller speed 300 rpm, air flow rate 0.3  $\text{l min}^{-1}$ , temperature 37°C and pH 7. Using the same process conditions,  $k_La$  values obtained in glycerol + distilled water (50% glycerol, w/w), distilled water containing biomass support particles (loading of 25%, particle volume of 0.1625  $\text{cm}^3$ ) and glycerol + dis-

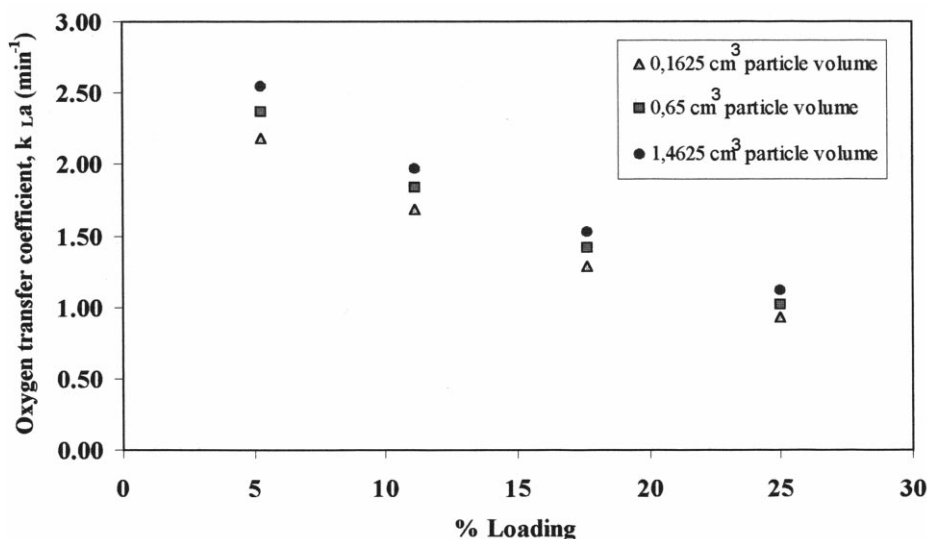


Fig. 10. The  $k_La$  values versus loading % of biomass support particles in distilled water.

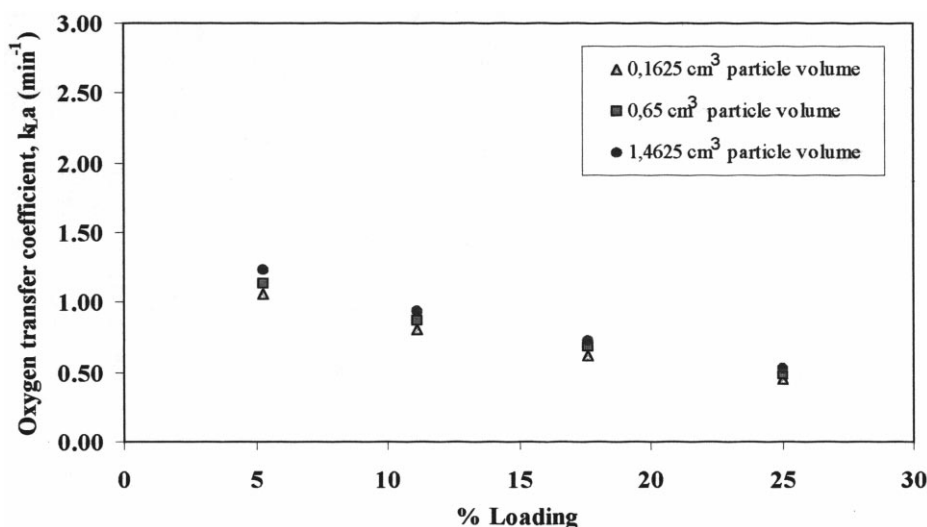


Fig. 11. The  $k_{La}$  values versus loading % of biomass support particles in glycerol + distilled water.

tilled water (50% glycerol, w/w) containing biomass support particles (loading of 25%, particle volume of 0.1625 cm<sup>3</sup>) were 1.383, 0.933 and 0.450 min<sup>-1</sup>, respectively. The experimental results showed that the addition of glycerol and biomass support particles into distilled water results in a reduction of the overall liquid phase mass transfer coefficient compared with the  $k_{La}$  values obtained in distilled water. The reductions of the  $k_{La}$  values were 50% for glycerol + distilled water, 66.3% for distilled water containing biomass support particles and 83.7% for glycerol + distilled water containing biomass support particles.

The  $k_{La}$  values obtained from the data of oxygen absorption were used to establish correlations as a function of the process variables. The exponents of power number ( $N^3D^2$ ) and superficial gas velocity ( $V_s$ ) found for distilled water were 0.42 and 0.62, respectively, are in sufficient agreement with the exponents given in the literature. The exponents of power number ( $N^3D^2$ ) and superficial gas velocity ( $V_s$ ) found for glycerol + distilled water, biomass support particles + distilled water and biomass support particles + glycerol + distilled water were 0.41 and 0.59, 0.31 and 0.39, 0.30 and 0.38, respectively.

The effect of the viscosity of the process fluid was also investigated on the  $k_{La}$  values by addition of glycerol into distilled water. The exponent of viscosity ( $-0.30$ ) obtained from this study was in the range obtained from the literature. The forces generated within the fluid associated with shear field by addition of glycerol are known to be of importance in generating conditions for reduction in the  $k_{La}$  values. As the viscosity increases, the air becomes less well distributed throughout the process fluid in the form of large bubbles.

Finally, the influence of loading (%) and sizes of biomass support particles on the  $k_{La}$  was also examined. The exponents of loading (%) of biomass support particles found for distilled water and glycerol + distilled water were  $-0.52$  and  $-0.51$ , respectively. At the same loading (%) of biomass support particles, it was obtained that the values of  $k_{La}$  with the larger size particles are higher than those for smaller particles.

To sum up, the  $k_{La}$  values were influenced by many factors involved in the fluid. The presence of biomass support particles negatively influences aeration due to a reduction in the gas–liquid interfacial area as a result of the coalescence process. Any change in the value of the specific interfacial area ( $a$ ) is likely to change the liquid side mass transfer coefficient. Thus, the operational parameters of the vessel (impeller speed, aeration rate, viscosity and loading % and size of biomass support particles) should be optimised to achieve good mixing and mass transfer. It is also necessary to obtain more data on the  $k_{La}$  values for different types of solid particles with different physical properties.

### Acknowledgements

This work was supported by the Yildiz. Technical University Research Fund. Project Number: 98-A-07-01-02.

### Appendix A

Table A1.  $R^2$ -statistical and standard error ( $\sigma$ ) values for glycerol + distilled water (Eq. (5))

Glycerol concentration, w/w (%)	$R^2$ -statistic	Standard error ( $\sigma$ )
10	0.9999	0.00027
20	0.9999	0.00014
30	0.9999	0.00014
40	0.9999	0.00017
50	0.9999	0.00014

Table A2.  $R^2$ -Statistical and standard error ( $\sigma$ ) values for BSP + glycerol + distilled water (Eq. (7))

Particle volume, $\text{cm}^3$	$R^2$ -statistic	Standard error ( $\sigma$ )
0.1625	0.9999	0.00001
0.65	0.9999	0.00004
1.4625	0.9983	0.00049

Table A3.  $R^2$ -statistical and standard error ( $\sigma$ ) values for BSP + glycerol + distilled water (Eq. (7))

Particle volume, $\text{cm}^3$	$R^2$ -statistic	Standard error ( $\sigma$ )
0.1625	0.9986	0.00015
0.65	0.9930	0.00041
1.4625	0.9974	0.00029

Table A4.  $R^2$ -statistical and standard error ( $\sigma$ ) values for BSP + distilled water (Eq. (13))

Particle volume, $\text{cm}^3$	$R^2$ -statistic	Standard error ( $\sigma$ )
0.1625	0.9799	0.00218
0.65	0.9775	0.00247
1.4625	0.9777	0.00257

Table A5.  $R^2$ -statistical and standard error ( $\sigma$ ) values for BSP + glycerol + distilled water (Eq. (14))

Particle volume, $\text{cm}^3$	$R^2$ -statistic	Standard error ( $\sigma$ )
0.1625	0.9848	0.00091

0.65	0.9788	0.00115
1.4625	0.9794	0.00120

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