ISSN 2229-5518

Study on the Hydrodynamics of Stirred Vessels

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Abstract— In this study, the mass transfer coefficient of oxygen in distilled water was studied with respect to various parameters such as impeller type and size, flow rate of air and agitation speed of the motor. When studying the effect of impeller size with three different sizes of sawtooth, the k_La value reached 0.0135 s^{-1} for the large size impeller with a diameter of 83.6 mm. On the other hand, the medium and small impellers reached k_La values of 0.0118 s^{-1} and 0.0069 s^{-1}, respectively. Furthermore, experiments on effect of air flow showed that the value of k_La increased as the flow of air introduced to the system increases. A range of air flow rate from 0.16 to 0.52 m^3/h was experimented for different types of impellers. It was noticed that the best result was recorded with Rushton turbine at a speed of 500 rpm and flow of 0.52 m^3/h, where the value of k_La reached is 0.0262 s^{-1}. While CD-6, paddle and sawtooth at the same mentioned speed and flow rate gave k_La values of 0.0232 s^{-1}, 0.0217 s^{-1} and 0.0135 s^{-1}, respectively but still CD-6 consumes less power than Rushton turbine as well established in literature. For the effect of various agitation speeds, it was found that as the speed increases the dispersion of gas bubbles enhanced in the vessel. A range of impeller speed from 300 to 700 rpm was experimented with different type of impellers. The best value of k_La of 0.0389 s^{-1} was obtained at a Rushton turbine unlike the k_La of CD-6 which was 0.4 s^{-1}. Due to advantages of CD-6, the k_La value of Rushton turbine is smaller than the k_La of CD-6. Moreover, paddle and large sawtooth diameter impeller scored low values of k_La of about 0.0231 s^{-1} and 0.0281 s^{-1}, respectively.

Index Terms— Bioreactors, impellers, agitation, aeration, volumetric mass transfer coefficient, Hydrodynamics.

1 Introduction

In all aerobic chemical and biological process, effective oxygen supply and absorption is one the most required and important principal. Some examples on operations that utilizes between oxygen gas and a liquid phase are leaching of metal concentrates and microbiological fermentation. Aeration is the process in which oxygen is added and dissolved in water by utilizing the principles of mass transfer. It is one of the most important processes used in public health engineering as it eliminates both smell and taste from water. Transfer of oxygen into a mass of water can either occur naturally for example, surface aeration of polluted surfaces, or under imposed conditions such as, the activated sludge process.

There are different devices that are used to bring oxygen and liquid phase into contact such as, packed bed, bubble column, tray tower, and plate columns [1]. Mechanically agitated device is also used in which the liquid phase is the continuous phase, compressed air is the dispersed phase and agitation is insured by a rotating impeller [2]. Mechanically agitated vessels are often preferred over other types of conductors if the following conditions are obtained: flow rate of gas is greater than liquid; use of low soluble gases; where good mass transfer will be required; good heat transfer is necessary especially in high endothermic and exothermic reactions; liquid phase is highly viscous or non-Newtonian liquids are used [3]. Although a mechanically agitated vessel seems the best option for contacting a liquid and a gas phase, but it has some disadvantages and difficulties such as: complexity of construction compared to other conductors; difficult to operate in conditions with high pressure and toxic material;difficult to scale up to very large sizes.

Oxygen is a non-polar gas and it is more soluble in water compared to nitrogen gas. The solubility of oxygen in water depends on the temperature at which this process occurs. It is observed that at 25^{o}C and 1atm of air, fresh water will contain approximately 6.04 mg of oxygen per litre. On the other hand, seawater contains almost 4.95 mg per litre. This is due to presence of salt and other impurities in seawater that will reduce the solubility of oxygen in water.

The volumetric mass transfer coefficient (k_La) is a lamped parameter as it depends only on time not on space. It indicates the rate of oxygen that has transferred from the gas phase to the liquid phase and has the unit of [1/time]. k_La is a very important parameter in designing, scaling up from laboratory scale to pilot scale or production scale of bioreactors [4]. Normally radial impellers were used to do the job. Recently it is appeared that axial flow impeller configuration may exhibited a larger production rate for biomaterial and low energy consumption in comparison to the radial flow impellers [5]. There are several factors that affect the transfer of oxygen to liquid phase which is characterized by the overall mass transfer coefficient (k_La). The k_La values are dependent on factors such as agitation rate, gas velocity, bubble size, temperature, gas sparging system and cell morphology [6]. In this study the effect of different impeller types and sizes, agitation speed, and gas flow rate on value of k_La will be studied and observed.

2 EXPERIMENTAL WORK

2.1 Determination of k_La from experiments:

The dynamic method that depends on the response of an oxygen probe to change in the concentration of dissolved oxygen in the liquid medium during the absorption or desorption of oxygen was used in this study. In absorption dynamic tech-

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nique, the concentration of dissolved oxygen is eliminated and reached to zero at the beginning by bubbling nitrogen gas. Then air is supplied to the liquid and the increase in the concentration of oxygen is measured with time until saturation point is reached. In desorption dynamic method, air is supplied at the beginning of the process until the saturation level of oxygen is reached. After that, nitrogen gas is supplied and the decrease in the oxygen concentration is recorded as a function of time [7].

The mass transfer resistance in the gas phase is usually neglected, because it is much smaller compared to the resistance in the liquid phase [8]. For a perfectly mixed liquid, the mass balance on the dissolved oxygen could be established as following:

$$\frac{dC}{dt} = OTR - OUR \tag{1}$$

Where: OTR is the oxygen transfer rate (mol $O_2/m^3.s$) and is:

$$OTR = k_L a \ (C^* - C) \tag{2}$$

OUR is the oxygen uptake rate which is the oxygen consumed by the microorganisms (mol $O_2/m^3.s$). Because the system used in this thesis does not contain any microorganisms; therefore, OUR is equal to zero and the equation 3.1 becomes as:

$$\frac{dC}{dt} = k_L a \ (C^* - C) \tag{3}$$

Solving equation 3.3 by separating the variables and integrating from C_0 to C and t_0 to t:

$$\ln \frac{(C^* - C)}{(C^* - C_0)} = -k_L a \ (t - t_0) \tag{4}$$

The plot between $\ln \frac{(C^* - C)}{(C^* - C_0)}$ and **t** will result a line with a slope of **-$k_L a$**

2.2 Experimental Set Up:

The arrangement of the equipment is shown in Fig. 1. Distilled water is used in all experiment. The list of main equipment used in this study is shown in Table 1. The data of k_La were recorded by computer interlog using data acquisition software. The different types of impellers used in this study are shown in Fig. 2.

For determining the effect of impeller sizes, three different sizes of sawtooth impellers were used. The impeller speed, gas flow rate and liquid volume were all kept constant at 500 rpm, 0.52 m^3/h, and 14 L, respectively. For determining the effect of air flow rate, four different ranges were inspected for all types of impellers and the flow rates were 0.16, 0.28, 0.4, and 0.52 m^3/h. The impeller speed and the liquid volume were kept constant at 500 rpm and 14 L, respectively. For determining the effect of impeller speed, 4 different ranges were inspected for all types of impellers and the impeller speeds were 300, 400, 500, and 700 rpm. The air flow rate and the liquid volume were kept constant at 0.52 m^3/h and 14 L, respectively.

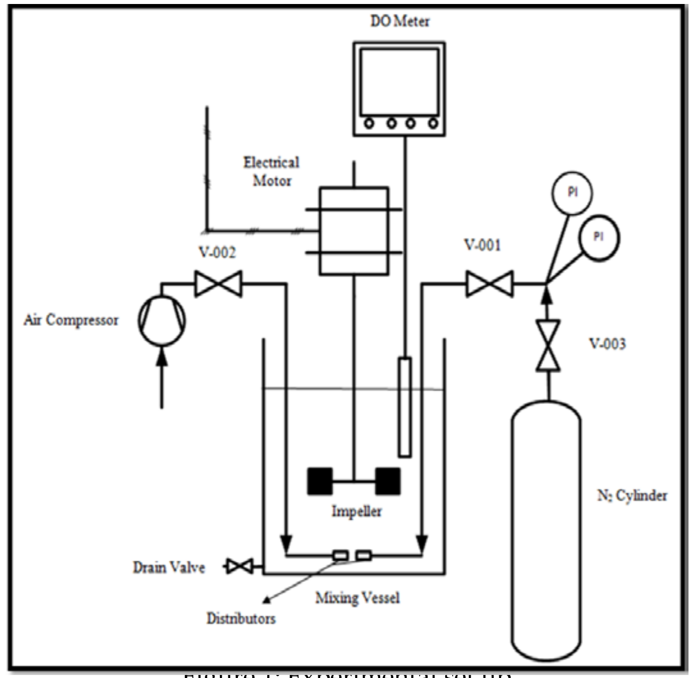

Figure 1: Experimental set up

Table 1: Specifications of equipment.

Equipment	Specification	company
Vessel	rectangular Perspex vessel 24 x 24 x 35 cm	
Air compressor	Model: ACO-005, Power: 80 W, Pressure: 0.035 MPa Output: 70 L/min	Yuting, China
Air flow meter	Range: 0.16-1.2 m^3/h	Yuyao Zhenxing flowmeter instrument factory/China
Dissolved oxygen meter	Bench-type Model: 980	Bante instruments /China
Nitrogen cylinder	Purity of nitrogen: 99.99%. Volume of cylinder: 40 L Regulator range: 0-10 bar side entry	SGC and gas arc. Group/UAE
Mixer	Multi-speed: 0-1500 rpm.	Huarui-instrument/China
Air stone	Porous ceramic	China

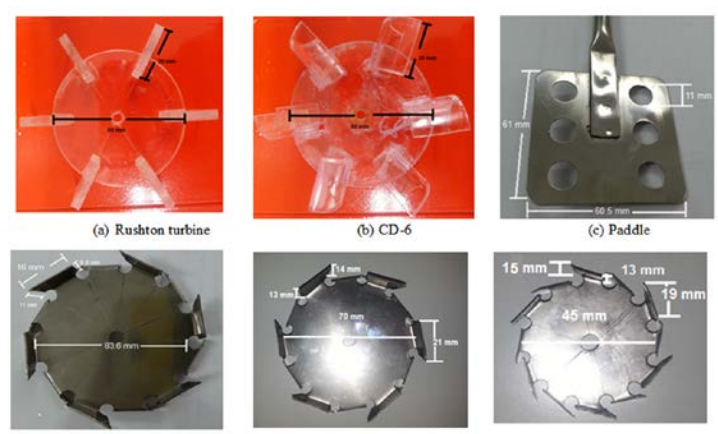

Figure 2: Impellers Used.

3 Results and discussion

3.1 Study on the Effect of Impeller Size

ISSN 2229-5518

The effect of impeller size was studied by conducting experiments under the same conditions of impeller speed, gas flow rate and liquid volume using three different sizes of saw-tooth impeller. The saw-tooth impeller is a high speed disperser disc, which contains a large number of upward and downward pointing teeth. It is classified as a radial flow impeller and usually used in high viscous fluids like paints and mixing of powder into the product to form a smooth mixture. In addition, it is applied to break droplet in oil-water dispersion system [9], because of the high shear stress. It is generally used in conjunction with a high flow impeller in applications involving a combination of blending and a need for physical change created by fluid shear [10].

This type of stirrer also provides high shear without a stator ring or baffles [11]. There is a study on using saw-tooth impeller for bioreactors [12] but the measurement will be for mixing time. In any case it gave bad results for the viewpoint of intensity and uniformity compared with other radial impellers. Although this type is not normally used for gas-liquid dispersion, in this study we want to exam the performance of this type for gas-liquid system. During the experiments it was noticed that in the large saw-tooth, the bubbles size were reduced more and dispersed better in the liquid phase. On the other hand, the mixing with the medium and small saw-tooth was not satisfactory, as the distribution of the bubbles were not enough to occupy the whole volume of the tank and large regions of dead volume were noticed. From the results presented in Fig. 3, it is noticed that the large diameter (D = 83.6 mm) saw-tooth provides the best k_La value compared to the other sizes used.

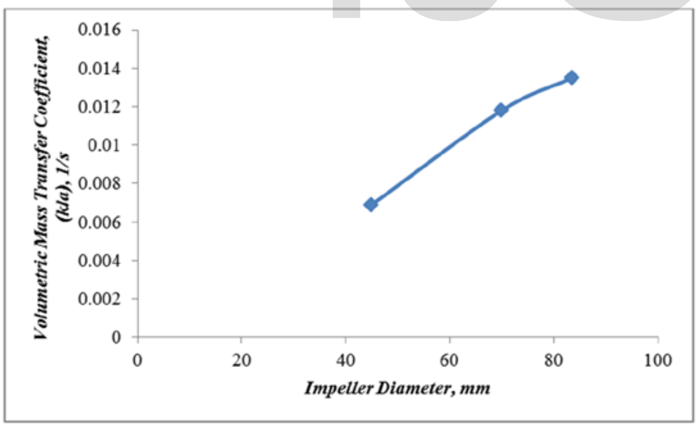

Fig. 3. The effect of impeller diameter on k_La for saw-tooth impellers at air flow = 0.52 m^3/h and impeller speed of =500 rpm.

This could be explained by the basic concepts of designing mixing systems. The high shear of the large impeller will dispersed the air into very small bubbles which will increase the interfacial area of contact between gas and liquid and then increase the overall mass transfer coefficient.

3.2 Study on the effect of air flow rate

The effect of air flow rate was studied by conducting experiments under the same conditions of impeller speed and liquid volume. The results of the experiments on the effect of air flow for different impeller type could be summarized in Fig. 4.

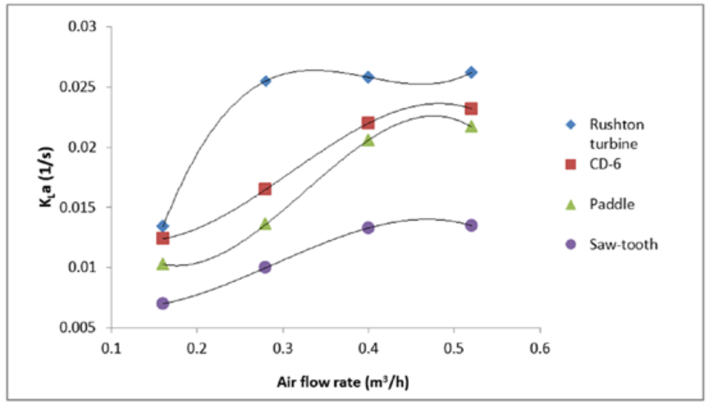

Fig. 4. The effect of air flow rate experiments at Saw-tooth diameter = 83.6 mm and impeller speed =500 rpm.

From the results obtained, it is noticed that the general trend for the different types of impellers used is the same and that is if the flow rate of air increases the value of k_La increase. The reason behind this is that when the air flow rate increases the number of bubbles introduced to the system will rise, this will cause an increase in the interfacial area available for mass transfer.

The Rushton impeller is one of the first mixing impeller designs to be documented. The classic design of this impeller provides a simple radial flow pattern that moves material from the centre of the vessel outward where it flows along the outer walls of the tank. Traditionally, gas dispersion in agitated vessels is carried out using radial disc turbines, such as the Rushton turbine [13]. Although they can be used for any type of single- and multiple-phase mixing duty, they are most effective for gas–liquid and liquid–liquid dispersion and provide higher shear and turbulence levels with lower pumping. Nevertheless, there are several disadvantages associated with Rushton turbine such as, low ability of gas handling and high gassed power, due to the effect of large cavitations. At very high gas flow rate operations it may cause serious flooding of the system [14]. The new generation of radial turbine is backswept turbine also known as CD-6 that has six curved blades. The backswept nature of the blades prevents material buildup on the blades and has highest gas dispersing capability available. It is also less susceptible to erosion [10].

The k_La was found to be the highest when using Rushton turbine compared with the other types of impellers applied. At the maximum air flow of 0.52 m^3/h the k_La value was 0.0262 s^{-1}. According to Khapre & Munshi [15] the power number of Rushton turbine and CD-6 differs according to Reynolds number. At a Re=300 the power number of Rushton turbine is about 35% higher than CD-6 impellers, while at a Re=30000 the difference is about 70% higher. That means that the power number difference is increasing with increasing Reynolds number. The operating Reynolds number for different impellers in our system are shown in Fig. 5.

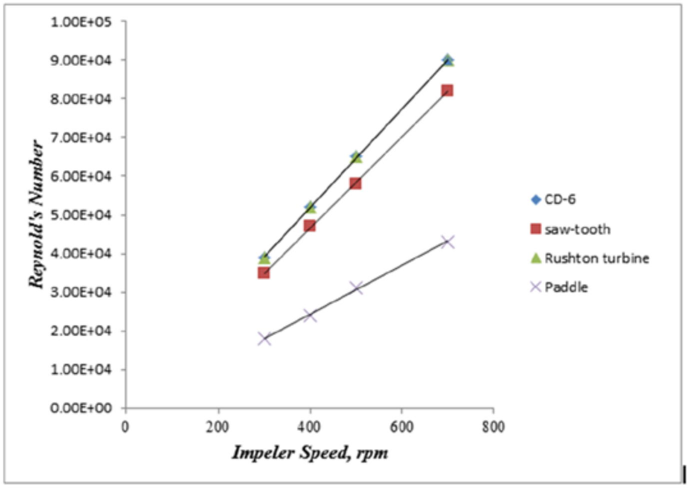

Fig. 5. Reynold's number for different Impellers (saw tooth diameter of =83.6 mm).

Since we are working with a minimum Reynolds number of 30,000 we expected that the power number of Rushton turbine is 75% higher at minimum and since the increase in k_La is 35% higher for Rushton turbine in the best conditions as shown in Table 2.

Table 2: Percentage of differences in k_La between Rushton and CD-6 impellers at different ranges of flow rate.

Air flow rate (m^3/h)	Velocity (Vg) m/s	k_La of Rushton Turbine (s^{-1})	k_La of CD-6 (s^{-1})	% difference in k_La
0.16	2.78	0.0134	0.0124	7.46
0.28	4.86	0.0255	0.0165	35.3
0.4	6.94	0.0258	0.022	14.7
0.52	9.03	0.0262	0.0232	11.45

As a conclusion it would be advised to use CD-6 impeller due to its low power consumption and the difference in the value of k_La could be tolerated.

Different trend was found by Devi & Kumar [16], while At lower values of gas velocity (Vg), there is no great difference of k_La between Rushton and CD-6 impellers, then at certain higher values of air velocity (V_g) Rushton impeller gradually decreases but CD-6 impeller decreases slightly greater than Rushton impeller and both go in the same magnitude if V_g is further increased.

The paddle type impeller showed a better behaviour than the saw-tooth as the values of k_La rose dramatically with the increases in air flow rate. This could be due to the better mixing observed by the paddle as vortex was formed which helped in enhancing the agitation and distribution of the bubbles. A paddle is used usually for low viscous fluids blending, dispersing gases in liquid, liquid-liquid contacting and suspending solid [17]. It is also known for its high power consumption due to its flat shape.

For every system there is an optimum air flow rate that should be used, because if the flow rate is very low then large time is required to reach saturation. On the other hand, if the air flow rate is very high then the impeller cannot handle the large amounts of air bubbles and will not be capable of reducing or breaking the size of bubbles and flooding occurs. From the results a flow rate of 0.4 m^3/h could be suggested for a volume of 14 L distilled water system.

3.1 Study on the Effect of Impeller Speed

The effect of impeller speed was studied by conducting experiments under the same conditions of air flow rate and liquid volume. The results of the experiments on the effect of impeller speed for different impeller type could be summarized in Fig. 6.

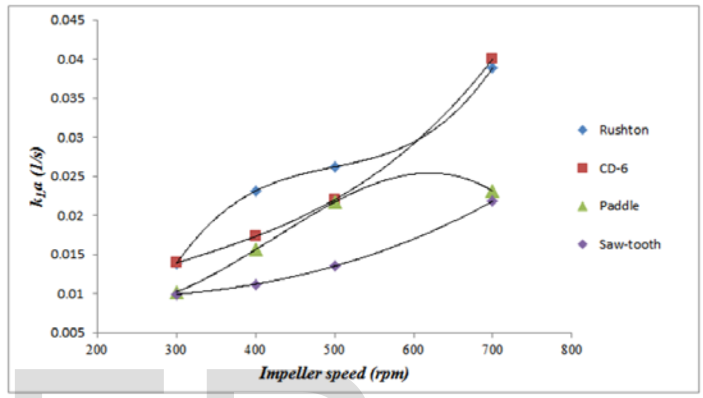

Fig. 6. The effect of impeller speed experiments at air flow of 0.52 m^3/h and saw tooth diameter of =83.6 mm on k_La.

The general trend noticed for the different impellers is the increase in the value of k_La with the rotational speed of the impeller. When air is introduced to the system it passes through the most turbulent region of the impeller and breaking of bubbles take place, this leads to the formation of smaller bubbles and results in a wider interfacial area between the gas and liquid phase. The rate at which bubbles break up is highly influenced by the degree of agitation, dispersion capacity, impeller type and configuration. The reason behind the increases in k_La value with agitation speed is that as the speed rises, the amount of energy applied by the impeller will increase, so the bubbles break up will be greater and this enhances the transfer of the gas phase to the liquid phase [14]. At the end of each experiment the dissolved oxygen becomes almost constant as the rate of bubble dispersion become in equilibrium with the rate of bubble collisions and there will be no change in the dissolved oxygen in the system. The same trends were noticed in this set of experiments as the previous set, Rushton turbine showed better results than CD-6 and the percentage difference in k_La value are shown in Table 3. These results are in agreement with other studies such as Gimbun et al. [18] and Zhu et al. [19] who noticed that at the same

Table 3: Percentage of differences in k_La between Rushton and CD-6 impellers at different ranges of impeller speed.

Impeller speed (rpm)	k_La of Rushton Turbine (s^{-1})	k_La of CD-6 (s^{-1})	% difference in k_La
300	0.0138	0.0139	0.72
400	0.0231	0.0173	25
500	0.0262	0.022	16
700	0.0389	0.04	2.8

conditions, CD-6 provides a slightly lower k_La value and they explained it as a result of several factors. The main reason is that CD-6 impeller has a slightly higher gas hold up compared to Rushton turbine. Higher gas hold up will cause high bubble coalescence resulting in smaller surface area and consequently lowering the value of k_La [18]. In the last speed region which is at 700 rpm an opposite trend was obtained as the CD-6 gave a better result than Rushton turbine. This could be that CD-6 has the advantage of preventing flooding and very high turbulence in the liquid, so the distribution of bubbles will be more uniform all over the tank.

When designing aeration tank there is an optimum value for the impeller speed, if the speed of the impeller is very low then the impeller will not be capable of reducing the size of the bubbles and the dispersion of gas in the liquid phase will not be effect able. On the other hand, if the impeller speed is very high then this will increase the power consumption and may damage the microorganism in the system if they were applied.

4 Conclusions

A series of laboratory experiments were conducted to determine the volumetric mass transfer coefficient (k_La) in an agitated vessel and the different factors that affect this processes. Four main factors were studied in this project and they are the impeller type and size, agitation speed and air flow rate. The following is the results that were obtained from the experiments:

-It was noticed that well design impellers provided better performance. Some of the impellers used in the study are specified for gas liquid mixing such as Rushton turbine and CD-6, which gave the best results of k_La. The poorest results were obtained with saw-tooth impeller, because it is specified for high viscous liquid mixing.

-It was noticed that as the size of the impeller increases and meets the standards of design, the value of k_La enhances.

-Proper impeller design that meets the standards show better results for example, Rushton turbine impeller had the best degree of mixing and k_La value, but when comparing the power number between Rushton turbine and CD-6 it is noticed that the power number of CD-6 is relatively low and the k_La value is not very small compared with Rushton turbine, so for economical reasons it is better to used CD-6 rather than Rushton turbine.

- It was observed that as the agitation speed and air flow to the system increased the value of k_La improved.

-There were different arguments on which is the most effective type of impeller that increases the mass transfer coefficient from different research papers. Suhaili et al. [14] proved that CD-6 impeller has higher mass transfer coefficient than the Rushton turbine, due to lower shear stress. On the other hand Gimbun et al.[18] and zhu et al. [19] reported better value of k_La in Rushton turbine.

Acknowledgment

The authors wish to thank Sohar University for supporting the project.

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