Oxygen Mass Transfer Coefficient and Power Consumption in a Conventional Stirred-Tank Bioreactor Using Different Impellers in a Non-Newtonian Fluid: An Experimental Approach

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ABSTRACT: *In this study, we investigated the power consumption and volumetric mass transfer characteristics in an un-baffled stirred-tank bioreactor using a non-Newtonian fluid and different impellers. The impellers studied were a Rushton turbine impeller, a paddle impeller, a marine impeller, a segmented impeller, and, an elephant ear impeller. Studies were performed over a wide range of agitation speeds (0–2000 rpm) and aeration (0.1–0.3 vvm). The effects of superficial gas velocity, impeller speed, power input, and liquid viscosity were studied as significant factors for* K_La *and power input estimation. The Rushton turbine impeller was found to be the most efficient in achieving higher* K_La *(0.015* min^{-1}*) even at lower agitation and aeration rates compared to other impellers. The trend of* K_La *was found to be similar for axial flow generating impellers. Correlations were derived for all the impellers at different superficial gas velocities (Vg) and gassed power per volume (Pg/V), and a correlation coefficient* $R^2>0.99$ *was achieved in all the cases. The power drawn by the impellers was tested, and maximum power consumption was observed using the Ruston impeller (198.04W), followed by the paddle impeller (152.3W). However, under aerated conditions, the power consumption was lowered by 25–35% in all the cases. The power input ratio (Pg/Po) was found to be in the range of 0.35–0.61 for all the impellers studied. The power number (Np) was estimated and the results were found to be comparable with earlier studies. Thus, the present study gives more insight into the performance of different impellers and will be helpful in process development.*

KEYWORDS: *Volumetric mass transfer; Power consumption; Impellers; Power number.*

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INTRODUCTION

Estimating the volumetric mass transfer coefficient (K_La) is an important study parameter during process development and scale-up in bioreactors. Mass transfer in bioreactors depends on various factors, such as the type of impeller, the impeller speed, the superficial gas velocity, and the viscosity of the broth [1]. The broth produced in an aerobic bioprocess shows non-Newtonian behaviors. This fluid pattern has a significant effect on volumetric mass transfer, mixing time, and power requirement inside the bioreactor [2]. This situation can be mitigated by increasing the impeller speed (N) and/or gas flow rate (Q). The rheological properties of the broth can impede efficient mass transfer [3] which causes temporary depletion or low oxygen levels in the culture, leading to cell damage and lowered product yield [4].

Various correlations were cited in the literature for estimating the K_La in non-Newtonian fluids [5]. However, the studies were performed with a Rushton turbine impeller and pitched-blade impeller, either as a single-or multi-impeller system [6]. The present study aimed to estimate the K_La in a non-Newtonian fluid using different impellers, such as the Rushton turbine, elephant ear, marine impeller, paddle impeller, and segmented impeller (Fig. 1a,b,c,d,e). The estimated K_La value for different impellers was fitted in the correlation developed by *Cooper et al.* [7].

$$K L a = \alpha \left(\frac{P g}{V} \right) \beta\, V_g\, \gamma \tag{1}$$

Where Pg is the mechanical agitation power (W), V = liquid volume (m^3), Vg = gas superficial velocity (m/s), α = is a constant, β and γ are exponents.

The second significant parameter in the design process is power consumption. The major power consumer in the bioprocess is the mixing system- agitator. Hence, the industry must be aware of the power consumption involved in order to minimize the expenditure of energy [8,9]. In the case of a shear-sensitive culture, the hydrodynamic stress generated by the power input may affect growth and productivity [10-12]. Most studies on power consumption have used standard impellers, like the Rushton turbine and pitch-blade impellers [13-18]. The aim of this study was to determine the power consumption by using different types of impellers and also the mass transfer characteristic for each impeller. The most suitable type can be used for process development in the biopharmaceutical industry.

EXPERIMENTAL SECTION

Materials and Methods.

Bioreactor configuration

The study was performed in a commercially available stir-tank bioreactor (5 L) (Sartorius, Germany). The un-baffled bioreactor had a tank diameter, (T) of 0.160 m and a tank height (H) of 0.32 m and was equipped with a dual impeller system. Five different types of impellers were used in this study: a Rushton turbine (Di = 0.064 m), a marine impeller (Di = 0.072 m), an elephant ear impeller (Di = 0.078 m), a paddle impeller (Di = 0.080 m), and a segmented impeller (Di = 0.072 m). Gasses were introduced into the bioreactor by using a stainless-steel ring sparger (diameter of drilled holes 1.0 mm).

Fluids

The viscosity of the cell culture broth was determined by using a viscometer (Bohlin Visco88 and TA-instruments AR2000) fitted with a coquette configuration. Additionally, carboxy methyl cellulose (Sigma, C5678) was added to water to make a solution with rheological properties similar to the cell culture broth, with a power-law index (n) = of 0.260 and a consistency index (K) = of 1.25 Pas^n. This solution was used as the non-Newtonian fluid for all the experiments.

Experimental determination of the K_La

The determination of the overall volumetric mass-transfer coefficient value of a bioreactor is essential to establish its aeration efficiency and to quantify the effect of operating variables on the provision of oxygen. The K_La estimation was done by following the static gassing-out method. The non-Newtonian fluid was deoxygenated by sparging nitrogen gas until the dissolved oxygen level reached below 5% saturation. The variation in the dissolved oxygen concentration, (C_L) in the liquid phase was detected using an oxygen probe. The dissolved oxygen concentration in the bioreactor liquid phase was measured by means of an oxygen probe inserted vertically and placed at 2 cm under the liquid level, the DO probe was fitted with a Teflon membrane and with an electrolytic solution of Na_3PO_4 in the cell. The oxygen probe signals were measured using an A/D converter and a recorder on a PC.

Table 1: Summary of the experimental details of the impellers investigated.

Impeller type	Impeller Diameter, Di (m)	Tank diameter, T (m)	Di/T	Angle of blades (°)	Reynolds number (N_{RE})
Rushton Turbine	0.064	0.160	0.40	90	461-9204
Marine	0.072	0.160	0.45	30	582-11,649
Paddle	0.080	0.160	0.50	45	719-14,382
Elephant ear	0.078	0.160	0.48	45	684-13,672
Segmented	0.072	0.160	0.45	30	582-11,649

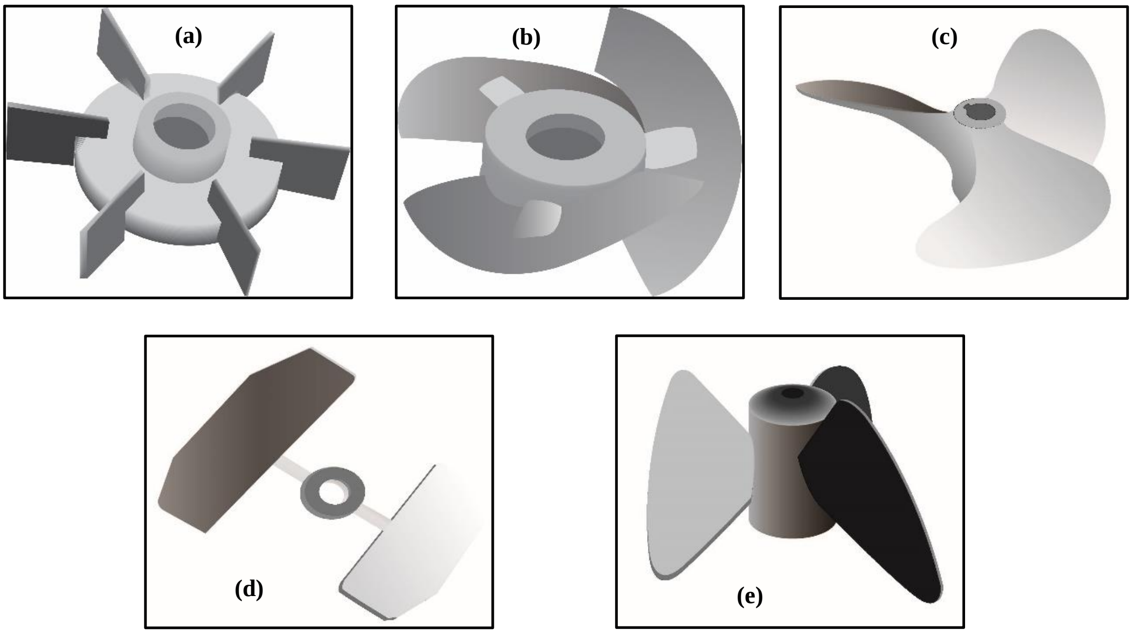

Fig. 1: Schematic view of the five different types of impellers: a: Rushton turbine impeller, b: Segmented impeller, c: Marine impeller, d: Paddle impeller, e: Elephant ear impeller.

After that, the nitrogen gas flow was turned off and the flow switched to the airflow with a specific volumetric flow rate using the rotameter. Then the dissolved oxygen concentration was recorded with respect to time as the air was distributed into the bioreactor until the water became saturated with oxygen. The dissolved oxygen was monitored until saturation, C* was reached. Gas composition was constant. The system was isothermal, and the effect of the dynamics of the dissolved oxygen electrode was negligible.

The rate of oxygen transfer from gas to liquid phase was given by the empirical relationship [19].

$$dCL/dt = K_L a\left(C^* - C_L\right) \tag{2}$$

Where C is the oxygen concentration, dC/dt is the accumulation oxygen rate in the liquid phase, C* is the equilibrium dissolved oxygen concentration.

The K_La values were calculated from the slope of the plot of ln ($C^*–C_L$) versus time, t. K_La was estimated in triplicates with Reynolds number for individual impeller described in table 1 and gas flow rate ranging from 0.025 to 0.25 vvm.

Measurement of Power Consumption

Consumed power by different impellers was calculated by the torque measurement; from the impeller shaft [20,21] using a torque meter Cosefeld Viscomix unit (Cosefeld, Germany). Power is related to torque by the equation.

Table 2: Correlations derived for different impellers at different gassing rates and power measurements.

Impeller Type	Proposed correlation
Rushton Turbine	$K_La = 0.900\,(Pg/V)^{0.324}\,(Vg)^{0.631}$ $(R^2 = 0.999)$
Segmented Impeller	$K_La = 0.847\,(Pg/V)^{0.294}\,(Vg)^{0.560}$ $(R^2 = 0.997)$
Paddle Impeller	$K_La = 0.254\,(Pg/V)^{0.161}\,(Vg)^{0.484}$ $(R^2 = 0.993)$
Elephant ear Impeller	$K_La = 0.730\,(Pg/V)^{0.245}\,(Vg)^{0.514}$ $(R^2 = 0.998)$
Marine Impeller	$K_La = 0.556\,(Pg/V)^{0.297}\,(Vg)^{0.491}$ $(R^2 = 0.996)$

$$P = 2\pi M N i \qquad (3)$$

Where P is power, Ni is impeller speed, and M is the torque on the impeller shaft.

The torque was estimated for a range of impeller speed covering a range of Reynolds numbers from 1000 to 12500. Power can also be estimated by using the impeller power number.

$$P = \rho N \rho N i^3 D i^5 \qquad (4)$$

Where ρ is the density and Np is the power number of the impeller.

Equating (3) and (4) helps in the estimation of power from measured torque.

Under aerated conditions, power consumption Pg was estimated by the equation

$$P g = 2\pi M g N i \qquad (5)$$

Aeration rate of 0.1, 0.2, and 0.3vvm was tested for all the impellers.

RESULTS AND DISCUSSION

To evaluate the optimal conditions of the bioreactor, the effect of oxygen mass transfer rate in several operational conditions including different types of impellers in various agitation and aeration rates was tested.

K_La estimation for different impellers (Effect of Pg/V and Vg on K_La)

In the present study, K_La values for different impellers were correlated with (Pg/V) and (Vg), Equation (1). The experimental data varied in the range of 0.0076–0.0184 min^{-1} for the paddle impeller, 0.008–0.050 min^{-1} for the segmented impeller, 0.01–0.0612 min^{-1} for the Rushton turbine impeller, 0.009–0.0520 min^{-1} for the marine impeller, and 0.015–0.0511min^{-1} for the elephant ear impeller. The experimental values were fitted to the correlation in Equation (1). The constant α and exponentials (β and γ) were estimated by least square non-linear regression by following Marquardt's procedure [22]. The proposed correlation for individual impeller along with correlation coefficient (R^2) is shown in Table 2.

Good fits were obtained by using the derived correlations. The high value of R^2 and Fig. 2 a,b,c,d,e depicts the derived correlations that can be used to estimate K_La.

A number of correlations for the prediction of the K_La were reported in the literature. However, certain dissimilarities between the estimated values and experimental data were observed. This disagreement can be attributed to the fact at size, air flow rate, and bioreactor gas holdup lead to a high (bubble surface area) type of bioreactor, impellers, testing ranges, etc. Table 3 summarizes a few correlations proposed by various authors for predicting the value of exponents (β and γ) and constant α.

Citations in the literature have reported, that in the case of non-Newtonian fluids, (Pg/V) is a weak function for affecting the K_La due to the formation of gas pocket in the vicinity of the impeller while the superficial gas velocity (Vg) significantly influences the K_La due to the direct dependence of bulk mixing on gas-phase velocity [23]. A similar pattern of dependence was observed in small-scale vessels whereas; the dependence of K_La on (Pg/V) is weak while there is a strong dependence on the superficial gas velocity (Vg). Hence, the value of the exponent γ in Eq. (1) is greater than β. Whereas, the correlations derived for large volume vessels have a higher value of β than γ implying that agitation has a more significant influence on K_La at higher volumes [27]. However, in the correlations reported in [5,28] for non- Newtonian fluids, the dependence of K_La was found to be three-fold higher for agitation as compared to gas flow.

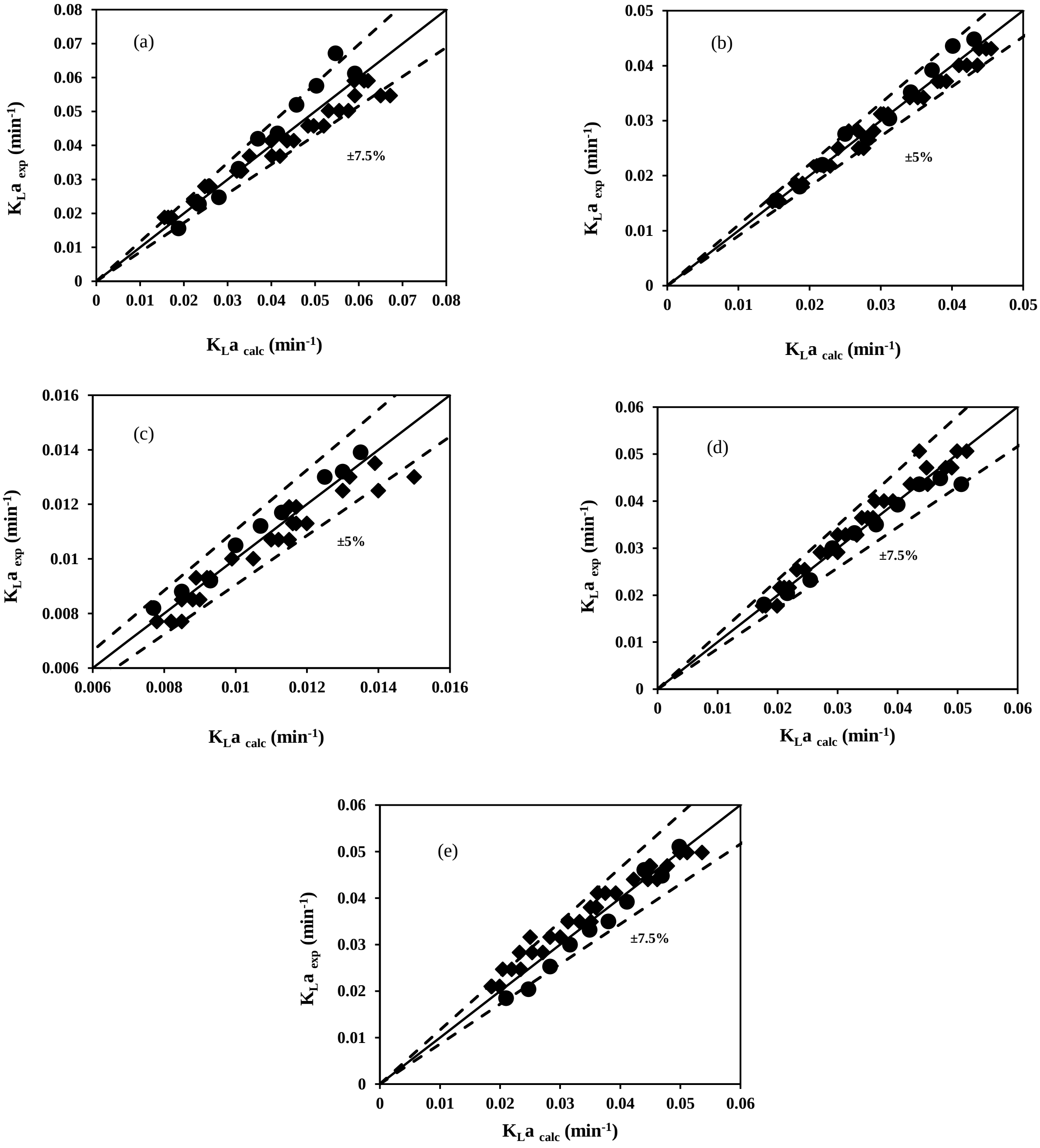

Fig. 2: Comparison between calculated and experimental data of K_La estimation at an aeration rate of 0.1 vvm. (◊) experimental values, (●) correlation values. (a) Rushton Turbine impeller, (b) Segmented impeller, (c) Paddle impeller, (d) Marine impeller (e) elephant ear impeller.

Fig.3 illustrates the results obtained showing the K_La values predicted over a range of agitation by using the correlations listed in Table 3.

A significant difference can be observed in the K_La values calculated by different correlations. It can be observed that the K_La values were underestimated when correlations derived by *Vilaca et al* and *Vasconcelos et al* were used. The most possible reason for this difference in values can be attributed to the variation in the volume of the vessel, agitator speed, and gassing rate used during the derivation of the above-mentioned correlations. The correlation proposed by Gill et al underestimated the K_La

Table 3: Commonly reported volumetric mass transfer correlations in the literature.

References	Vessel Diameter (m)	Proposed Correlation
[23]	0.06	$K_La = 0.224\ (Pg/V)^{0.35}\ (Vg)^{0.52}$
[24]	Various	$K_La = 0.2 \times 10^{-2}\ (Pg/V)^{0.7}\ (Vg)^{0.2}$
[25]	0.39	$K_La = 0.83 \times 10^{-2}\ (Pg/V)^{0.62}\ (Vg)^{0.49}$
[26]	0.21	$K_La = 0.67 \times 10^{-2}\ (Pg/V)^{0.94}\ (Vg)^{0.65}$
This work	0.16	$K_La = 0.90\ (Pg/V)^{0.324}\ (Vg)^{0.631}$

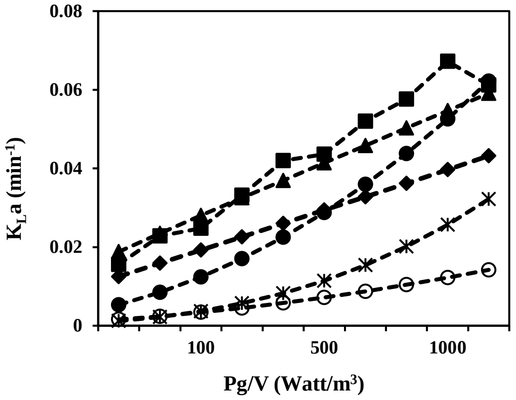

Fig. 3: Comparison of various correlations for K_La estimation at an aeration rate of 0.1 vvm. (■) measured values, (▲) derived correlation, (♦) Gill et al (2008), (●) Van't Riet et al (1979), (×) Vilaca et al (2000), (○) Vasconcelos et al (2000).

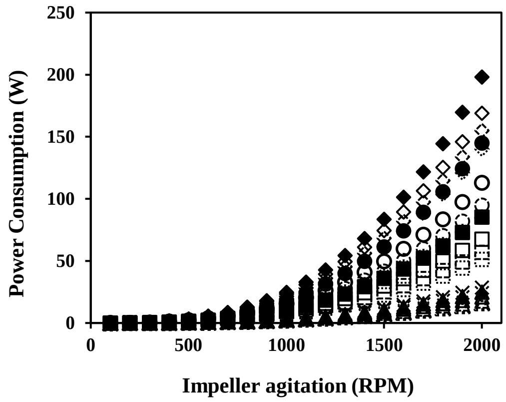

Fig. 4: Power consumption in gassed and ungassed conditions by different impellers. Filled symbols represent ungassed power. (♦) Rushton turbine, (●) Paddle impeller, (▲) Segmented impeller, (■) Elephant ear impeller, (×) Marine impeller. Empty symbols for gassed power. 0.1 vvm is depicted by symbols with complete lines (—), 0.2 vvm is represented by symbols with dashed lines (---) and symbols with dotted lines (······) for 0.3 vvm.

values but show a similar gradient as compared with the derived correlation of this study. The Van'tRiet equation over and underestimated the K_La values for different Pg/V values. The experimental values were also fitted in the correlations proposed by [5,28,29]. However, the K_La values estimated by the above correlations were significantly higher as compared to the experimental values (Data not shown). Hence, a correlation was derived for the small-scale bioreactor using the K_La values estimated experimentally at different flow rates and power requirements. The estimated correlations for different impellers are shown in Table 2.

Power Characteristics

Power draw measurements by different impellers

The power consumption by the impeller under gassed conditions is always lower compared to the ungassed system. The effect of gassing on power requirement has been studied extensively [30-33]. Citations have reported that gassed power requirements are usually 20-30% of the ungassed system. The gas cavities which are formed behind the impeller blades and the difference in the density of the fluid under gassed and ungassed conditions is responsible for this reduction in power requirements [34].

Fig. 4 displays the increase in power consumption under gassed and unguessed conditions by different impellers. Maximum power input under ungassed conditions was seen in the case of Rushton turbine impeller and the lowest by the Marine and Segmented impeller. At the impeller speed of 2000 rpm, the measured power consumption by the Rushton turbine impeller was 198.04 W. while the power input of the same impeller was lowered to 169.04 W, 154.98 W and139.90 W on sparging of gas at 0.1, 0.2 and 0.3 vvm respectively. From the above figure, it can be observed that under ungassed conditions, the maximum power consumption was done by Rushton

Table 4: Summary of relative decrease in gassed power consumption (Pg) at varied sparging rates for different impellers.

Impeller type	% decrease in power consumption (Pg)		
	0.1 VVM	0.2 VVM	0.3 VVM
Rushton Turbine	15	22	30
Segmented impeller	15	29	36
Paddle impeller	22	35	41
Marine impeller	21	33	40
Elephant ear	15	29	36

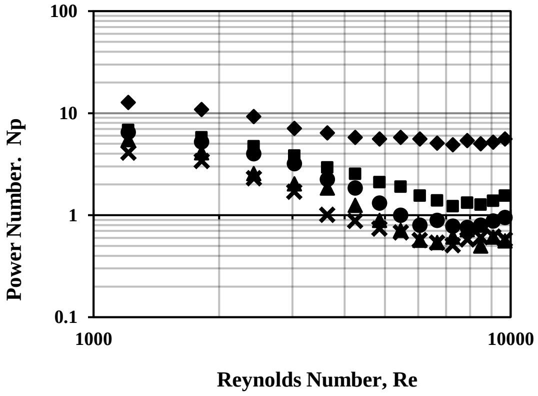

Fig. 5: Power number (Np) as a function of Reynolds Number (Re). (♦) Rushton turbine, (■) Paddle impeller, (▲) Segmented impeller, (●) Elephant ear impeller, (×) Marine impeller.

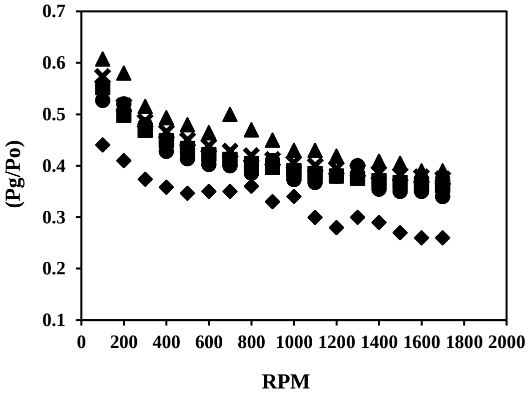

Fig. 6: Power input ratio (Pg/Po) as a function of impeller speed. (♦) Rushton turbine, (■) Paddle impeller, (▲) Segmented impeller, (●) Elephant ear impeller, (×) Marine impeller.

turbine impeller followed with Paddle and Elephant ear impeller. While the Segmented and Marine impellers showed a similar pattern of power consumption. However it is on sparging of air, the power consumption was lowered by 25-35% in all the cases of impellers which is in agreement with the previous literature [35]. Table 4 shows the decrease in gassed power (Pg) under influence of varied sparging rates.

The power characteristic for different impellers is shown in Fig. 5. As this figure shows, all the impellers operated in the laminar zone for the Re < 2000, and when the Re >2000, the flow pattern becomes transitional irrespective of the impeller investigated. Individual profiles for all the impellers were obtained which showed a decrease in Np with an increase in Reynolds number.

As expected, the highest Np values were observed in the Rushton Turbine impeller followed by the Paddle impeller and axial flow generating impellers. The power curves of marine and segmented impeller were found to be identical and the Np values were found to be closer. (0.56 and 0.61 respectively). The Np values of Rushton turbine and Paddle impeller were found to be lower as compared to the literature values (value obtained 4.9 while reported 5.50-6.0). However, in a few citations, it is proposed that the Np values of the impeller vary depending on the vessel geometry and agitation [36,37]. The majority of the literature related to Np has been published for a flat bottom vessel with baffles. While in the present study, an unbaffled tropospheric bottom vessel is used.

Power input ratio (Pg/Po) for different impellers.

As shown in Fig. 6, the ratio of Pg/Po as a function of agitation is presented. The ratio of Pg/Po is important for the estimation of power requirements and the gas dispersion characteristics of the impellers. The gassing flow rate of 0.2vvm was kept constant for all the impellers tested. The value of Pg/Po ranges between 0.3-1.0 depending on the impeller used [38]. The Pg/Po ratio was found to decrease linearly and after reaching the complete dispersion point, the values remained almost constant.

Table 5: Commonly reported gassed to ungassed (Pg/Po) power consumption correlations in literature.

References	Vessel Diameter (m)	Proposed Correlation
[28]	0.238-1.83	$1-\frac{Pg}{Po} = 9.9(\frac{QN^{-0.25}}{Di^2})$
[42]	0.19	$\frac{Pg}{V} = 0.0377\ N^{3.16}Vg^{-0.379}$
[43]	0.22	$\frac{Pg}{Po} = 0.497(\frac{Q}{NDi^3})\ -0.38\ (\frac{N^2\rho Di^3}{\sigma})\ -0.18$
[44]	various	$Pg = \alpha(\frac{Po^2NDi^3}{Q^{0.56}})^n$

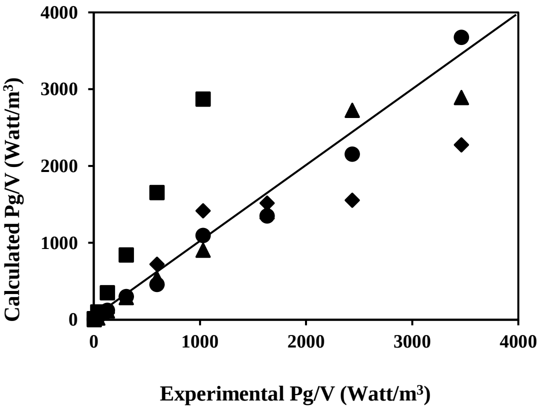

Fig. 7: Parity plot of experimental Pg/V. Aeration at 8.33 x 10^{-6} m^3/s. Experimental values from figure 4 and correlations from table 5. (♦) Michel and Miller, (■) Luong and Volesky, (▲) Linek et al., (●) Cui et al.

These results are in agreement with the previous studies [39,40]. The complete dispersion point of the Rushton Turbine was achieved at a lower impeller speed as compared to other impellers.

A very similar gas dispersion characteristic was displayed by the axial flow impellers in which the Pg/Po ratio was in the range of 0.35-0.61. The maximum value of Pg/Po ratio was observed in the Segmented and Marine impeller. In a comparison of the flow produced by the impeller, it was observed that Pg/Po ratio was lower in the radial flow as compared to the axial flow. Moreover, citations are available in the literature which proposes a better primary and secondary hydraulic efficiency in the case of axial flow impellers [41]. This finding signifies that by using axial flow generating impellers a better hydrodynamic efficiency is observed at less power input. In table 5, we summarize a few correlations of gassed to ungassed power consumption proposed by various authors.

The majority of the studies carried out for estimation and predicting of Pg/Po ratio have been performed using Rushton turbine and pitched blade impeller. Therefore the experimental value obtained for the Rushton turbine impeller was compared with the correlations listed in Table 5.

Fig. 7, illustrates the parity plot comparing the experimental Pg/V values with the predicted values of the correlations listed in Table 5.

A very close prediction of the calculated value to the experimental data was reported by the correlation proposed by [42]. The proposed correlation was based on the work over the range of vessel size $0.238 < T < 1.83$m and agitation of $5.5 < N < 10$ RPS. The mean deviation of the value reported in their work was <6%. The correlation proposed by [28] also shows a close prediction of the experimental values. The correlation is based on the data over a range of agitation $5.5 < N < 18.8$ RPS. The correlation proposed by [43] over-predicted the calculated value. Whereas, [44] correlation predicted lower values as compared to the experimental data. The constants α and n are used in the correlation obtained from [45].

CONCLUSIONS

The aim of this work was to study the performance of 5 different types of impellers with respect to their power requirements and mass transfer characteristics. Good fits were obtained for all the correlations derived for different impellers. Different correlations for predicting K_La in bioreactors were evaluated. However, the correlation proposed in [24] gave a reasonable prediction of the K_La while the rest of the correlations underestimated the K_La values and were found to be unsuitable. Rushton turbine impeller which has a higher power number achieved with higher K_La at lower agitation as compared to other impellers. This is in agreement with the result reported in [1]. However the K_La

estimated for Segmented impeller, Marine impeller, and Elephant ear impeller varied in narrower ranges. Additionally, the low shear rate generated by these impellers [46] and good oxygen mass transfer characteristics make them suitable for use in the Cell culture process which is shear sensitive. In the case of the power requirement of impellers, for axial flow impellers at reduced energy consumption, a better gas dispersion was observed. Different correlations cited in the literature for estimating Pg/Po were evaluated. However, correlations proposed in [28,43] showed a better prediction of the experimental values. The ratio of Pg/Po was found to be inferior for the Rushton turbine as compared to other impellers studied. This signifies that with given power input, the pumping capacity of the impeller is better conserved in case of axial flow mixing. The Marine and Segmented impeller showed very less variation in the power input curve and also in the Pg/Po pattern. This might be due to structural similarity and nearly identical solidity ratio.

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Pardhasaradhi Mathi equally contributed as the first author and is a co-corresponding author.

Nomenclature

C*	Dissolved oxygen saturation concentration, mg/L
C_L	Initial dissolved oxygen concentration, mg/L
Di	Diameter of the impeller, m
g	Acceleration due to gravity, m^2/s
H	Tank height, m
K_La	Volumetric mass transfer coefficient, min^{-1}
K	Consistency index, Pa S^n
M	Torque, Nm
Ni	Stirrer speed, rps
N	Stirrer speed, rpm
n	Flow behavior index
Np	Power number
Pg	Power drawn under gassed condition, Watts
Po	Power drawn under ungassed condition, Watts
Q	Gas flow rate, m^3/s
Re	Reynolds number
T	Tank diameter, m
Vg	Superficial gas velocity, m/s
vvm	Vessel volume per minute
V	Working volume, m^3
α	Constant of Cooper's correlation
β,γ	Exponents of Cooper's correlation
ρ	Density, Kg/m^3
σ	Surface tension of fluid, N/m

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