Comparative Study of Mass Transfer and Bubble Hydrodynamic Parameters in Bubble Column Reactor: Physical Configurations and Operating Conditions

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ABSTRACT

In this paper, effects of physical configurations and operating conditions on bubble column performance were analyzed in terms of bubble hydrodynamic and mass transfer parameters. Bubble column with 3 different dimensions and 7 gas diffusers (single / multiple orifice and rigid / flexible orifice) were applied. High speed camera and image analysis program were used for analyzing the bubble hydrodynamic parameters. The local liquid-side mass transfer coefficient (k_L) was estimated from the volumetric mass transfer coefficient (k_La) and the interfacial area (a), which was deduced from the bubble diameter (D_B) and the terminal bubble rising velocity (U_B). The result showed that the values of k_La and a increased with the superficial gas velocity (V_g) and the size of bubble column. Influences of gas diffuser physical property (orifice size, thickness and orifice number) can be proven on the generated bubble size and the mass transfer performance in bubble column. Concerning the variation of k_L coefficients with bubble size, 3 zones (Zone A, B and C) can be observed. For Zone A and Zone C, a good agreement between the experimental and the predicted K_L coefficients was obtained (average difference of $\pm 15\%$), whereas the inaccuracy result (of $\pm 40\%$) was found in Zone B. To enhance the high k_La coefficient and absorption efficiency in bubble column, it was unnecessary to generate numerous fine bubbles at high superficial gas velocity since it causes high power consumption with the great decrease of k_L coefficients.

Keywords: Bubble column, Bubble size, Interfacial area, Liquid-side mass transfer coefficient, Superficial gas velocity, Volumetric mass transfer coefficient

1. Introduction

Bubble column reactors belong to the general class of multiphase reactors which is basically a cylindrical vessel with a gas distributor (diffuser) at the bottom. The gas is sparged in form of bubbles into either liquid phase or liquid-solid suspension. In practice, bubble columns are widely used in industrial gas-liquid operations (absorption) and industrial chemical and biochemical processes due to their simple construction, low operating cost, and high-energy efficiency. From many advantages, this process is applied in aeration and purification process of VOCs, CO₂, and odor abatement [1]. Gas-liquid mass transfer is one of the key factor governing the reactor performance, which relates to hydrodynamics and physical properties.

To improve the overall performance, numerous researches have studied the diffuser characteristics as well as influences of liquid phase for modifying and controlling the bubble hydrodynamic and mass transfer parameters. In industrial operation, various gas spargers (diffusers) are used as such as perforated plate, porous disk diffuser, membrane gas diffuser, which can be classified as rigid and flexible diffusers. Several studies regarding bubble diameters generated from different gas sparger types in bubble columns have been published by Bouaifi et al. [2] and Hébrard et al. [3].

The bubble hydrodynamic parameters (bubble diameter, bubble rising velocity and its formation frequency) can be significantly affected by different types of gas diffusers and contaminants (e.g., surfactants and organic substances) presence in liquid phases. Note that the interfacial area (a) can be experimentally determined

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using detached bubble diameters, bubble formation frequencies, and terminal bubble rising velocities as in Painmanakul *et al.* [4]. Concerning the study of mass transfer parameters, the volumetric mass transfer coefficient ($k_L a$), which is the product of the liquid-film mass transfer coefficient (k_L) and the interfacial area (a), is generally used for analyzing the global mass transfer mechanism and comparing different operating conditions in a bubble column. However, this $k_L a$ coefficient is global and insufficient to describe mass transfer mechanisms relating with effects of gas diffusers and liquid phase contamination [5, 6]. It is therefore necessary to separate the parameters, the k_L coefficient and the interfacial area, in order to provide a better understanding on gas-liquid mass transfer mechanism in bubble column.

Several studies on bubble column were regarded effects of various physical configurations (bubble column dimension and gas diffuser) and operating conditions (superficial gas velocity) on bubble hydrodynamic and mass transfer parameters [3, 7-9]. Most of those results were in small bubble column, which should be validated in larger scale column with different gas diffusers. Higher superficial velocity of bubble should be also applied. Moreover, the role of orifice physical characteristic (size, thickness, and elasticity) should be well analyzed to propose a suitable bubble column design and operation for aeration and absorption processes. Therefore, the objective of this work was to study and validate influences of physical configurations and operating conditions on bubble column performance in terms of bubble hydrodynamic, and mass transfer parameters. Different bubble column dimension and gas diffusers (i.e., single and multiple orifices as well as rigid and flexible orifices) were applied. Air and tap water were respectively selected as absorbate and absorbent for operating under room temperature ($T \gg 25^\circ\text{C}$). The local experimental methods for measuring the bubble hydrodynamic parameters were applied. Moreover, the method for separately analyzing the liquid-film mass transfer coefficient (k_L) and the interfacial area (a) was used for enhance the absorption efficiency in a bubble column.

2. Materials and Methods

2.1. Experimental Setup

The experiment set up is schematically represented in Fig. 1. The experiments were conducted in three bubble column configurations as summarized in Table 1. Bubble is generated by an air pump passing through different gas diffusers (5) with the flow rate regulated by a gas flow meter (2). Examples of gas diffusers installation are presented in Fig. 2.

Bubble hydrodynamic parameters were investigated by using the high speed camera with 120 images/sec (3) and image analysis software (4) (Basler Inc., USA). The Unisense oxygen microsensor with very fast response time (≈ 50 ms) was used for measuring the change of dissolved oxygen concentration. All chemical solutions were injected at the top of the column. Note that sodium sulfite (Na_2SO_3) was used for decreasing amount of dissolved oxygen in water before $k_L a$ coefficient was analyzed.

Fig. 1. Schematic diagram of the experimental set-up.

Fig. 2. Installation of flexible orifice in bubble column - Fixable (F1).

2.2. Gas Diffusers Used in This Study

Air diffusers used in this work were 2 rigid diffusers (R1 and R2) and 5 flexible diffusers (Fo1, F1, F2, F3 and F4) as shown in Fig. 3. Bubbles were generated by a diffuser that located at the membrane center. In case of small bubble column configuration, gas diffusers with single orifice (R1, F1 and Fo1) were applied. Therefore, it was necessary to close several holes without modifying the elastic properties of flexible diffuser.

The physical characteristics and the diffuser configuration in bubble column can be summarized in Table 1. Without liquid phase, the flexible orifice size measurements were based on the joint use of Sony DXC 930P 3CCD color camera (Japan) and Nikon SMZ-U microscope (Japan). The image processing was performed by the Visilog 5.4 software (C++ program).

2.3. Determination of Bubble Hydrodynamic Parameters

In order to achieve statistically significant distribution, the average bubble diameter (d_B) in this study was deduced from the measurement of 150-200 bubbles. The average bubble formation frequency, f_B (i.e., the number of bubbles formed at the membrane orifice per unit time) was determined as in Eq. (1) [4].

Fig. 3. Different types of gas diffusers used in this study.

Table 1. Physical Characteristic of Diffuser and Operating Conditions

Bubble column configuration			Gas diffuser types and characteristics				
	Diameter (cm)	Height (cm)		Type	Name	Thickness (mm)	Orifice size (mm)
Small	5	30	Single orifice	Rigid	R1	-	0.50
				Flexible	F1	2.06	0.25 - 0.55
				Flexible	Fo1	2.15	0.12 - 0.19
Medium	10	100	Multiple orifices	Rigid	R2	-	0.25
				Flexible	F2	1.65	0.2 - 0.25
				Rigid	R2	-	0.25
Large	15	100		Flexible	F3	2.9	0.14 - 0.25
				Flexible	F4	2.08	0.15 - 0.30

$$f_B = \frac{Q_G}{V_B} \quad (1)$$

$$a = N_B \times \frac{S_B}{V_{Total}} = f_B \times \frac{H_L}{U_B} \times \frac{S_B}{V_{Total}} \quad (3)$$

where V_B is the average detached bubble volume and Q_G is the gas flow rate. Owing to the image processing system, the terminal rising velocity of bubble (U_B) can be estimated from the distance covered by a bubble (DD) in two frames with known capture duration (T_{frame}).

$$U_B = \frac{\Delta D}{T_{frame}} \quad (2)$$

From Painmanakul et al. [10], the interfacial area (a) is a function of f_B , U_B , and d_B . It can be expressed as in Eq. (3) where H_L and V_{Total} are height and overall volume of liquid phase in a column. S_B is a surface area of a bubble.

2.4. Determination of Mass Transfer Coefficients

The experimental approach presented in Painmanakul et al. [10] was used to determine the specific interfacial area (a) and the corresponding volumetric mass transfer coefficient ($k_L a$). Due to the absorption of oxygen in water, the gas-liquid mass transfer mechanism is governed by the liquid phase. The volumetric mass transfer coefficient ($k_L a$) then can be determined from Eq. (4).

$$\frac{\partial C_L}{\partial t} = k_L a (C_L^S - C_L) \quad (4)$$

C_L is the dissolved oxygen concentration, and C_L^S is the saturation

oxygen concentration in liquid phase. The coefficient $k_L a$ is the product of the liquid-side mass transfer coefficient (k_L) and the interfacial area (a). Therefore, k_L coefficient can be simply determined by:

$$k_L = \frac{k_L a}{a} \quad (5)$$

3. Results and Discussion

3.1. Volumetric Mass Transfer Coefficient ($k_L a$)

Fig. 4 presents the variation of $k_L a$ values with the superficial gas velocity (V_g) for different gas diffusers (rigid and flexible) and bubble columns types. Fig. 4(a)-(c) respectively present the $k_L a$ coefficients from the small, medium, and large column (i.e., column diameters of 5, 10, and 150 cm) with a summary in Fig. 4(d).

As can be seen, the $k_L a$ coefficients were obviously affected by the V_g . The increase of bubble number in the column can enhance the total surface of bubble for gas-liquid mass transfer. The $k_L a$ values of 0.001 - 0.05 sec^{-1} were obtained for the V_g of 0.000425 - 0.0283 m/sec in all experiments. The coefficients obtained from larger column were higher than those of the smaller one. Influences of V_g and Q_G should be applied for describing the results.

Concerning effects of diffusers, the difference of $k_L a$ coefficients

was more pronounced in the larger column as shown in Fig. 4(d). The diffusers with single orifice (R1, F1 and Fo1) provided similar $k_L a$ coefficients from small column. However, the $k_L a$ obtained in the medium column with rigid orifice with multi-orifice (R2) were higher than those of flexible one (F2). The same tendency can also be observed in large column as $k_L a$ (R2) > $k_L a$ (F3) > $k_L a$ (F4). These results presented the advantage of using rigid orifice in bubble column, especially for large diameter. Moreover, the experimental results in this work can be validated by using the same rigid diffuser (R2) in medium and large column. The $k_L a$ coefficients were increased continuously with the superficial gas velocity. Therefore, the simple prediction model can be proposed as expressed in Eq. (6).

$$k_L a = 0.5643 \times V^{0.7332} \quad (6)$$

The $k_L a$ values calculated by Eq. (6) are compared with the experimental results in Fig. 5 for different gas diffusers (rigid and flexible) and bubble columns types (small, medium and large). The discrepancy range of 35% can be noticed. The differences of bubble column configurations and operating conditions should be responsible for these results. In addition, the $k_L a$ coefficients are generally too global and difficultly evaluated in practical application. Therefore, local measurement of bubble diameter and the interfacial area (a) was performed and presented in next section to provide a better understanding on effects of gas diffusers and the gas-liquid mass transfer mechanisms.

Fig. 4. Volumetric mass transfer coefficients ($k_L a$) vs. superficial gas velocity (V_g) in (a) small bubble column, (b) medium bubble column, (c) large bubble column, and (d) summary.

Fig. 5. Comparison of experimental and predicted volumetric mass transfer coefficient (k_{La}).

3.2. Bubble Diameter (D_B)

Variations of bubble diameter (D_B) with the superficial gas velocity (V_g) in the small column are depicted in Fig. 6(a). Rigid diffusers with single orifice (R1) tended to produce constant bubble sizes (> 4.5 mm) as the orifice was unchanged with increased gas flow rate ($d_{OR} = 0.5$ mm). On the contrary, bubble sizes from the flexible diffuser with single orifice (F1 and Fo1) were increased with the gas flow rate as the orifice sizes of the diffusers were enlarged at larger gas flow rate.

Fig. 6(b) depicts the growth of orifice size (0.25–0.55 mm) of flexible diffuser (F1) with increased V_g . It was worth noting that the bubble diameter was about 10 times of the orifice size. These results conformed to the data from flexible diffusers with small orifice size of 0.12–0.19 mm (Fo1) as well as the data from single orifice diffuser [4, 11]. The importance of orifice size and its characteristic can be concluded, especially for diffuser with single orifice. It should be noted that the flexible diffuser (Fo1) cannot be operated at higher V_g due to its manual fabrication and physical properties. The results therefore cannot be used for comparing with other diffusers (F1 and R1) regarding effects of superficial gas velocity.

For the results from R1 and F1, the difference in D_B was more pronounced at low superficial gas velocities ($V_g < 7.5 \times 10^{-4}$ m/sec). At low V_g , the difference in bubble diameter directly linked to the surface tension. The balance between the surface tension and the buoyancy force during the bubble growth and detachment was consequently different for dissimilar orifice diameter. However, a bubble diameter was no longer controlled by the force balance at higher V_g , but instead governed by the power dissipated in a liquid phase. This can cause the break-up of and coalescence of bubbles [12, 13].

Bubble sizes generated with different types of multi-orifice diffusers and column dimensions (medium and large column) is shown in Fig. 7. Bubble sizes from the single orifice diffuser in the small column (2.5–6 mm) were larger than those from the multiple-orifice diffuser in the medium and the large columns (1.5–3.5 mm). Influence of the orifice characteristic (i.e., flexible or rigid) cannot be clearly seen as bubble sizes seemed to be

Fig. 6. (a) Bubble diameter (D_B) vs. superficial gas velocity (V_g) for small bubble column, (b) example of orifice size obtained with flexible diffuser with single orifice (F1) at different superficial gas velocities.

Fig. 7. Bubble diameter (D_B) vs. superficial gas velocity (V_g) for (a) medium bubble column and (b) large bubble column.

constant at every condition. This can confirm effects of power dissipated in the liquid causing the bubble break-up and coalescence phenomena at high superficial gas velocity ($V_g > 7.5 \times 10^{-4}$ m/sec). Furthermore, the same ranges of bubble size (1.75-2.3 mm) were found from the rigid diffuser (R2) in the medium and the large column, but smaller than bubbles generated from the R1 diffuser. The orifice size should be responsible for these results since the orifice diameter of R2 (0.25 mm) was smaller than that of R1 (0.5 mm).

In the medium column, bubble sizes from the flexible diffusers (F2, F3, and F4) were similar and close with the R2. The difference can be noticed in the large column with higher V_g that D_b from the F3 and F4 diffusers were obviously greater than that of R2 since the orifice sizes were enlarged with the gas velocity. According

Fig. 8. Bubble velocity (U_b) vs. bubble diameter (D_b).

to the physical properties of diffusers in Table 1, the smallest bubbles were found from the F2 diffuser, which was the thinnest one (1.65 mm). Therefore, it can be stated that the physical property can affect the orifice size due to the elasticity or deflection at the centerline. The thin flexible diffuser provided small orifice size and smaller bubble size as a result.

In conclusion, the diffuser properties as in Table 1 can impact the generated bubble sizes. The rigid diffuser should be operated at high superficial gas velocity in a large bubble column as the produced bubble size was related with the orifice size. However, this kind of diffuser usually encounters the clogging problem, which should be well considered in the operation. In the case of flexible diffuser, the orifice size and the velocity V_g have to be controlled for maintaining the generation of small bubbles. In the next part, the interfacial area, which is one of key parameters in the gas-liquid mass transfer study, was determined from bubble sizes obtained experimentally.

3.3. Interfacial Area (a)

Fig. 8 displays the relation between bubble velocities and bubble diameters in different bubble columns and operating conditions with the experimental U_b values obtained by Grace and Wairegi [14]. The bubble velocity (U_b) of 0.15-0.25 m/sec were obtained from the diameters of 1.6-6.2 mm. Small bubbles in the large column tended to have lower rising velocity than in the small column due to effects of power dissipated in the liquid resulting in the break-up of bubbles. Bubbles then obstructed movement of each other out of the column. Moreover, it can be stated that

Fig. 9. Interfacial area (a) vs. superficial gas velocity (V_g) for (b) small bubble column, (c) medium bubble column, and (d) large bubble column.

small bubbles (low U_B values) can enhance the retention time of bubble in column, thus increasing the bubble specific interfacial area (a).

By using the experimental results of the bubble sizes and their rising velocities, the bubble formation frequencies (f_b) at different gas superficial velocities can be calculated. The local interfacial area (a) can then be determined. Fig. 9 presents the relation between the interfacial area (a) and the superficial gas velocity for different diffusers (F1, Fo1, F2, F3, F4, R1 and R2) and bubble column dimensions (small, medium and large) used in this work.

For gas diffusers with single orifice, the interfacial areas (a) varied between 2.5 and 13 m^{-1} while superficial gas velocities were between 0.0002 and 0.0015 m/sec as shown in Fig. 9(a). Whatever the orifice type, the values of a were linearly increased with the superficial gas velocities. The values obtained from Fo1 were obviously greater than those of F1 and R1, which corresponded to the lowest d_b and U_B as aforementioned. However, the physical property of diffuser (Fo1) in terms of elasticity and shear stress should be well considered in practical operation, especially at higher superficial gas velocity.

Regarding effects of diffuser and column types, interfacial area were rose along with V_g as shown Fig. 9(b), (c) for the medium and large columns, respectively. Moreover, the increase of the cross-sectional area of column also played a role since the gas flow rate was enhanced as a result. The a values obtained from the rigid diffuser (R2) were clearly greater than those of flexible diffusers (F2, F3 and F4). Small bubbles with low rising velocity from the rigid orifice (R2) were responsible for this result. Moreover, the results of the R2 diffuser were validated in the medium and the large columns as increased with V_g depicting in Fig. 9(d). This result conformed to those obtained with the $k_L a$ coefficient as in Fig. 4(d). Note that the difference in a can be clearly observed from the Fo1 diffuser in the small column whereas the related $k_L a$ coefficients were close to those obtained from different diffusers (F1 and R1) as shown in Fig. 4(a). For a better understanding of the gas-liquid transfer phenomena, the liquid-side mass transfer coefficient (k_L) was considered in the next part.

3.4. Liquid-side Mass Transfer Coefficient (k_L)

The k_L coefficient can be calculated from the experimental values of the volumetric mass transfer coefficient (Fig. 4) and the interfacial area (Fig. 9) by Eq. (5). The values of k_L were scatter since the calculation of k_L could possess errors from the measurements of both $k_L a$ and a. The average and maximum experimental errors for determining the k_L were estimated at 10% and 15%, respectively [10]. Fig. 10 shows the variation of the liquid-side mass transfer coefficient (k_L) with the superficial gas velocity (V_g) for different gas diffusers and bubble column types.

According to Fig. 10, the obtained k_L varied between 1×10^{-4} and 4×10^{-4} m/sec for V_g in the range of 0.0002-0.03 m/sec. At every operating condition, the k_L values tended to be constant for the gas flow rates greater than 0.0004 m/sec. On the contrary, k_L was increased with V_g at lower velocities. Fig. 11 displays the variation of k_L with the bubble diameter (D_b) for the different gas diffusers and bubble columns. This plot was applied for analyzing and comparing the results in this study with the three zones

Fig. 10. Liquid-side mass transfer coefficient (k_L) vs. superficial gas velocity (V_g) or different bubble column configurations.

Fig. 11. Liquid-side mass transfer coefficient (k_L) vs. bubble diameter (D_b).

of k_L coefficients proposed by Painmanakul et al. [10] and Sardeing et al. [15].

According to Fig. 11, the k_L coefficient was roughly constant at D_b larger than 3.5 mm and then slightly decreased up to the D_b of 1.5 mm before remaining constant until 1.5 mm. The dimension of bubble columns cannot affect the k_L coefficient. The coefficient k_L only depend on bubble sizes due to a modification of the gas-liquid interface nature (size and shape of generated bubbles) coupled with local hydrodynamic changes (terminal rising bubble velocity and drag coefficient of bubbles). Three zone of the variation between k_L and D_b can be observed in Fig. 11 as follows.

- 1) **Zone A ($d_b < 1.5mm$):** k_L are low for small bubbles (about 1×10^{-4} m/sec) [16] corresponded with the results obtained from the flexible diffuser (Fo1).
- 2) **Zone B ($1.5 < d_b < 3.5mm$):** k_L values were increased (1×10^{-4} to 4×10^{-4} m/sec) with the bubble diameter. The modification of the bubble shape (from sphere to ellipsoid) as well as the bubble interface should be responsible for

these result [15]. The diffusers (R2, F2, F3, and F4) can provide the bubble sizes and the k_L coefficient in this zone.

3) Zone C ($d_B > 3.5\text{mm}$): k_L values were independent on bubble diameters conforming with the results of Higbie [17]. The k_L were constant for larger bubble size behaving as fluid particles with a mobile surface. This zone can be related with the results obtained from the diffusers (F1 and R1).

Table 2 summarizes the existing model for prediction of liquid-side mass transfer coefficient (k_L). Note that, the value of surface coverage ratio at equilibrium (s_e) in case of clean liquid phase, used in this work. In Fig. 12, the comparison between the experimental results and the predicted values from the existing models is presented.

This figure shows that a good agreement between the experimental and the predicted k_L coefficients was obtained (average difference of $\pm 15\%$), especially for Zone A and Zone C. However, more experimental data are necessary for more accurate predicting and validating the Zone B correlation (average difference of $\pm 40\%$). These zone related with the diffusers (R2, F2, F3 and F4) operated at high superficial gas velocities in medium and large columns. The bubble break-up and coalescence phenomena due to the power dissipated in the liquid phase should be responsible for these results. Moreover, this can possibly affect the k_{La} prediction model (average difference about $\pm 35\%$) as shown in Fig. 5. In the future,

Table 2. Prediction Model for Liquid-Side Mass Transfer Coefficient (k_L)

	Prediction model for k_L coefficient	References
Zone A	$k_L = \frac{D}{d_B} \left(2 + 0.6 Re^{1/2} Sc^{1/3} \right)$	Frössling equation Treybal [16]
		Sardieng et al. [15]
Zone B	$\frac{k_L - k_L^{Zone A}}{k_L^{Zone C} - k_L^{Zone A}} = (1 - s_e) \times \left(\frac{d_B - d_B^1}{d_B^0 - d_B^1} \right)$	d_B^1 is equal to 1.5 mm d_B^0 is equal to 3.5 mm
Zone C	$k_L = 2 \sqrt{\frac{D}{\pi t_e}} = 2 \sqrt{\frac{DU_B}{\pi D_B}}$	Higbie [17]

Fig. 12. Comparison of experimental and predicted the liquid-side mass transfer coefficient (k_L).

effects of the geometrical transition from the sphere to ellipsoid of bubbles on the k_L coefficient should be focused, especially for Zone B in order to propose more precision model for mass transfer parameters (k_{La} and k_L).

Due to low k_L in Zone A, it can be stated that the generation of tiny bubbles ($D_B < 1\text{mm}$) was unnecessary to increase the mass transfer capacity. The increase of interfacial area from generated fine bubbles can be compromised by the great decrease of the k_L coefficient. These results conformed to the case of diffuser (Fo1) in the small bubble column. Even the increase of a can be clearly observed, the related k_{La} coefficients were close to those observed from the different diffusers (F1 and R1). Therefore, within the range of bubble sizes (1.5-2.3 mm) generated by the R2 diffuser, high interfacial area and moderate k_L coefficient can be obtained. These can provide the maximum k_{La} coefficient for gas-liquid mass transfer. In the case of a gas-liquid reactor equipped with gas diffuser, the total specific power consumption (P_g/V_{Total}) for mixing condition could be related to the total gas pressure drop as in Eq. (7).

$$\frac{P_G}{V_{Total}} = Q \times \frac{\Delta P_{Total}}{V_{Total}} = Q \times \frac{(\rho_L \cdot g \cdot H_L + \Delta P)}{V_{Total}} \quad (7)$$

The total gas pressure drop (ΔP_{Total}) is a function of the liquid height ($r \cdot g \cdot H_L$) and the specific sparger pressure drop (ΔP), which is increased with the gas velocity through the orifice ($V_g = Q_g/A_{OR}$). From Painmanakul et al. [4], the value of ΔP increases with the gas flow rate as well as the decrease of hole area or orifice size for small bubble generation. The drawback in term of energy consumption for small bubble size has to be taken into account as the important consequences for using the bubble column in real operating condition.

In conclusion, the influence of gas diffuser in bubble column can be concluded and validated within the different bubble column configurations and operating conditions. To obtain high interfacial area and k_{La} coefficient, small orifice size should be used for generating the small bubbles. From the obtained results, the advantage of rigid diffuser operated at high superficial gas velocity in the large bubble column can be found. However, the clogging problem of a diffuser must be taken into account. For flexible diffuser, the control of superficial gas velocity and orifice size should be well considered in order to maintain a small bubble generation in the reactor. Moreover, it was unnecessary to generate numerous fine bubbles at high superficial gas velocity for enhancing the k_{La} coefficient and absorption efficiency in the bubble column. The increase of values can be withdrawn by the great decrease of the k_L coefficients as well as the increase of related power consumption.

4. Conclusions

The objective of this work was to study influences of bubble column dimensions, gas diffuser types, and superficial gas velocities (V_g) on bubble column performance in terms of bubble hydrodynamic and mass transfer parameters. For this purpose, the methods for

determining the volumetric mass transfer coefficient ($k_L a$), bubble size (D_B), interfacial area (a), and liquid-film mass transfer coefficient (k_L) were applied to enable the absorption efficiency in a bubble column. The following results were obtained:

- The $k_L a$ coefficients increased with the superficial gas velocity (V_g) and the bubble column size. The prediction model was proposed with the average difference between the experimental and predicted k_L of $\pm 35\%$:

$$k_L a = 0.5643 \times V^{0.7332}$$

- For single orifice gas diffuser, physical property of gas orifice can clearly influence the generated bubble size, especially at low superficial gas velocity. Less effect was found at higher V_g due to the power dissipated in the liquid resulting in the bubble break-up and coalescence phenomena;
- In the case of gas diffuser with multiple orifices, effects of orifice size, diffuser thickness, and superficial gas velocity were noticed on the modification of generated bubble size presence in bubble column;
- At highest interfacial area, the advantage of rigid diffuser can be obtained for high V_g operation in large bubble column due to the generation of small bubbles with low rising velocity;
- Three zones of k_L coefficients with different bubble sizes (1×10^{-4} m/sec in Zone A, $1 \times 10^{-4} - 4 \times 10^{-4}$ m/sec in Zone B, and 4×10^{-4} m/sec in Zone C) can be found. The result was validated with different bubble column configurations and operating conditions;
- To enhance the $k_L a$ coefficient and absorption efficiency in bubble column, it was unnecessary to generate numerous fine bubbles at high superficial gas velocity for highest interfacial area as this can be cancelled out by the great decrease of the k_L coefficients as well as the increase of power consumption.

In the future, further study should be conducted on effects of different liquid phase contamination in order to validate the role of bubble column configuration and operating condition obtained in this work as well as provide a better understanding on gas-liquid mass transfer mechanism. To propose more accurate model for predicting mass transfer parameters ($k_L a$ and k_L coefficients), more experimental data are required, especially for the gas diffuser or bubble size ranging within Zone B ($1.5 < d_B < 3.5$ mm). Finally, the industrial-scale bubble column (larger column dimension and higher superficial gas velocity) should be studied for extending the lab-scale results into the practical operating condition.

Notation

C_L^*	oxygen concentration at saturation, $\text{kg} \cdot \text{m}^{-3}$
D	gas diffusivity coefficient, $\text{m}^2 \cdot \text{sec}^{-1}$

k_L	liquid-side mass transfer coefficient, $\text{m} \cdot \text{sec}^{-1}$
k_L^{rigid}	liquid-side mass transfer coefficient for bubbles with a rigid interface, $\text{m} \cdot \text{sec}^{-1}$
k_L^{ZoneA}	liquid-side mass transfer coefficient for bubble diameters smaller than 1.5 mm (Zone A), $\text{m} \cdot \text{sec}^{-1}$
k_L^{ZoneB}	liquid-side mass transfer coefficient for bubble diameters between 1.5 and 3.5 mm (Zone B), $\text{m} \cdot \text{sec}^{-1}$
k_L^{ZoneC}	liquid-side mass transfer coefficient for bubble diameters greater than 3.5 mm (Zone C), $\text{m} \cdot \text{sec}^{-1}$
a	specific interfacial area, m^{-1}
$k_L a$	volumetric mass transfer coefficient, sec^{-1}
Sc	Schmidt number defined by, $(= \frac{\mu_L}{\rho_L D})$, dimensionless
Re	bubble Reynolds number defined by, $(= \frac{\rho_L d_B U_B}{\mu_L})$, dimensionless
Se	surface coverage ratio at equilibrium, dimensionless
d_B	bubble diameter, m
d_B^0	maximum bubble diameter to have a spherical shape, m
d_B^1	minimum bubble diameter to have an ellipsoidal shape, m
d_{OR}	equivalent hole diameter, m
t_e	time of exposure, sec
V_B	bubble volume, m^3
U_B	terminal bubble rising velocity, $\text{m} \cdot \text{sec}^{-1}$
V_L	liquid volume in the reactor, m^3
V_{total}	total volume in reactor, m^3
V_g	superficial gas velocity, $\text{m} \cdot \text{sec}^{-1}$
f_B	bubble formation frequency, sec^{-1}
h	height of an ellipsoidal bubble, m
H_L	liquid height in the bubble column, m
g	gravitational acceleration, $\text{m} \cdot \text{sec}^{-2}$
ΔP	specific sparger pressure drop

Greek letters

μ_L	liquid viscosity, Pa·s
ρ_L	gas density, $\text{kg} \cdot \text{m}^{-3}$

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