Journal of Industrial Technology 15 (1), 2006, 23-34

THE SIGNIFICANCE OF HYDRODYNAMICS DIFFERENCE BETWEEN RUSHTON TURBINE AND MARINE IMPELLER ON THE K_LA IN A 16-LITRE BIOREACTOR

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RINGKASAN : *Kajian kesan ke atas perbezaan hidrodinamik yang ketara yang dihasilkan oleh pengaduk turbin Rushton dan marin terhadap k_La di dalam bioreaktor 16 liter telah dilakukan. Melakukan teknik penyingkiran gas secara statik, nilai-nilai k_La telah dihitung pada set kelajuan putaran pengaduk dan kadar alir udara yang berbeza, dan pada pelbagai kelikatan dan suhu. Korelasi empirikal telah digunakan untuk mengkaji kebergantungan k_La terhadap kuasa masukan tentu dan halaju gas luaran. Keputusan-keputusan eksperimen menunjukkan bahawa pengaduk turbin Rushton adalah lebih berkesan dalam penyebaran gas dan memberikan kadar pemindahan oksigen yang lebih tinggi daripada pengaduk marin.*

ABSTRACT : An investigation on the significance of hydrodynamic difference between Rushton and marine impeller on the k_La in the 16-litre bioreactor was performed. By employing the static gassing out technique, the k_La values were calculated at different sets of impeller speeds and air flow rates, and at various viscosities and temperatures. The empirical correlation was employed to investigate the dependence of k_La on the specific power input and superficial air velocity. Our experimental results discovered that the Rushton turbine was more effective in gas distribution and provided a greater oxygen transfer rate than the marine impeller.

KEYWORDS : Empirical relationship, stirred bioreactor, marine impeller, Rushton turbine, oxygen transfer coefficient

INTRODUCTION

In aerobic fermentations, sufficient supply of oxygen to the microorganisms is very crucial. Oxygen in the air is sparingly soluble in the water (i.e. 10 ppm at 1 atm) and its transfer rate is always limited particularly through the gas-liquid interfaces (Bailey and Ollis, 1986). The limited solubility of oxygen in water is a physical constraint on bioreactor aerobic operation. This problem becomes worse especially in the larger scales since maintaining such homogeneous environment is no longer easy due to increased mixing time. The consequent anaerobic conditions result in lower fermentation performance and yields. Systematic engineering approaches to tackle this problem have been reported (Arjunwadkar *et al.*, 1998; Badino Jr *et al.*, 2001, Cooper *et al.*, 1944). The oxygen transfer capacity in a bioreactor depends on the mechanical design and geometry of the air distributor, bioreactor aspect ratio, impeller type, and the agitation rate. All of them can be related to the oxygen transfer coefficient or the k_La. Cooper and his co-workers (1944) proposed that the k_La may be empirically linked to the gassed power consumption per unit volume of broth (P_g/V_L) and the superficial air velocity (v_g) as described by the following equation.

$$k_La = a' \left(\frac{P_g}{V_L} \right)^b (v_g)^c \qquad (1)$$

In this equation, the values of the constants *b* and *c* may vary considerably, depending on the bioreactor geometry and operating conditions. Data in Table 1 summarise the values of constant *b* and *c* from several works. Constant *b* represents the level of dependence of k_La on the agitation, while, constant *c* represents the level of dependence of k_La on the sparging rate applied to the system.

Table 1. Values of parameter *b* and *c* from several works estimated from the empirical relationship proposed by Cooper *et al.* (1944)

Author	Constant b	Constant c	Type of impeller	Liquid Model	Liquid Volume
Cooper *et al.* (1944)	0.95	0.67	N/A	Air-water system	66 L
Shukla *et al.* (2001)	0.68	0.58	Disc turbine and pitched blade turbine	Air-water system	5.125 L
Badino Jr. *et al.* (2001)	0.47	0.39	Flat-blade disc style turbine	Aspergillus fermented broth	10 L
Martinov & Vlaev (2002)	0.82	0.4	Narcissus blade	Xanthan gum solution	50 L
Arjunwadkar *et al.* (1998)	0.68	0.4	Disc turbine and pitched blade turbine	(0.7% w/v) CMC solution	5.125 L

In literature reported by Geankoplis (1993) and Martinov & Vlaev (2002), it was discovered that the marine impeller provided a better bulk mixing, but gave low mixing power. On the other hand, Rushton turbine provided a better mixing power but resulted in compartmentalisation problem. Despite these observations, determining the overall impact of Rushton and marine impeller on the k_La needs to be investigated. The aim of this work was to investigate the significance of hydrodynamic difference between Rushton turbine and marine impeller on the oxygen transfer in 16 litre bioreactor. By employing the empirical equation introduced by Cooper *et al.* (1944), the dependence of k_La on superficial air velocity and volumetric gassed power input in 16 litre bioreactor using Rushton turbine and marine impeller is investigated. The constant *b* and *c* in the Cooper *et al.* (1944) correlation is graphically determined and compared with other published data.

MATERIALS AND METHODS

Bioreactor dimensions and Operating Conditions

The dimensions of bioreactor are summarised in Table 2.

Table 2. Dimensions of 16 litre bioreactor

Total volume	$0.016\ m^3$	Impeller type	Rushton turbine	Marine impeller
Working volume	$0.01\ m^3$			
Vessel height, H_T	0.507 m	Number of impellers	2	1
Liquid height	0.393 m	Impeller diameter, D_i	70 mm	70 mm
Vessel diameter, D^T	0.2 m	Impeller thickness	3 mm	3 mm
Surface area	$0.0005\ m^2$	Impeller width	14 mm	N/A
		Ratio D_i/D_T	0.35	0.4
Sparger diameter, D_S	0.095 m	Top impeller distance from top plate, Δ_i	0.26 m	0.2535 m
Sparger distance from impeller	0.055 m			
		Spacing between impeller, Δ_C	0.155 m	
Baffles	Yes			

Based on the previous works as summarised in Table 3, the operating variables for the experiment in 16 litre bioreactor were determined.

Table 3. Operating conditions and techniques to determine the oxygen transfer coefficient (k_La) reported in several works

Author	Impeller speed	Air flow rate	Technique Used
Shukla *et al.* (2001)	50 - 300 rpm	0.293 - 1.56 vvm	Dynamic
Badino Jr. *et al.* (2001)	300 - 700 rpm	0.2 - 1 vvm	Modified dynamic
Martinov & Vlaev (2002)	$0.1 < P_g/V_L < 2$ kW m^{-3}	$3.3 \times 10^{-3} < v_g < 6.6 \times 10^{-3}$ ms^{-1}	Static
Arjunwadkar *et al.* (1998)	400 - 750 rpm	0.29 - 0.975 vvm	Dynamic

The operating variables for the experimental work in 16 litre scale is given in Table 4. For each combination of impeller speeds and air flow rates, the experiments were performed on distilled water at temperature of 30°C, 40°C and at 50°C. The pH was set at 7 ±0.03 for the entire experiment. The liquid viscosity was increased by dissolving the carboxy methyl cellulose to obtain concentrations of 0.25%(w/v), 0.5%(w/v) and 1%(w/v) at 30°C. The experiment was repeated by using the marine impeller for comparison.

Table 4. Operating variables at 16 litre bioreactor

Scale	Impeller speeds, N	Air flow rates, Q	Liquid model	Impeller type
16 liter	200 - 1000 rpm	3 - 15 l/min	Water & CMC	Rushton turbine
16 liter	200 - 1000 rpm	3 - 15 l/min	Water & CMC	Marine impeller

Determination of the k_La

The rate of oxygen transfer from air bubbles to liquid in a batch stirred bioreactor was given by the following relationship.

$$\frac{dC_L}{dt} = k_La\ (C^* - C_L) \qquad (2)$$

Where C_L represents the dissolved oxygen concentration (mg/L), C^* represents the dissolved oxygen concentration in equilibrium with oxygen concentration in the gas phase (mg/L), t represents the time (s) and k_La represents the oxygen transfer coefficient (s^{-1}).

The oxygen transfer rate (OTR) was determined by 'the static gassing out' method (Stanbury and Whitaker, 1984). The change in dissolved oxygen concentration (C_L) in the liquid phase was detected by using a polarographic oxygen probe attached to the bottom of the bioreactor (Bioengineering^{TM}). At different combinations of airflow rates and stirrer speeds as described earlier, the dissolved oxygen concentration (C_L) profile with respect to time was plotted. To calculate the k_La, Equation 2 was firstly integrated with respect to the time taken for the oxygen concentration to reach the saturation level from the lowest point.

$$t = \left[\frac{1}{k_La}\right] ln \left[\frac{C^* - C^0_L}{C^* - C_L}\right] \quad (3)$$

Where the C^o_L represents the initial (at time zero) dissolved oxygen concentration (mg/L). The k_La was then determined by reciprocating the slope obtained from the semi logarithmic plot of time (t) versus $\left[\frac{C^* - C^0}{C^* - C_L}\right]$. The dissolved oxygen saturation concentration in the liquid or C^* calculated from Henry's Law was quoted from the Table (Perry and Green, 1997).

Power Consumption

The ungassed power consumption (P_o) was determined from the plot power number (N_p) versus Reynolds number (N_{RE}) for both Newtonian and non-Newtonian fluid in a different type of flow regime (Rushton *et al.*, 1950). The power number, N_p is:

$$\left[\frac{P_o}{\rho_L N^3 D_i^5}\right] = N_p \quad (4)$$

Whilst the Reynolds number, N_{RE} is given as:

$$N_{RE} = \left[\frac{N D_i^2 \rho_L}{\mu_L}\right] \quad (5)$$

The gassed power consumption (P_g) was estimated through a correlation proposed by Michel and Miller (1962).

$$P_g = m\left[\frac{P_o^2 N D_i^3}{Q^{0.56}}\right] \quad (6)$$

Where N represents the impeller speed (rpm), Q represents the air flow rate (l/min), μ_L represents the liquid viscosity (kg/m.s) and ρ_L represents the liquid density (kg/m^3). Constant *m* depends on the impeller geometry. In this case, the value of constant *m* is 0.832 for both Rushton and marine impeller (Badino Jr. *et al.*, 2001).

Oswald-de Waele Model

The behaviour of pseudoplastic fluid has been successfully investigated by Garcia-Ochoa *et al.* (2000), Martinov and Vlaev (2002), and Shukla *et al.* (2001). Their work described the flow behaviour and determined the power-law quantities by employing the Oswald-de Waele model via Equation 7.

$$\tau = k\gamma^n \qquad (7)$$

Metzner and Otto (1962) suggested that the effective shear rate of the liquid may be determined according to the following equation.

$$\gamma = AN \qquad (8)$$

And the apparent viscosity as:

$$\mu_{app} = k\,[AN]^{n-1} \qquad (8)$$

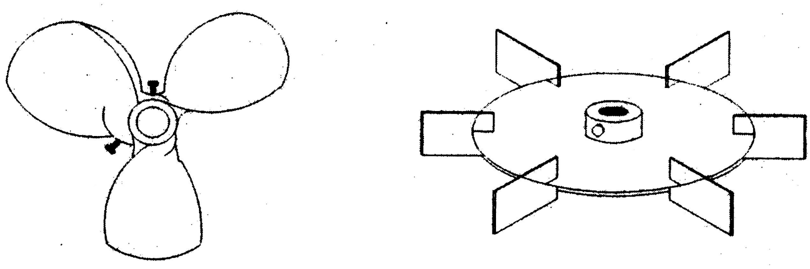
Where τ represents the shear stress (N/m2), γ represents the shear rate (s-1), *k* represents the consistency index in power-law model (Pa.s^n), *n* represents the dimensionless flow behaviour index and μ_{app} represents the apparent liquid viscosity (Pa.s). The parameter (value of A) in Meztner-Otto's equation is based on the type of impeller used. The value of A for turbine stirrer type value was assumed 11.5 (Garcia-Ochoa *et al.*, 2000) and 10, for marine impeller (Nagata, 1975). Table 5 shows the viscometric parameters of the model fluid employed.

Table 5. Viscometric data and power-law quantities for CMC solutions

CMC concentrations	Consistency index, k (Pa.s^n) x 10^3	Flow behaviour index, n
0.25%(w/v)	6.16	0.7654
0.5%(w/v)	14.6	0.8825
1%(w/v)	53.9	0.9501

RESULTS AND DISCUSSION

Investigation was performed on the significance of hydrodynamic difference between Rushton and marine impellers on the oxygen transfer rate in 16 litre bioreactor at the various operational conditions. At different viscosities and temperatures, the impeller speed was varied from 200 to 1000 rpm at constant aeration rate of 0.9 vvm and the air flow rate was varied from 0.3 to 1.5 vvm under constant agitation at 600 rpm. Two different types of impeller (refer Figure 1) show a resemblance in the dependence of k_La on the superficial air velocity and similar effect was also achieved on the increasing of temperatures and viscosities. However, a significant difference in the dependence of k_La on the volumetric gassed power input and difference in mixing capacity was observed between the Rushton and marine impellers.



(a) (b)

Figure 1. *Type of agitator (a) Marine impeller (b) Rushton turbine*

As illustrated on the logarithmic plots in Figure 2, 3, 4 and 5, it is evident from the results that the oxygen transfer coefficient, k_La was a strong function of the agitation and airflow rate. The increase of the k_La due to the agitation and sparging was due to the decrease of bubble size and subsequently led to the increase of the specific interfacial area resulting in higher interfacial contact between the gaseous and liquid phase for the oxygen transfer. Most importantly, higher agitation provides a better oxygen transfer because its decreases the thickness of the gas liquid film at the gas-liquid interface by creating turbulence in the culture. However, a deviation from the trend in the dependence of k_La on superficial air velocity for the marine impeller experiments was observed. Nevertheless, similar behaviour on the linear dependence of k_La on the agitation and aeration rates was seen for both Rushton and marine impellers.

Increase of temperature will improve the oxygen transfer rate and reduce the oxygen solubility. Oxygen solubility in water decreases from 7.55 mg/L to 5.61 mg/L as the temperature is increased from 30°C to 50°C. Although the oxygen solubility significantly decreases at higher temperature, the net increase of the k_La observed in this experiment was due to the improved oxygen transfer through a series of transport resistances between the bubbles and the liquid. The strong influence of broth viscosities on the k_La is illustrated in Figure 2, 3, 4 and 5. The decrease in k_La was caused by an increase of broth apparent viscosities from 0.00081 Pa.s to 0.035 Pa.s. Identical results were obtained for both Rushton and marine impeller. The increased pseudoplastic behaviour of the liquid significantly altered the mechanical property of the liquid. Consequently, lower Reynolds number (i.e. lower mixing level or lower turbulence) in the viscous liquid in comparison to Newtonian liquid at the same agitation and airflow rate was obtained. It is also believed that the accumulation of the polymers (CMC) at the gas-liquid interface may be responsible for the increase of the oxygen transfer resistance from the air bubbles to the liquid. In general, introducing polymer into the liquid will suppress the turbulence and increase the oxygen transfer resistance. In correlating the k_La values with the operating parameter; namely volumetric power consumption and superficial velocity, it was found that the k_La values attained was consistent with that found in the literature by Arjunwadkar *et al.* (1998), Shukla *et al.* (2001) and Martinov and Vlaev (2002).

The trends in Figure 2 and 3 show that the k_La increase as the specific power input increases. It is evidently shown that the Rushton turbine provided a greater oxygen transfer rate compared to that of marine impeller. In order to reach $k_La \sim 0.0073\ s^{-1}$ in air-water system at 30°C, marine impeller requires 22.4 Wm^{-3} while Rushton turbine requires 12.7 Wm^{-3}. On the other hand, to reach $k_La \sim 0.0093\ s^{-1}$ in strong pseudoplastic fluid the values are 461 Wm^{-3} and 227 Wm^{-3} for the marine impeller and Rushton turbine, respectively (see Figure 2 and 3). Consequently, the same oxygen transfer rate was obtained by the Rushton turbine at lower power consumption. However, the power required for the marine impeller to provide the same agitation and aeration rates was much lower compared to the Rushton turbine. The measured volumetric power consumption for marine and Rushton impeller was in the range of 0.002 kW/m^3 to 0.5 kW/m^3 and from 0.01 kW/m^3 to 2 kW/m^3 respectively. As illustrated in the power curve reported by Aiba *et al.* (1973), power provided by Rushton turbine is 5 times higher than the marine impeller. Under the same Reynolds number, Rushton turbine offer better local mixing and a greater k_La than the marine impeller. This fact may look strange on the general conclusion that equal power per unit volume and superficial gas velocity leads to the same k_La regardless of the impeller type (Geankoplis, 1993).

Different flow pattern by Rushton and marine impellers significantly affects the mixing capacity and k_La in the bioreactor. Radial flow pattern by the Rushton turbine drives the liquid radially from the impeller causing a compartmentalisation problem when strong pseudoplastic fluids are introduced into the liquid which results in a development of stagnant zones away from the impellers. The axial-flow pattern created by the marine impeller produced a higher turbulence compared to the Rushton turbine at the same agitation rates. Under this condition, a better bulk mixing with a significant energy saving is in favour of marine impeller. A larger diameter of marine impeller would give better bulk mixing, however, Rushton turbine are preferable for breaking up gas bubbles and promoting oxygen transfer to the liquid. This will favour turbulent mixing over bulk mixing and significantly increase the k_La values in the bioreactor. Although liquid phase mixing is crucial, the effect of agitation rate on k_La values was also due to the shearing and dispersing of gas bubbles, which leads to an increase of k_La and contact times. The results attained concur with several authors, i.e. Shukla *et al.* (2001), Badino Jr. *et al.* (2001) and Arjunwadkar *et al.* (1998).

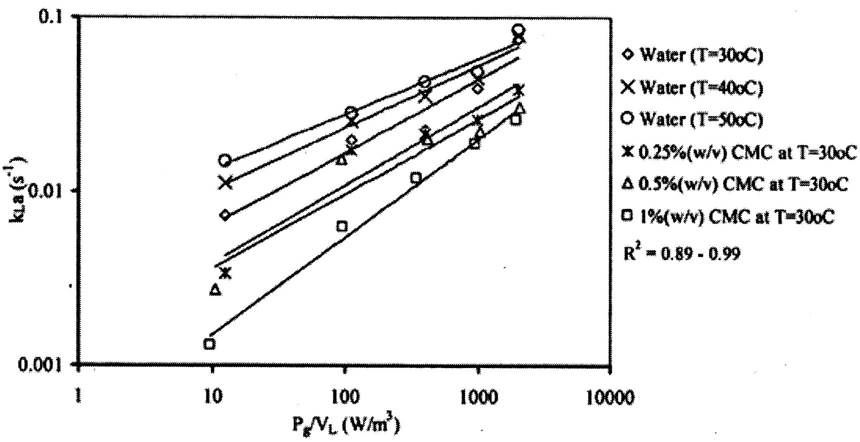


Figure 2. *Dependence of k_La on volumetric power consumption, P_g / V_L at different temperatures and viscosities for Rushton turbine*

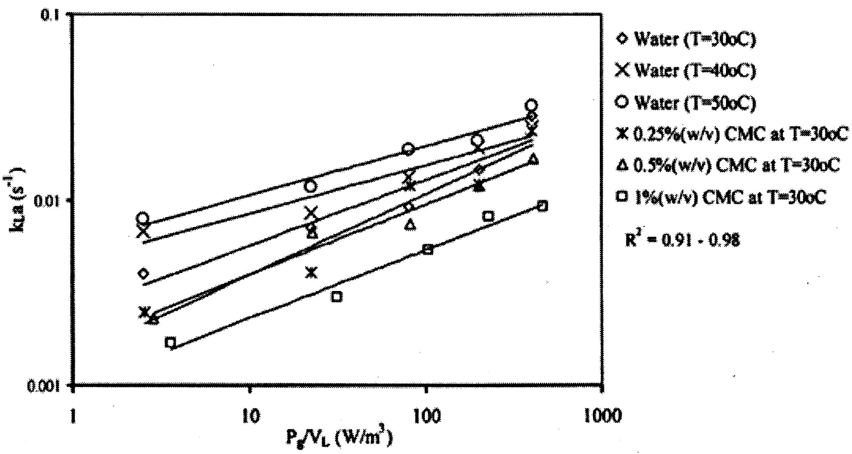


Figure 3. *Dependence of k_La on volumetric power consumption, P_g / V_L at different temperatures and viscosities for Marine impeller*

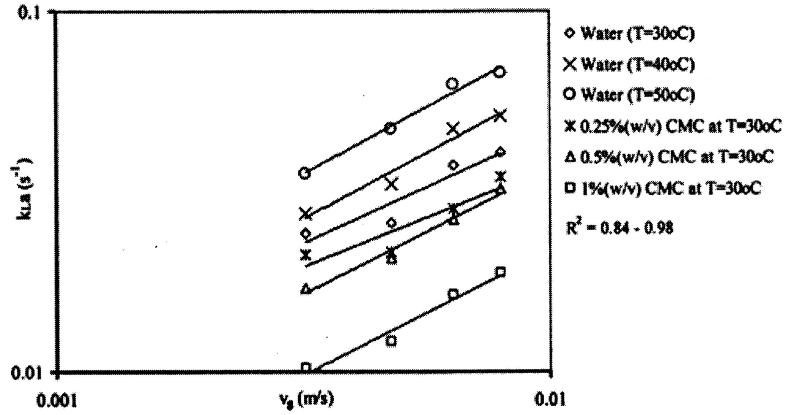


Figure 4. *Dependence of k_La on superficial air velocity, v_g at different temperatures and viscosities for Rushton turbine*

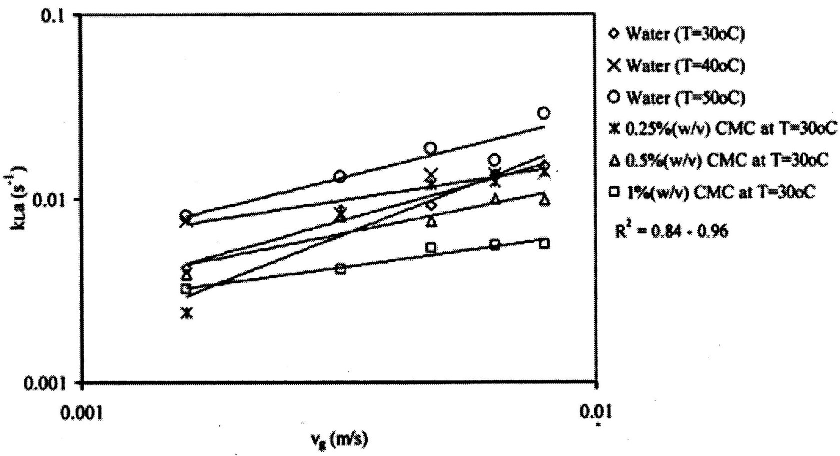


Figure 5. *Dependence of k_La on superficial air velocity, v_g at different temperatures and viscosities for Marine impeller*

The straight-line trend (indicated by excellent regression coefficients) of the k_La with respect to the operating variable values in Figures 2, 3, 4 and 5 signifies that our experimental work matched with the published results and agreed well with the empirical relationship developed by Cooper *et al.* (1944). The parameter estimates (constant *b* and *c*) as shown in Table 6, reflect the influence of volumetric power consumption and superficial air velocity on k_La. Constant *b* is the slope of the graph at constant air flow rate. The magnitude of *b* represents the level of dependence of k_La on the agitation. Constant *c* is the slope of the graph at constant agitation speed. The magnitude of c represents the level of dependence of k_La on the sparging rate applied to the system. These values are tested for specific power consumption within range from 0.01 to 2 kW/m^3 and 0.002 to 0.5 kW/m^3 for Rushton and marine impellers respectively. The operating variables were correlated at corresponding ranges of superficial air velocity of 1.5 x 10^{-3} to 8 x 10^{-3} and at apparent viscosity of 0.00081 to 0.035 Pa.s for Rushton and Marine impellers.

Table 6. Comparison of experimental values of constant *b* and *c* between Rushton turbine and Marine impeller

Liquid system	Temperature (°C)	Constant *b*		Constant *c*	
		Marine Impeller	Rushton Turbine	Marine Impeller	Rushton Turbine
Water-air	30	0.356	0.420	0.773	0.406
	40	0.261	0.356	0.427	0.501
	50	0.266	0.318	0.693	0.605
Water-air	30	0.356	0.420	0.773	0.406
0.25%(w/v) CMC - air	30	0.439	0.450	1.084	0.278
0.5%(w/v) CMC - air	30	0.381	0.431	0.555	0.485
1%(w/v) CMC - air	30	0.368	0.563	0.375	0.626

CONCLUSIONS

The changes of k_La due to agitation by Rushton turbine impeller was more pronounced in comparison to the marine one. On the other hand, the effect of sparging rate on k_La was more dominant in the marine system in comparison to the turbine. Hence, the significance of hydrodynamic difference between Rushton turbine and marine impeller on the oxygen transfer rate in 16 litre bioreactor was successfully confirmed.

ACKNOWLEDGEMENTS

We would like to record our thanks to Mohd Sabri Sethpa and Nor Zalina Othman of the Chemical Engineering Pilot Plant (CEPP), Universiti Teknologi Malaysia for their significant contribution in this research.

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