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ORIGINAL ARTICLE

Investigation of Gas Hold up and Power Consumption in a Stirred Tank Bioreactor Using Single and Dual Impeller Configurations

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ABSTRACT

A laboratory stirred tank bioreactor with six single and dual-impeller configurations was tested to obtain the optimum operating conditions for future biological processes. Six impeller combinations consisting of three basic impeller types, namely Rushton turbine (RT), pitched 4blade (P4B) and pitched 2blade (P2B) downward flow were investigated in 1.77 L bioreactor working volume. Power consumption and gas hold-up measurements were taken over a range of 100-1000 rpm of stirring speed and 1-5 $Lmin^{-1}$ of air flowrates, for all the six combinations consisting of any single and dual impellers. Using predicted data some empirical correlations were derived which present relations in estimation of power consumption in stirred tanks with various impeller configurations. Electrical measurement method was use to determine the power drown in the stirred bioreactor. Gas hold-up increased with an increase in stirring speed and superficial gas velocity for all the impellers employed. The number and type of impellers in stirred bioreactor had considerable influence on gas hold-up behavior of the stirred bioreactor. Besides, Rushton turbine-dual Impeller gave comparably maximum gas hold-up, but at significantly higher power consumption levels. The proposed correlations offered good agreement with the experimental data.

Keywords: *Gas hold-up, Stirred bioreactor, Power consumption, Dual-impeller*

INTRODUCTION

Stirred tanks as a means of mechanical agitation for mixing of bioreactor media are one of the most commonly used equipment in biotechnology [1]. The most common equipment used for effective contact between gas and liquid phases in chemical and biochemical processes is Rushton turbine agitated vessel [2, 3]. Although the Rushton turbine has been used for decades as reactor agitation tool, several designs have been developed to enhance and optimize gas–liquid contact in recent years. In full-scale reactors, multiple impellers are often used with either impellers of the same type or a combination of novel and traditional blades [4]. Several researches declared that "multi-

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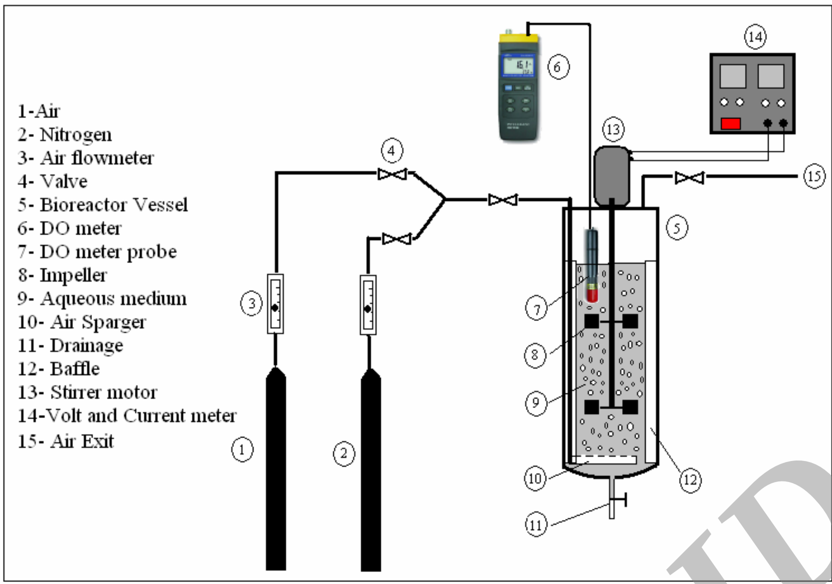

Fig 1. Schematic view of stirred tank bioreactor used in this study

impeller gas–liquid reactors have been found ensuring higher efficiency of gas utilization and longer retention time of gas than single impeller systems" [5].

Breaking up of bubbles is mainly caused by stirrer speed and the mixing intensity in bioreactor vessels [6]. Gas hold-up and mass transfer between several phases of reactor media very closely linked to each other. Gas hold-up is defined as a measure of the efficiency of gas–liquid contacting. Several variables such as: vessel and impeller design, impeller speed (power input), gas velocity and liquid physical properties may influence the rate of gas hold up in an impeller agitated reactor [7].

The effect of impeller design on gas hold-up in water and viscous liquids have been investigated in several studies. Khare et al. showed that impeller selection remains critical from the point of view of generating gas hold-up, even in the coalescence inhibited high viscosity, especially at the lower gas velocity. They also found that total gas hold-up in Carboxyl Methyl Cellulose solution increases with impeller speed at different gas velocities [7]. Gas hold-up, mixing intensity of dispersion and gas–liquid volumetric mass transfer coefficient for 18 impeller configurations in triple-impeller have been studied by Tomoa et al. They found that the impeller configurations with low power number provide higher dispersion mixing intensities, while the impeller configurations with high power number provide better mass transfer performance [8]. Dohi et al. used Rushton turbines and pitched blade impellers (four impellers on a common shaft) [9]. Several Pitched blade impellers on a common shaft have also been used by Saravanan et al. who selected them as the most effective ones from several types tested [10, 11]. The axial impellers to compare with the radial ones are more efficient from view point of mixing performances [8].

Power consumption in stirred tank bioreactors is known as one of the most important design parameters which is influence by several factors such as: the physical properties, operating and geometrical parameters of the of equipments . Most of the studies announced that being aware of power consumption of the stirring equipments may lead to better decision making on operating conditions so, achieving the needed mixing process with a minimum expenditure of energy and cost is of great concern [12, 13]. It was said that electrical power play major role to the overall manufacturing cost of a bio-filtration process. Also other parts of equipments air such as compressors and circulation pumps need electrical energy; but the major consumer is the agitator agent.

Given this background, it is evident that study on the effect of impeller design on gas hold-up and power consumption in bioreactors is advantageous. This study is devoted to optimization of agitation and aeration conditions in a system with geometrical configuration commonly used in laboratory scale stirred tank bioreactors with mixing equipment consisting of single and dual impellers on a single shaft. The performance was assessed on the basis of gas hold-up, which is a basic measure of the efficiency of gas-liquid contacting and, at the same time, very closely linked with mass transfer.

The aim of this work is to compare the power dissipation and its effect on gas hold-up, which in turn decides the gas-liquid interfacial area for various combinations of impellers. The optimum combination can then be selected for industrial bioprocesses with total confidence.

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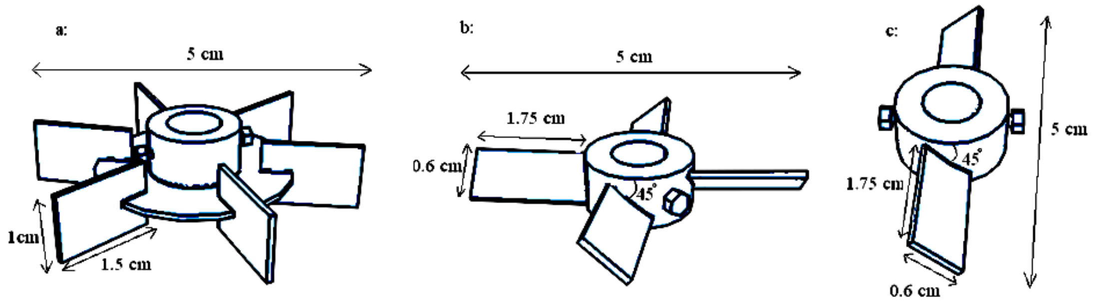

Fig 2. Schemes and details of the impellers: a: Standard Rushton turbine with vertical Blades (RT), b: Pitched 4blade (P4B), c: Pitched 2blade (P2B)

MATERIAL AND METHODS

The Stirred Bioreactor in detail

The experimental conditions have been selected in order to generate efficient mixing condition inside the tank. A schematic diagram of the stirred tank bioreactor is shown in Fig. 1. The semi-circle bottom cylindrical tank was made of transparent glass with an internal diameter of 10 cm and ratio H_b: T_i = 3 fitted with four T_i/10 wide vertical wall baffles symmetrically. The distance between impellers is chosen equal to the tank diameter in order to avoid interaction between them [14]. The experiments were performed at room temperature and atmospheric pressure. De-ionized water (28±0.5 ˚C) was used as the liquid phase and filtered air was supplied to the system through an orifice sparger contains 9 orifices with total open area of 0.28 cm^2, located 5 cm (T_i/2) below the lower impeller. "In mechanically agitated reactors, the impeller is the main gas-dispersing tool and will naturally have a pronounced effect on mass transfer characteristics of the system" [15]. Also it was recommended that "the impeller must be located neither close to the dispersion device nor close to the free surface" [13]. Three types of impellers, namely, Rushton turbine (RT), Pitched 4blade (P4B) and Pitched 2blade (P2B) impellers (blade angle 45˚) with downward pumping (Fig 2) were tested with 1.77 L total working volume of aqueous phase in order to evaluate their effect on the gas hold-up and power consumption in the bioreactor. Aeration rates ranging from 1 to 5 L min^{-1} were tested in ten agitation speeds (100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 rpm).

Gas hold up

Gas hold-up (ε) as an important design parameter of a reactor is defined as the ratio of the gas phase volume to the total volume. This parameter accompanies with information regarding to mean bubble diameter used to calculate the gas-liquid interfacial area and so has noticeable effect on the mass transfer coefficient (K_La) [13, 16]. The overall gas hold-up at a given impeller speed and gas velocity was determined by visual measurements using the volume expansion method [17]. This was quantified by measuring the difference between the volume of un-aerated and aerated liquid. The gas hold-up was computed from the following equation [18]:

$$\varepsilon = \frac{H - H_0}{H_0} \quad (1)$$

Where, ε is the gas hold-up, H_0 is the un-gassed column height (m) and H is the column dispersion height due to the presence of gas bubbles (m).

Power consumption

Looking at the literature, it was found that the most frequently used techniques for the evaluation of power consumption in stirred tanks and fermentors are wattmeters, ammeters, colorimeters, dynamometers, torquemeters and systems based on strain gauges. Each of these systems has its own advantages and disadvantages, and is chosen based on some factors such as investment, scale, precision, and range of measurement. The first technique is electrical measurement that used for power draw quantifications by wattmeters and ammeters directly in the motor of stirred vessels. For the case of direct current motors (DC), the power draw by an electrical device is simply the result of the supplied voltage (V) and the current greatness (I). Power consumption in these networks could be calculated by an ammeter, as well as directly by means of a wattmeter [12].

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 that is presented in Fig 1.

RESULTS

The effect of impeller combination and power on gas hold-up was studied for several impeller configurations. The results are represented in Fig 3. As

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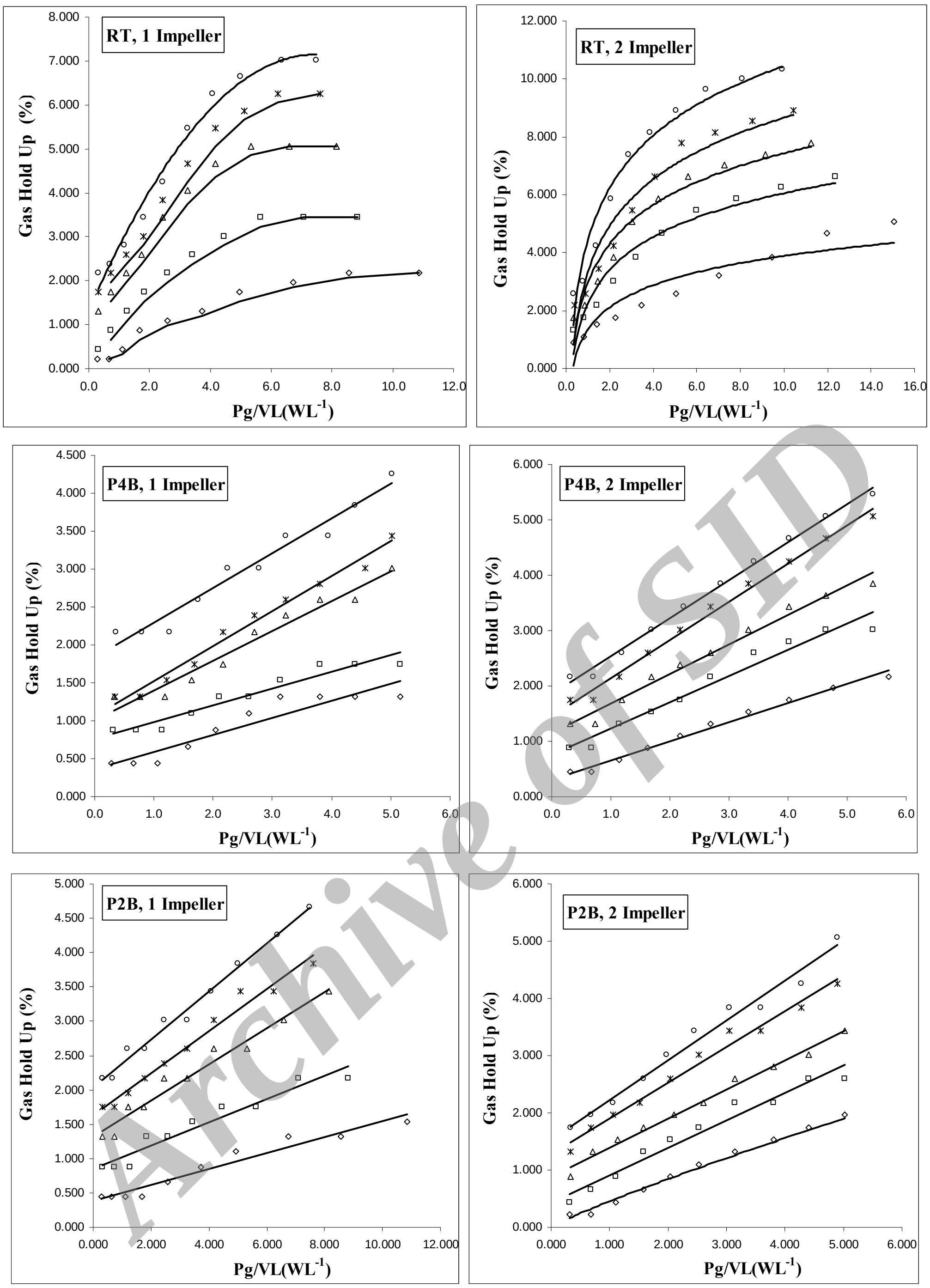

Fig 3. Gas hold-up as a function of power consumption per unit volume with flowrates of 1 to 5 $Lmin^{-1}$ using three types of impellers (RT, P4B and P2B) in 6 different single and dual configurations.(1 $Lmin^{-1}$ - - -◆- - -, 2 $Lmin^{-1}$ —□—, 3 $Lmin^{-1}$ —△—, 4 $Lmin^{-1}$ —✳—, 5 $Lmin^{-1}$ —○—)

seen from this figure, the gas hold-up increases with increase in flowrate, although the trend is the same for all flowrates (1 to 5 L/min). Also the extent of the increase is much higher at higher flowrates. A reduction of power consumption is notable with increase of gas flowrate in each impeller configuration. This reduction for RT 2 impeller composition is about 30% in flowrate of 5 L/min to compare with 1 L/min.

In addition, Fig 3 shows gas hold-up increment of 40 to 120% in lower and higher gas flowrates respectively in RT 2 impeller to compare with RT 1 impeller configuration. The RT 2 impeller vs. P4B and P2B in Fig. 3 appears an increase of 90 and 100% of gas hold-up in RT 2 impeller to compare with P4B and P2B respectively. Comparison of single and dual impeller configurations of P4B and P2B in Fig. 3 shows an

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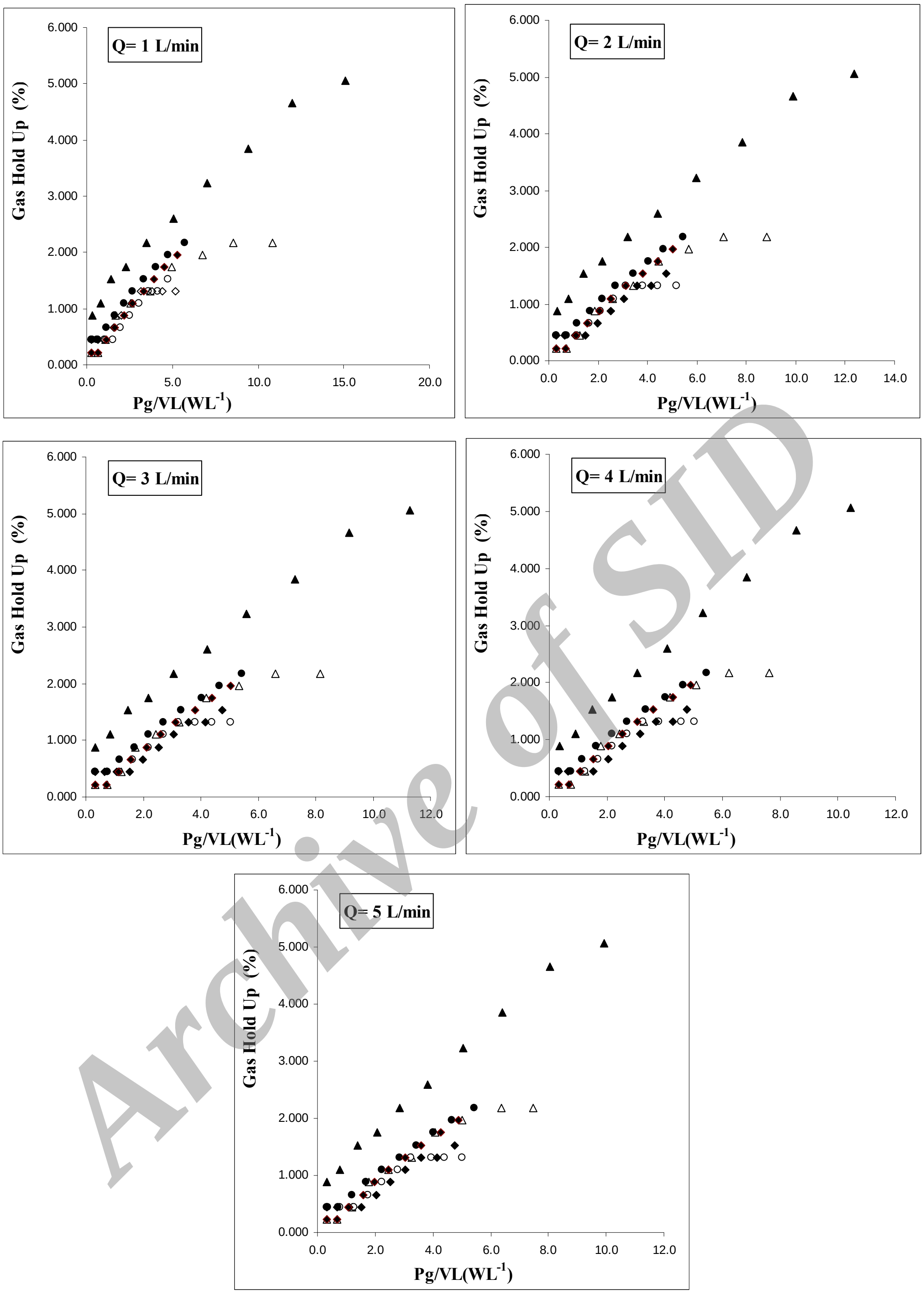

Fig 4. Power consumption comparisons of three types of impellers (RT, P4B and P2B) in 6 different single and dual impeller configurations with flowrate of 1 to 5 Lmin-1(RT single impeller △, RT twin impellers ▲, P4B single impeller ○,P4B twin impeller ●, P2B single impeller ◇, P2B twin impeller ◆)

increase of 20 to 30% in dual configurations. Also, Fig 4 approves the difference of gas hold-up rates in difference impeller configurations.

Predictions of the absorption rate of a gaseous species in a stirred tank are usually based on correlations of overall volumetric mass transfer coefficient (K_La) and gas hold-up with mechanical agitation power per unit volume (P_g/V_L) and gas sparging rate that expressed as the superficial velocity (V_g) [6]. The power input per unit volume (P_g /V_L) and,

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Table 1. Calculated constants and Exponents of Eq. 2 for 6 impeller configurations.

Configuration	**Gas hold-up exponents of Eq. 2**			
	α	**β**	**c**	**R^2**
RT, single impeller	21.6	0.56	1.03	0.92
RT, dual impeller	2.11	0.48	0.67	0.97
P4B, single impeller	2.73	0.36	0.74	0.94
P4B, dual impeller	2.64	0.46	0.74	0.97
P2B, single impeller	7.74	0.37	0.86	0.95
P2B, dual impeller	4.25	0.57	0.86	0.93

superficial gas velocity V_g are major factors in gas hold-up correlations.

There are a lot of proposed equations for the fractional gas hold-up as a function of different variables in previous studies [8, 19, 20]. Also frequent disagreements between experimental data and those estimated from these equations are found. This can be as the results of strong impact of the style and size of bioreactors, the different range of operational circumstances, the system considered solutions or real broths, the influence of physicochemical specifications on hydrodynamics due to high viscosity of the liquid, its rheological behavior or even the measuring technique used [6]. The following equations are frequently found in the literature [8, 19, 20]:

$$\varepsilon_g = \alpha\left(\frac{P_g}{V_L}\right)^{\beta}(V_g)^c \qquad (2)$$

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

In this present work on the base of these concepts, some empirical correlations for the gas hold-up rate in the bioreactor with three type of single and dual-impellers are developed and gas hold-up values obtained from the experimental data were plotted against the operating variables and mathematical correlations which describe the influence of the studied parameters on the gas hold-up have been established in order to predict biodegradation performances. These correlations ware developed using Datafit 9 software.

Fig 5 plots the experimental gas hold-up for three types of impellers, the RT, P4B and P2B with single and dual impeller configurations, versus calculated gas hold-up using Eq. (2) for different gas flow rates (1 to 5 $Lmin^{-1}$) and agitation speeds (100 to 1000 rpm). In this Figure the proposed correlation offers a good agreement with the experimental data with an average deviation of ±8 %, which presents the predicted versus the experimental results.

DISCUSSION

The gas hold-up gives the volume fraction of gas phase in the reactor and thus gives the mean value of residence time for the gas phase. The effect of impeller combination and power on gas hold-up was studied for several impeller configurations. In Fig. 3 it was found that the number of impeller in stirred bioreactor has considerable influence in gas hold-up specifications. Also it revealed that type of impeller has the most efficient impact on gas hold-up behavior of stirred bioreactor.

It is clear from Fig. 4 that even though the maximum values of gas hold-up vary markedly between the impellers tested, the power for gas dispersion is also significantly different. Based on the power consumption

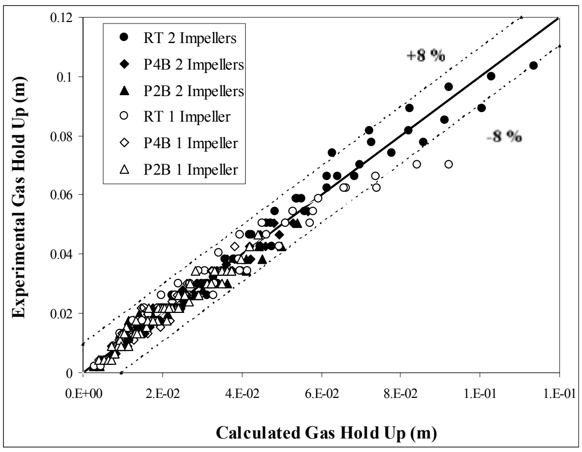

Fig 5. Correlation between the experimental and calculated values of gas hold up for single and dual impeller of RT, P4B and P2B in six configurations, agitation rates from 100 to 1000 rpm and aeration rates from 1 to 5 $Lmin^{-1}$

value, it is evident that RT dual impeller gives comparably maximum hold-up, but at significantly higher power dissipation levels. In other words, Rushton turbine impellers appear to be superior to pitched blade turbine under these conditions. At the higher gas velocity, the picture is somewhat similar to Fig. 4, however the holdup values is also correspondingly higher (Figures not shown).

In this study, it was considered the case where the objective was to choose an impeller which gave the highest gas hold-up. If we now consider the case where an impeller is to be selected Rushton turbines generate higher gas hold-up than pitched blade at all studied gas velocity, and dual impeller configurations showed superior performances to compare with single impeller configurations. Thus, Rushton turbine-type dual impeller can demonstrate better performance over other compositions with regard to generating gas hold-up in low viscous non-Newtonian liquid.

Changing gas flow rate will also affect the K_La values of a bioreactor by changing the fractional gas hold-up and hence the gas-liquid interfacial area. It was observed that with an increase in the gas flow rates, the gas hold-up values increased (Fig. 3). Similar results were obtained with single and dual impeller systems.

Also, the results presented in Fig. 3 illustrate that for RT impeller type the gas hold up increment trends in different aeration rates(1-5 $Lmin^{-1}$), begins from a highly sloped curve in lower agitation rates(lower power consumption) and continue to increase, then this trend approaches to a plateau in 900 and 1000 rpm(higher power consumption). On the other hands in pitched blade impellers the gas hold-up increment trends in different aeration rates (1-5 $Lmin^{-1}$), begin with a sloped line and this slop is maintained to all agitation speeds.

The constants obtained from the correlations of the 6 single and dual impeller configurations are shown in table 1. The exponent over (P_g/V_L) increased with single to dual impeller configurations in pitched blade impellers, indicating more effective utilization of the power with multiple impeller systems. No significant effect was observed on the exponent over V_g for single and dual impeller systems especially in pitched blade impellers. In the gas hold-up data we can find many trends with number and type of impellers so it is not easy to make general conclusions about multi-impeller vessels design from the gas hold-up data. Empirical correlations for gas hold-up depend on several geometrical parameters, although there is no conformity in the literature about how to take into accounts this influence [8].

CONCLUSION

The objectives of this work were to study the behavior and the performances of several impeller configurations. It was found that the number of impeller in stirred bioreactor has considerable influence in gas hold-up specifications. Also the result illustrated that the gas hold-up increases with increase in gas flowrate. From the above discussion it is clear that Rushton turbine-type impellers running in non-Newtonian liquid, gives the highest gas hold-up. It is therefore desirable to operate this impeller, preferably in order to ensure that the gas bubbles are fully dispersed throughout the liquid. As the results have shown, dual Rushton turbine represents an average enhancement on the gas hold-up values of 90 and 100% with respect to P4B and P2B impellers respectively**.** Based on the power consumption value, it was found that RT dual impeller gives comparably maximum gas hold-up, but at significantly higher power dissipation levels. The proposed correlation offers good agreement with the experimental data with an average deviation of ±8%, which presents the predicted versus the experimental results.

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Nomenclature

α, b, c,	Exponents in Eq. (2)
ε	Gas hold-up
H_0	ungassed column height (m)
H	column dispersion height due to the presence of gas bubbles (m)
T_i	bioreactor internal diameter (cm)
H_b	bioreactor height (cm)
N	impeller rotation speed (rpm)
P	power consumption for mixing of non-aerated (W)
P_g	power consumption for mixing of aerated (W)
Q	volumetric air flow rate ($Lmin^{-1}$)
P_g/V_L	specific power input (WL^{-1})
V_g	superficial air velocity ($m\ s^{-1}$)
V_L	Volume of the liquid in the Vessel (L)

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