

Investigation of Oxygen Transfer in a Two-phase Partition Stirred Tank Bioreactor in the Presence of Silicone Oil

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A lab scale bioreactor was designed for treatment of waste gas containing benzene, toluene and xylene (BTX). Initial characterization of the bioreactor involved quantification of the oxygen transfer coefficient (k_La) as a function of some main operational variables. To evaluate and obtain optimal conditions in the 2.36 L bioreactor, the effect on oxygen transfer rate in several operational conditions including different proportions of organic phase (0, 5, 10, 20 and 30 %) in eleven agitation speeds (0 to 1000) and five aeration levels (1 to 5 L min⁻¹) were tested. The results showed that the presence of silicone oil caused a reduction in the k_La of the aqueous phase for all the concentrations studied. Reduction of k_La due to the presence of silicone oil increased with augmentation of silicone oil fractions. The positive impact of agitation speed and gas flow on oxygen transfer was also observed in the presence of silicone oil, although their impact was somewhat reduced at higher silicone oil content. In addition, it was found that total power consumption declined with addition of different fractions of silicone oil to bioreactor aqueous phase. It was deduced that the most optimal silicone oil fraction and stirring rate are 10 % and 800 rpm respectively, from the viewpoint of oxygen transfer and total power consumption rate. Empirical correlations for the oxygen transfer rate in the bioreactor with the presence of different fractions of silicone oil revealed that the experimental k_La lay within the values predicted. Variations pattern in exponents of correlations showed that addition of silicone oil up to 10 % improves the superficial gas velocity that leads to enhanced k_La of oxygen and higher proportion of silicone oil, which may have negative effect.

Key words:

Oxygen transfer rate, two-phase partition, stirred bioreactor, silicone oil

Introduction

Biotreatment with the advantages of high efficiency, low-cost, and non-secondary pollution is suitable to purify waste gas in low concentrations.^{1–4} Also the efficiency of biotreatment depends on pollutants concentration and solubility. Transport of oxygen, volatile organic compounds

and other poorly water-soluble compounds from the gaseous phase to the liquid phase controls the most of aerated fermentation systems. The amount of dissolved oxygen into the broths is limited by its solubility and mass transfer rate, as well as by its consumption rate on cells metabolic pathways.⁵ The oxygen transfer can be described and analyzed by means of mass transfer coefficient, k_La . It represents the most important parameter implied on the design and operation of mixing–sparging equipment of the bioreactors. The k_La values are affected by many

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factors, such as geometrical and operational characteristics of the vessels, media composition, impeller type, concentration and microorganism's morphology, biocatalysts properties (particle size, porosity, etc.).^{6–12}

For a specific partition bioreactor and medium, it is normally possible to increase the liquid–liquid interfacial area and k_La , and consequently mass transfer rates, using high agitation and aeration rates. However, this causes high total power consumption and significantly increases operating costs. High stirring rates also present a limitation when applied to cells sensitive to hydrodynamic stress and can promote stable emulsion formation leading to downstream processing problems. For partition bioreactors, the addition of a second, water-immiscible phase in which substrate and oxygen has a higher solubility than in water, has been proposed by several authors as an alternative approach to mass transfer rate improvement.^{13–16} However, the presence of a third phase can have a large impact on k_La , which must be accounted for in order to ensure that the system is not oxygen limited, nor over-designed. Liquid-liquid two-phase partition bioreactors (TPPBs), comprised of an aqueous phase, containing cells and inorganic nutrients, as well as an immiscible (typically organic) phase also sequesters high concentrations of toxic substrates away from the cells through equilibrium partition in biotechnological processes.^{6,11,17}

Some hydrophobic phases like silicone oil, with a large affinity for organic pollutants, can be used for their degradation to harmless substances such as carbon dioxide, water and cell components. Silicone oil acts as a reservoir for the controlled delivery of organic pollutants to the aqueous phase, where biodegradation occurs. At the same time, silicone oil is assumed to enhance the oxygen transfer by acting as a surface-active agent to lower the surface tension of water and increase the gaseous specific interfacial area. However, the influence of the addition of an organic phase to water on the mass transfer of a solute (organic pollutant or oxygen) from the gas to the water phase is not well understood,¹⁸ and it is not possible to propose a unified theory to describe adequately the effect of the presence of organic solvent on the enhancement of the mass transfer of oxygen.¹⁹

Quijano *et al.* have investigated oxygen transfer in three-phase airlift and stirred tank reactors using silicone oil as transfer vector. Their experimental model was used to describe oxygen transfer in airlift and stirred tank reactors containing 0 to 50 % of silicone oil. Under the experimental conditions, they found that silicone oil had a positive effect on the overall oxygen transfer. In both reactor designs, the maximum overall oxygen transfer compared to

reactors operated without silicone oil was observed with 10 % silicone oil which was increased by 65 and 84 % in the airlift and stirred reactor, respectively.⁵ Peeva *et al.* experimentally measured the k_La of *n*-decane in 0 to 90 % of water–silicone oil emulsions and found that the volumetric mass transfer coefficient of oxygen was independent of the emulsion composition. They reported that a small fraction of silicone oil was enough to provide a strong enhancement of volatile organic compounds (VOC).²⁰

Although there are numerous papers studying the biodegradation (or the mass transfer rate) of toxic and poorly water-soluble compounds improved by silicone oils,²¹ only a few studies are devoted to the determination of k_La .¹⁹

Review of the information available on gas-liquid mass transfer in the presence of oil droplets revealed that experimental investigations have led to large variations in the reported mass transfer enhancement results. Comparison between results is difficult due to the variety of gas-oil-liquid systems used, and the large number of relevant parameters. Furthermore, there is a sharp contrast between the numerous papers presenting models and the few papers presenting experimental data in gas-liquid-liquid systems. To date, it is not possible to propose a unified theory to describe adequately the influence of the presence of immiscible oil on mass transfer enhancement. There are many gaps in our knowledge, especially about the influence of oil addition on the mass transfer parameters.^{18,19,22,23}

One of the significant design parameters for a multiphase stirred tank reactor is the power input by the agitator, which is affected by the physical properties, operating parameters, and geometrical parameters. Knowledge of the dependence of the power input on operating conditions gives a useful insight into the process; hence, efficiently performing the mixing process with minimum energy is of great interest. The most valuable information for industrial purposes is the optimal utilization of supplied power, i.e. in the creation of gas-liquid interfacial area and mixing.^{10,24} Electricity contributes significantly to the overall manufacturing cost of a fermentation process. Electricity is consumed by air compressors and circulation pumps; however, the major consumer is the agitator motor. Although the power input requirement per unit volume (KW m^{-3}) decreases with increasing bioreactor volume.¹⁰ Also, power draw has been used as a criterion for process scale-up and bioreactor design and commonly, it is referred to as the volumetric power draw.^{24,25} The power consumption in two-phase partition bioreactors may be influenced by the presence of an immiscible liquid phase. Almost all researches have been focused on the effects of or-

ganic phase on the performance of two-phase partition bioreactors, but the effect of organic phase on power input and possible energy saving has been rarely discussed.

In this work, we carried out experiments using silicone oil in a two-phase partition stirred bioreactor. Silicone oil has been shown to be safe and compatible with the aqueous phase and growth of microorganisms.²⁶ Measurements of $k_L a$ in a stirred and aerated bioreactor were conducted to identify the optimal operational conditions in the presence of silicone oil as a second immiscible liquid phase. This work has focused on the influence of the hydrodynamic conditions on the oxygen transfer. The mechanisms involved in the oxygen transfer from the gas phase to the aqueous phase in the presence of the second liquid phase as a function of agitation and aeration rates were studied through their impact on the $k_L a$ values. Also, the total power consumption of the system was investigated in the presence of different volume fraction of silicone oil.

Materials and methods

Bioreactor setup

The experimental setup that can be seen in Fig. 1 consisted of a glass 2.36 L stirred tank bioreactor, designed and used for all mass transfer studies. The bioreactor had an internal diameter of 10 cm and operating volume of 1.77 L (75 %). The bioreactor was tested with dual Rushton turbine impeller configuration, and lower impeller located 5 cm from the semi-circular base of the vessel. The bioreactor

was equipped with 4 equidistant baffles of 1 cm width to enhance liquid-liquid mixing and prevent vortex condition. Silicone oil was selected as vector. It has been reported as a non-toxic and non-biodegradable organic phase.^{5,26–29} De-ionized water accompanied with different fractions of silicone oil (28 ± 0.5 °C) was used as the liquid phase, and filtered air was supplied to the system through an orifice sparger containing 9 orifices with total open area of 0.28 cm^2 , located $T_i/2$ below the lower impeller. The experiments were performed at room temperature and atmospheric pressure. Aeration rates ranging from 1 to 5 L min^{-1} were tested in eleven agitation speeds (0, 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 rpm). The experimental conditions have been selected in order to generate normal flow patterns inside the tank. Table 1 gives the dimensions of stirred tank bioreactor designed, constructed and utilized in this study. The schematic view and details of the Rushton turbine impeller is presented in Fig. 2.

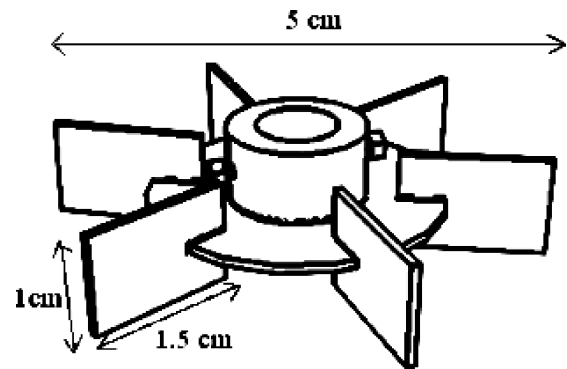


Fig. 2 – Schemes and details of the standard Rushton turbine (RT) impeller with vertical blades

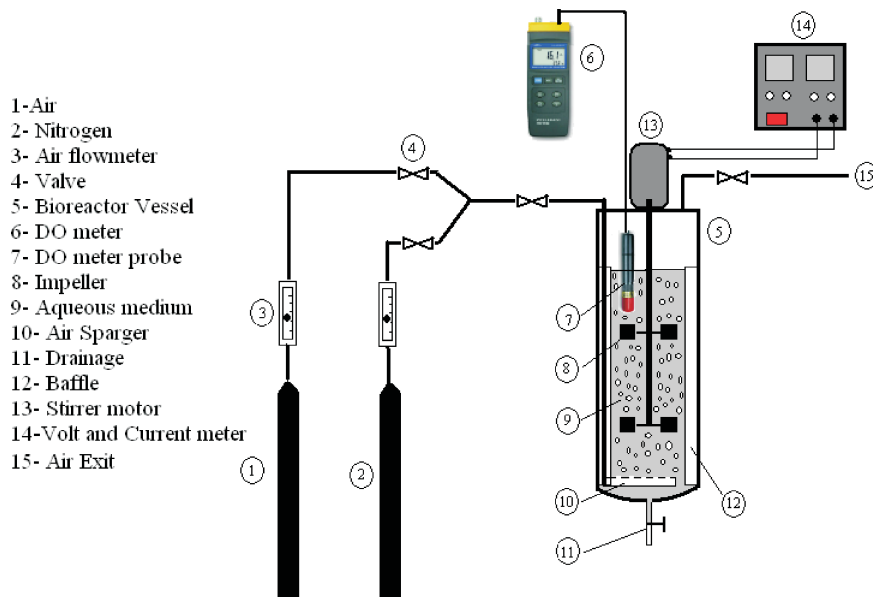


Fig. 1 – Schematic view of stirred tank bioreactor used in this study

Table 1 – Characteristics of the stirred tank bioreactor in this study

Descriptions	Unit	Value
Body of vessel (material)	#	Glass (semi-circular bottom)
Internal diameter of vessel (T_i)	cm	10
External diameter of vessel (T_e)	cm	11
Impeller diameter (D)	cm	5
Vessel height (H)	cm	30
Vessel aspect ratio ($H:T_i$)	#	3 : 1
Bottom impeller clearance	cm	5 ($T_i/2$)
Distance between impellers (h_i)	cm	10 (T_i)
Height of stirrer motor Shaft	cm	25
Working volume (V_L)	liter	1.77 (75 %)
Number of baffles	#	4
Baffles width (w_b)	cm	1 ($T_i/10$)
Impellers type	#	RT
Number of impellers	#	Two
Sparger types	#	Orifice

Oxygen transfer coefficient

The mass transfer rate is controlled by the liquid phase resistance and the contact area. In a stirred tank, the flow developed by the impeller and its effect on the bubbles is what determines both.³⁰ The addition of a second liquid phase, in which oxygen has a greater affinity, such as silicone oil is an alternative to overcome the problem of oxygen limitation in aqueous aerobic bioscrubbers. The determination of $k_L a$ in bioreactors is essential in order to establish aeration efficiency and to quantify the effects of the operating variables on the provision of dissolved oxygen. A number of methods have been developed to determine the oxygen transfer rate in bioreactors. The mass balance for the dissolved oxygen in the well-mixed liquid phase, in the absence of biomass or with non-respiring cells, when biochemical reactions do not take place can be established as:⁷

$$\frac{dC}{dt} = k_L a(C^* - C) \quad (1)$$

Where dC/dt is the accumulation oxygen rate in the liquid phase, C^* is the equilibrium dissolved oxygen concentration. Some measuring methods are based on eq. (1) and different techniques for measuring the dissolved oxygen concentration can be used.

The volumetric coefficient of oxygen transfer from gas to aqueous phase was determined by the

dynamic gassing-out method. This method was performed by sparging nitrogen until the dissolved oxygen concentration fell to about zero and then monitoring the dissolved oxygen concentration (C) after the start of the aeration with atmospheric air. Eq. (2) was then used to determine the $k_L a$;

$$\ln \frac{C^* - C_2}{C^* - C_1} = -k_L a(t_2 - t_1) \quad (2)$$

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 that could affect the liquid film resistance.^{8,9} This technique is interesting for studying the influence of operating conditions on the volumetric mass transfer coefficient, and is widely employed in the literature.^{6,7,10,31–33} The dissolved oxygen concentration was monitored with an oxygen electrode, Lutron oxygen meter model YK – 2001 DO, fitted with a teflon membrane and with an electrolytic solution of Na_3PO_4 in the cell. The measurements for dissolved oxygen concentration were repeated three times in identical conditions, and the average for $k_L a$ values was determined. All the readings were reproducible with errors of measurements being 0–3 %.

Table 2 – Specifications of Silicone oil as organic phase at 25 °C

Name	Appearance	Viscosity (Pa · s)	Specific gravity	Refractive index
Silicone oil	Transparent	339.5	0.97	1.403

Total power consumption

The most frequently used techniques for the evaluation of power consumption in stirred tanks and fermentors are wattmeters, ammeters, colorimeters, dynamometers, torque meters and systems based on strain gauges. Each of these systems has its own advantages and disadvantages, and is chosen based on several factors such as investment, scale, precision, and range of measurement. Electrical measurement as the first technique used for power draw measurements in stirred tanks were based directly in the motor by wattmeters and ammeters. For the case of direct current motors (DC), the power draw by an electrical motor is simply the product of the supplied voltage (V) and the current intensity (I). Power draw in these systems could be properly measured by means of an ammeter, as well as directly by a wattmeter.²⁴

In the present work, the stirring power input was measured by electrical measurement method,

using a circuit control that monitored the electrical current (A) and voltage (V) of the DC stirrer motor mounted on the bioreactor presented in Fig. 1.

Correlation studies

The volumetric oxygen transfer coefficient, $k_L a$, depends on different factors, such as geometrical and operational characteristics of the vessels, media composition, agitation power per unit volume or the impeller rotation speed and on the gas superficial velocity.⁶ Predictions of the rate of absorption of a gaseous species in a stirred tank are usually based on correlations of overall volumetric mass transfer coefficient ($k_L a$) with mechanical agitation power per unit volume (P_g/V_L) and gas sparging rate expressed as the superficial gas velocity (V_g).⁹ The power input per unit volume and, superficial gas velocity are major factors in the $k_L a$ correlations. Therefore, equation of the following type are frequently found in the literature:^{9,34,35}

$$k_L a = \alpha \left(\frac{P_g}{V_L} \right)^\beta (V_g)^c \quad (3)$$

Where, P_g is the mechanical agitation power in gas liquid dispersion (W); V_L , liquid volume (m^3); V_g , superficial gas velocity ($m\ s^{-1}$); α , constant; β and c are exponents.

This model can be explained as:

$$Y = \alpha (X_1)^\beta (X_2)^c \quad (4)$$

$$E(\ln Y) = \ln \alpha + \beta \ln X_1 + c \ln X_2 \quad (5)$$

In this model $\ln Y$ represent dependent variable and $\ln X_1$ and $\ln X_2$ are independent variables or predictor variables. α , β and c are regression parameters that are estimated by least square method.³⁶

Scale-up is usually based on correlations of various kinds to predict $k_L a$ for specific vessel geometry. In the presence of a single interface, gas-liquid, the amount of oxygen transferred depends on the $k_L a$ value and on the difference between the dissolved oxygen concentration and its saturation. The introduction of an immiscible liquid phase, such as silicone oil, in the medium, makes the system more complex from the oxygen transfer point of view. The transfer mechanism of oxygen is yet to be fully understood and an exhaustive study evaluating the effects of a number of design parameters on the overall values of $k_L a$ is required.⁶

Based on these concepts, some empirical correlations for the oxygen transfer rate in the bioreactor with existence of different proportion of silicone oil as organic phase were developed, and $k_L a$ values obtained from the experimental data were plotted against the operating variables, whereas mathemati-

cal correlations describing the influence of the studied parameters on the $k_L a$ have been established in order to predict biodegradation performances from view points of oxygen transfer, when using models that account for the effect of dissolved oxygen. These correlations were developed using Datafit 9 software.

Results and discussions

Oxygen transfer

Besides the $k_L a$ measurements in pure water, studies with various silicone oil fractions (from 0 % to 30 %) as a second liquid immiscible phase were carried out, with dual Rushton turbine impellers, and at eleven agitation speeds ranging from 0 to 1000 rpm and aeration rates of 1 to 5 $L\ min^{-1}$. Figs. 3 and 4 present overviews of the results obtained in terms of $k_L a$ values that show how the presence of a second liquid phase influences the oxygen transfer coefficient of the overall system.

The silicone oil, having lower density to compare with water, stays at the top of the bioreactor when no agitation is supplied. This situation makes the dispersion of the second phase more difficult requiring very high agitation speeds to create a vortex that could effectively disperse the organic phase. It was observed during the measurements that some agitation speeds studied (100, 200 and 300) were not enough to disperse all the silicone oil through the lower aqueous phase.

Impeller speed is the major factor that affects $k_L a$ values of a bioreactor. Results in Fig. 3 indicate that with an increase in the impeller speed, $k_L a$ values were found to increase. This effect 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. The results obtained in the presence of different volume fractions of silicone oil are presented in Fig. 3 and indicate that for the higher agitation speeds (800 to 1000 rpm), the difference observed is not noticeable and falls within the experimental uncertainty of the measurements. There is only a significant enhancement on $k_L a$ values for the agitation speeds of 400 to 800 rpm. For low agitation speeds (0 to 300 rpm) the turbulence is not enough to trap and hold up the air bubbles and consequently performance of volumetric mass transfer may not increase noticeably.

Also, the results in Fig. 4 suggest that for all aeration rates, at high agitation speeds (400 to 1000 rpm), the $k_L a$ reaches a maximum in pure water without silicone oil. However, in lower agitation speeds (0 to 300) the trend is vice versa. This im-

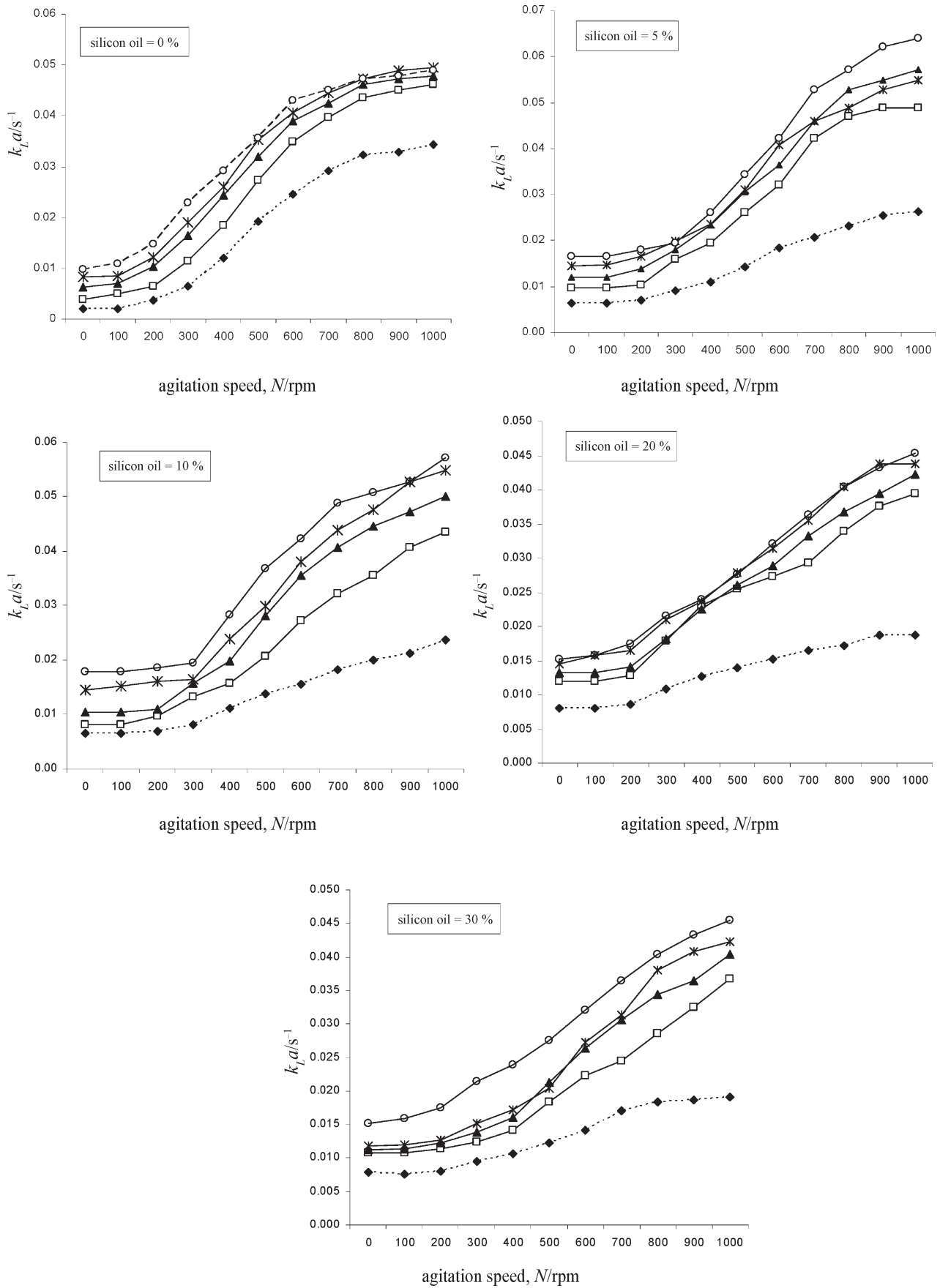


Fig. 3 – $k_L a$ as a function of agitation speeds (rpm) with flow rates of 1 to 5 $L min^{-1}$ adding different volume fraction of silicone oil (%) as organic phase (1 $L min^{-1}$ ---◆---, RT 2 $L min^{-1}$ —□—, 3 $L min^{-1}$ —▲—, 4 $L min^{-1}$ —*—, 5 $L min^{-1}$ —○—)

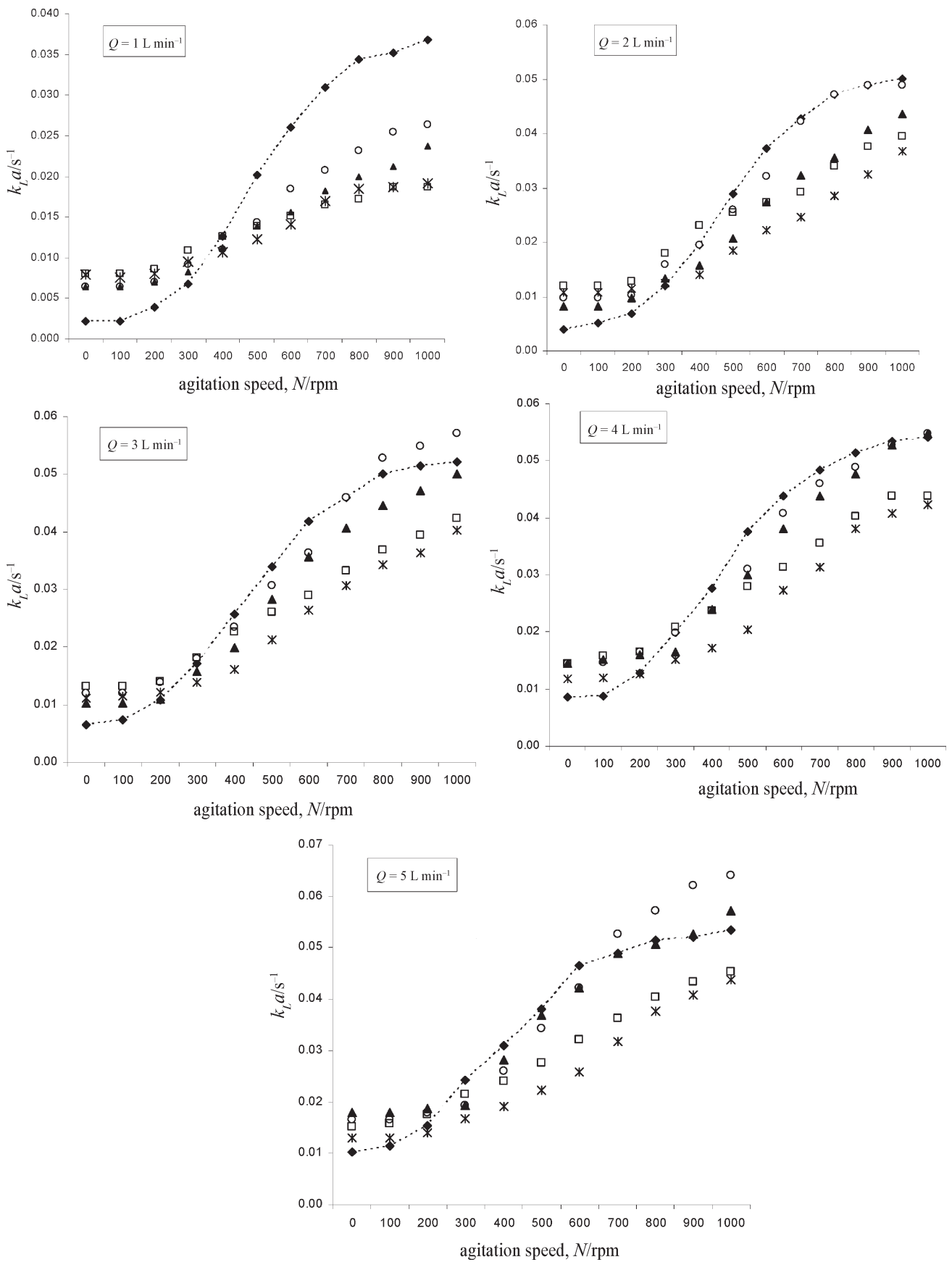


Fig. 4 – Performance comparisons of volume fraction of silicone oil (%) as organic phase from viewpoint of oxygen transfer at different flow rates (1 to 5 L min⁻¹). (---◆--- 0 %, ○ 5 %, ▲ 10 %, □ 20 %, * 30 %)

plies that the presence of silicone oil has caused a reduction in the $k_L a$ of the aqueous phase for all the concentrations studied. Reduction of $k_L a$ due to the presence of silicone oil augmented with increment of silicone oil fractions (Fig. 4). This behavior is in agreement with the results of Aldric *et al.*²⁶ This reduction in oxygen transfer could be explained by the decrease of oxygen diffusion through oil droplets partially occupying the liquid film around bubbles or by the decrease of the interfacial area.²² This mechanism of flux reduction can only be applied to high viscosity oils; for example, *n*-paraffin has a lower oxygen permeability than water.¹⁴ On the other hand, silicone oil has a good affinity to oxygen in aqueous media. So it can be regarded as an organic phase reservoir for the toxic substrates since the substrate concentration in the biotic phase can be maintained below the inhibitory level. The partition process itself is controlled by the mass transfer from organic to aqueous phase and afterwards by the subsequent metabolic activity of microorganisms.

Considering the oxygen transfer, the results of the present study are similar to the experimental values of $k_L a$ obtained by Aldric *et al.*, and Nielsen *et al.*^{15,26} At various operating conditions and organic phase proportion, the two studies have shown a reduction of $k_L a$ at higher organic phase proportions. Dumont *et al.* have shown that addition of silicone oils hinders oxygen transfer compared to air/water systems.²² Nevertheless their results have shown an interesting synergistic effect between an oil fraction of 10 % and a peripheral speed of 1.5 m s^{-1} leading to $k_L a$ values similar to those observed for an aqueous medium. Also, Quijano *et al.* found that the maximum overall oxygen transfer rate was observed with 10 % of silicone oil as organic phase in a stirred tank bioreactor.⁵ Dumont *et al.* found that the addition of silicone oil hinders oxygen transfer compared to an air–water system. They reported decreases in $k_L a$ of up to 25 %. They declared the addition of more than 5 % silicone oil should be beneficial to increase the oxygen transfer rate.¹⁸ In an another study, Dumont *et al.* confirmed his idea about the presence of silicone oil in air–water biological systems, however they reported that the addition of decane, hexadecane and perfluorocarbon PFC40 had no significant influence. They believed that the addition of a non-biodegradable organic solvent, acting as an oxygen reservoir and/or a substrate reservoir, improves the efficiency of bioprocesses.¹⁹ Guillermo Quijano *et al.* investigated solid and liquid vectors on the gaseous interfacial area and oxygen transfer rates in two-phase partitioning bioreactors, and found that mass transfer enhancements in TPPBs might correspond to an increase in gaseous interfacial area rather than to

the establishment of a high-performance gas/vector/water transfer pathway.²³ Jean M. A. *et al.* reported that the addition of 10 % of low viscosity silicone oil (9.35 Pa s) in the reactor does not significantly affect the oxygen transfer rate.¹⁴ Clarke reported that the influence of the presence of an organic phase on $k_L a$ was shown to be markedly dependent on the agitation speed in stirred bioreactors. They found that at agitation speeds below 800 rpm, the $k_L a$ in the presence of organic phase (alkane) was repressed below that in water. They obtained maximum $k_L a$ at an agitation speed between 1000 and 1200 rpm and an alkane concentration between 5 and 10 %.³⁸

In this study, at higher aeration rates (4 and 5 L min^{-1}) the values of $k_L a$ are similar to pure aqueous phase. Gas flow rate will also affect the $k_L a$ values of a bioreactor by changing the fractional gas hold-up and hence the gas-liquid interfacial area. Fig. 3 shows that with an increase in the gas flow rates, the $k_L a$ values increased.

Total power consumption

The results in Fig. 5 and Table 3 represent a decline in total power consumption with the addition of different proportions of silicone oil to bioreactor aqueous phase. This reduction in power input probably originates from diminution of surface tension of aqueous phase due to the presence of micro droplets of silicone oil as an organic immiscible phase. The trend of total power consumption declining with the addition of 10 % of silicone oil in bioreactor media is obvious from Fig. 5. However, for silicone oil volume fraction of 20 and 30 % there is a negligible difference in power input

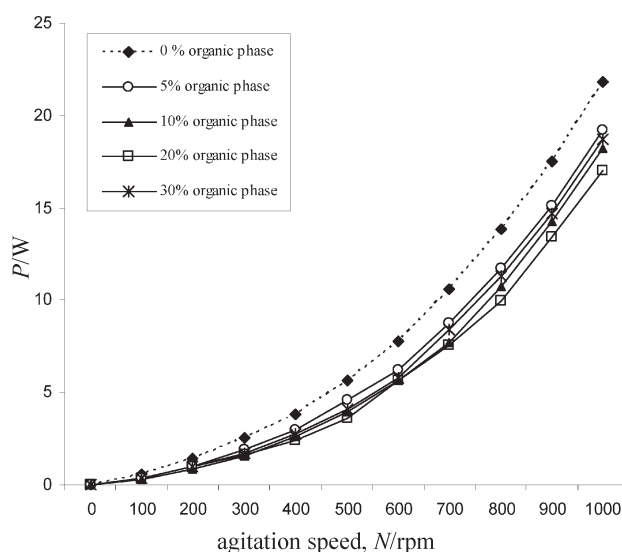


Fig. 5 – Total power consumption (P) as a function of agitation speed, N (rpm) with different volume fraction of silicone oil (%) as organic phase at flow rate of 2 L min^{-1}

Table 3 – Total power consumption in the presence of different fractions of silicone oil at several agitation speeds ($Q = 5 \text{ L min}^{-1}$)

Silicone oil (%)	Total power consumption (W m^{-3}) in different agitation speeds (rpm)									
	100	200	300	400	500	600	700	800	900	1000
0	325	786	1383	2061	2847	3824	5031	6400	8054	9898
5	203	569	976	1573	2237	3173	4271	5532	7078	8949
10	190	542	936	1464	2169	2929	4081	5207	6712	8407
20	203	515	1098	1627	2508	3417	4556	5966	7688	9492
30	190	542	1017	1627	2237	3092	4366	5641	7200	9220

compared with 10 %, and somehow at higher agitation speeds exceeds the 10 % fractional volume of silicone oil. Also, the findings in Table 3 demonstrate that with an increase in the agitation speed, total power consumption values were found to increase. Enhancement of total power consumption at agitation speeds limited up to 800 rpm seems reasonable and agrees with what Nielsen *et al.* reported (between 1 000 and 5 000 W m^{-3}). These energy requirements are acceptable from the viewpoint of scaling up.¹⁵ However, at higher impeller speeds (900 and 1000 rpm) the total power consumption increases noticeably (about 27 and 63 % respectively), nevertheless this over-consumption of power seems to be wasteful because it led to no improvement of $k_L a$. Therefore, it was found that the most optimal silicone oil fraction and agitation speed are 10 % and 300 to 800 rpm respectively, from the viewpoint of oxygen transfer and total power consumption rate.

Correlations

The constants obtained from the correlations of the measured and calculated $k_L a$ in the presence of different fractions of silicone oil are shown in Table 4. In all experiments, most of the correlation factor was systematically above 0.90 (r^2 : maximum 0.96; minimum 0.82; average 0.91 and Std. deviation 0.053). In Fig. 6, it can be seen that the experimental $k_L a$ turned out to lay within the values predicted. Enhancement of silicon oil volume fraction up to 10 %

display a regular trend in decline or growth of constants and exponents α , β and c in eq. (3) in a way that the increase in organic phase concentration in the bioreactor media, causes the α and c to raise or reduce exponent β . This implies that the addition of silicone oil enhances the influence of V_g and reduces the effect of P_g/V_L on oxygen transfer behavior of the bioreactor. This finding is in good agreement with Aldric *et al.*²⁶ In 20 and 30 % volume fractions of silicone oil the variations of constants α , β and c in eq. (2) seem vice versa, meaning that an increase in silicone oil concentrations lead to the decline of P_g/V_L and V_g on $k_L a$. Variations pattern in eq. (2) exponents reveal that the addition of silicone oil up to 10 % improve the superficial gas velocity that enhances $k_L a$ of oxygen and a greater proportion of silicone oil may have a negative effect.

Conclusions

In this study, initial characterization of the bioreactor involved quantification of the oxygen transfer coefficient as a function of agitation speeds and aeration rates in the presence of different fractions of silicone oil as organic immiscible phase. Considering the oxygen transfer, the results of the present study are similar to the results obtained by several researchers. The results presented here allowed a better understanding of multiphase mass transfer. It was found that $k_L a$ of oxygen decreased when the silicone oil fraction increased. The positive impact of agitation

Table 4 – Calculated constants and exponents of eq. (2) for 6 impeller configurations

Proportion of silicone oil (%)	Mass transfer coefficient correlation, exponents of eq. (2)			
	α	β	c	r^2
0	0.33	0.66	0.58	0.82
5	0.94	0.43	0.60	0.93
10	1.18	0.40	0.62	0.96
20	0.45	0.30	0.47	0.90
30	0.23	0.34	0.42	0.92

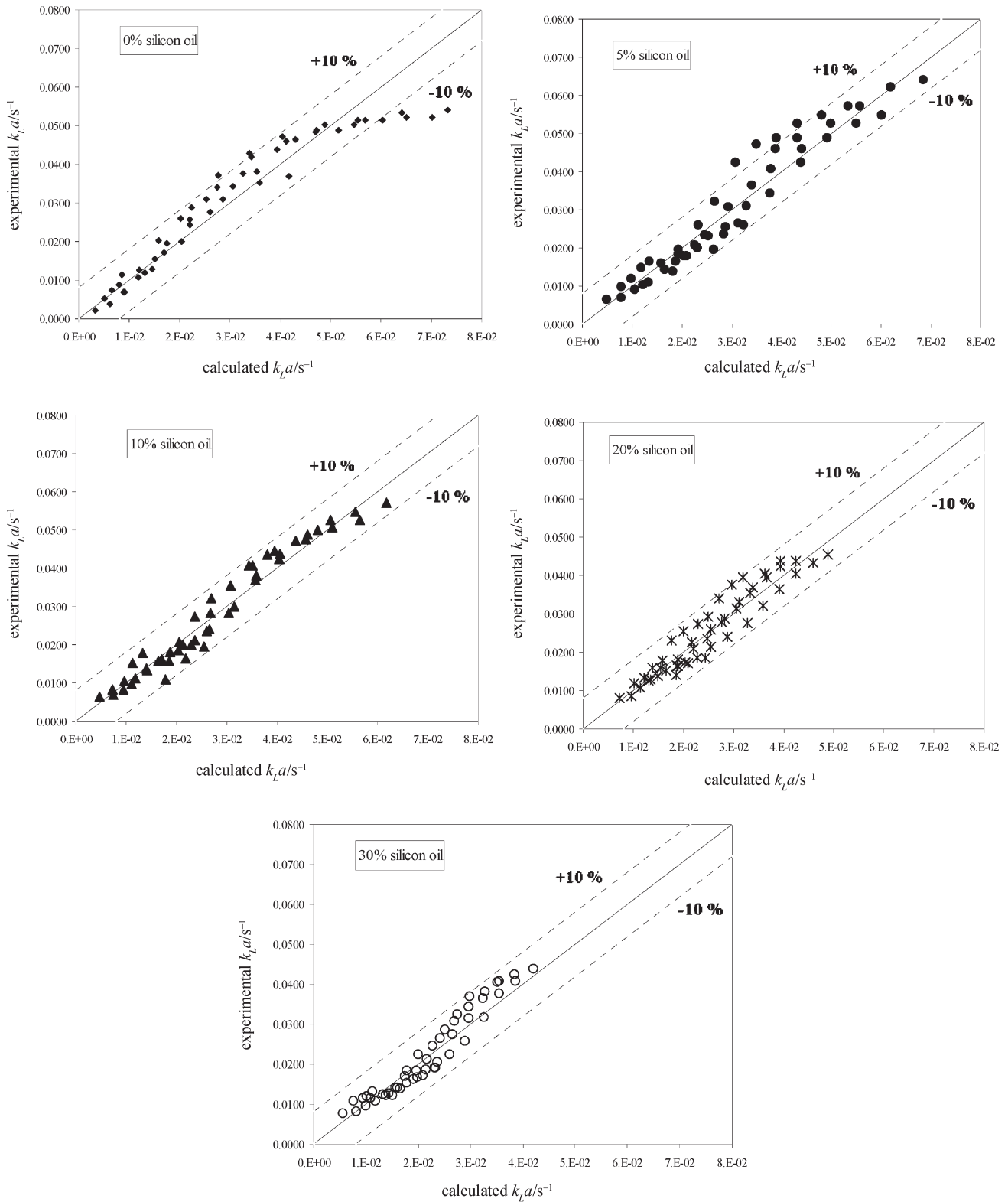


Fig. 6 – Correlations between the experimental and calculated values of $k_L a$ for different volume fraction of silicone oil (%) as organic phase, agitation speeds from 100 to 1000 rpm and aeration rates from 1 to 5 L min⁻¹

speed and gas flow on oxygen transfer was also observed in the presence of silicone oil, although their impact was somewhat reduced at higher silicone oil content. In addition, it was found that total power consumption declined in the presence of

different proportions of silicone oil in the aqueous phase. It was concluded that the most optimal silicone oil fraction and agitation speed were 10% and 300 to 800 rpm respectively, from the viewpoint of oxygen transfer and total power consumption rate.

Empirical correlations for the oxygen transfer rate in the bioreactor in the presence of different fractions of silicone oil revealed that the experimental $k_L a$ lay within the predicted values. Variations pattern in exponents of the equations showed that the addition of silicone oil up to 10 % improved the superficial gas velocity, which enhanced the $k_L a$ of oxygen, and higher silicone oil fractions may have a negative effect.

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Nomenclature

- α, β, c – exponents in eq. (3)
 C – oxygen concentration, mg L⁻¹
 C^* – saturation concentration of oxygen, mg L⁻¹
 D – impeller diameter, cm
 T_i – bioreactor internal diameter, cm
 T_e – bioreactor external diameter, cm
 h_1 – distance between impellers, cm
 H – bioreactor height, cm
 $k_L a$ – volumetric oxygen transfer coefficient, s⁻¹
 D_i – impeller diameter, cm
 w_i – impeller blade width, cm
 h_i – impeller blade height, cm
 N – impeller rotation speed, rpm
 P – total power consumption for mixing of non-aerated, W
 P_g – total power consumption for mixing of aerated, W
 Q – volumetric air flow rate, L min⁻¹
 P_g/V_L – specific power input, W L⁻¹
 w_b – baffle width, cm
 V_g – superficial gas velocity, m s⁻¹
 t – time, s
 V_L – volume of the liquid in the vessel, L

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