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Effect of Impeller Blade Number on K_La in Mechanically Agitated Vessels

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Abstract–Effects of impeller blade number on gas dispersion and mass transfer rate were thoroughly investigated for mechanically agitated vessels equipped with 2-, 4-, 6- and 8-straight blades disk turbine impellers. The results show that under the same rotational speed, the impeller with more blades always can disperse gas more effectively, which induces a higher value of $\langle K_La \rangle$. However, with the same total power consumption, the 4-blade impeller can obtain a higher $\langle K_La \rangle$ value than the 6- and 8-blade impellers under a lower gassing rate condition (Q_g<0.5 vvm), but if Q_g exceeds 0.5 vvm, the 6-blade impeller will perform better than the 4- and 8-blade impellers. To examine the results obtained from the single impeller systems, the same approach is applied to measure $\langle K_La \rangle$ values for the triple stage 6-blade impeller system (3×6) and quadruple stage 4-blade impeller system (4×4). From the experimental results, it can be found that the 4×4 system gives higher $\langle K_La \rangle$ value than the 3×6 system under gas completely dispersed conditions. By correlating $\langle K_La \rangle$ with n_b, N and V_s, the following correlation can be given as:

$$\langle K_La \rangle = 0.00119 n_b^{0.62} N^{1.56} V_s^{0.4}$$

or

$$\langle K_La \rangle = 0.0297 n_b^{0.1} (P_g/V)^{0.34} V_s^{0.48}$$

These two correlations can also be used to evaluate the mass transfer coefficient of each impeller region for the multiple impeller systems and the deviation is always less than 10%.

Key words : Stirred Vessel, Blade Number, Mass Transfer Coefficient, Power Consumption, Multiple Impeller System

INTRODUCTION

The effects of hydrodynamic parameters on the mass transfer rate in mechanically agitated vessels have been studied extensively by many researchers. Most of the previous works have been carried out using the 6-blade disk turbine impeller, the so-called the standard Rushton turbine impeller. However, the effects of power input on the mass transfer rate have only been discussed by changing the rotational speed and aeration rate. It is acknowledged that the selection of the impeller will affect not only the power consumption, but also the flow patterns and gas dispersion. At a given rotational speed, impellers with different blade numbers will contribute a different level of power input, which always plays an important role in the gas dispersion within the vessel, hence affecting the mass transfer rate pronouncedly.

There are only few research efforts emphasizing the effect of impeller blade number on the gas dispersion and mass transfer. Van't Riet [1979] gathered the mass transfer coefficient data shown in the literature and proposed a comprehensive $\langle K_La \rangle$ correlation for the air-water single Rushton turbine impeller system as:

$$\langle K_La \rangle = 0.026 (P_g/V)^{0.4} V_s^{0.5} \tag{1}$$

Although Van't Riet [1979] discussed the influences of some geometrical parameters on the mass transfer rate, the effects of the impeller geometry were still not taken into account.

In this study, the effect of the impeller blade number of a straight blade disk impeller on the mass transfer rate is discussed thoroughly for single and multiple impeller systems by adopting the N_2 gassing out method. By combining the measured power consumption data and superficial gas velocity, we propose an applicable correlation for the volume-averaged mass transfer coefficient $\langle K_La \rangle$ estimation.

EXPERIMENTAL

A transparent acrylic tank with diameter T=0.141 m was used as the stirred vessel. The liquid height H in the single impeller system was controlled at 0.169 m and 0.329 m in the multiple impeller systems to prevent surface aeration. Standard flat-blade disk-type turbines having 2, 4, 6 or 8 blades were used as the impellers, whose diameter D=T/3. Four vertical baffles with a width of B=1/10 T were installed in the periphery of the tank. The distance from the tank bottom to the lowest impeller is always D; however, the clearance between the impeller was maintained at 2 D in the triple impeller system and 1.5 D in the quadruple impeller systems to keep the liquid height constant. Tap water and filtered air were used as the working fluids. The N_2 gassing out method [Linek et al., 1989] was adopted to evaluate the local K_La value. A dissolved oxygen probe combined with a signal amplifier and computer system was used to record the change in dissolved oxygen concentration with the lapse of time. This was done by changing the gas inlet from N_2

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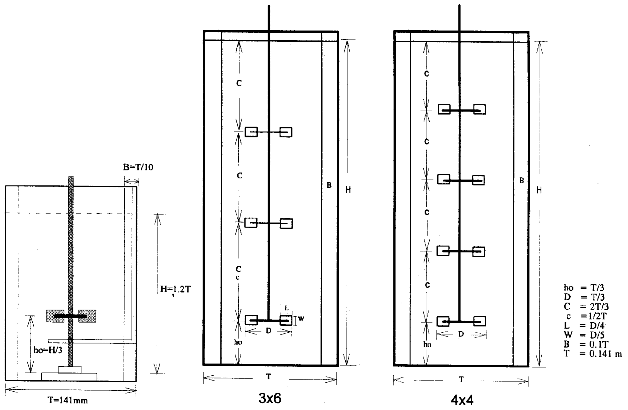

Fig. 1. Major dimensions for the impellers and the stirred vessels used in this study.

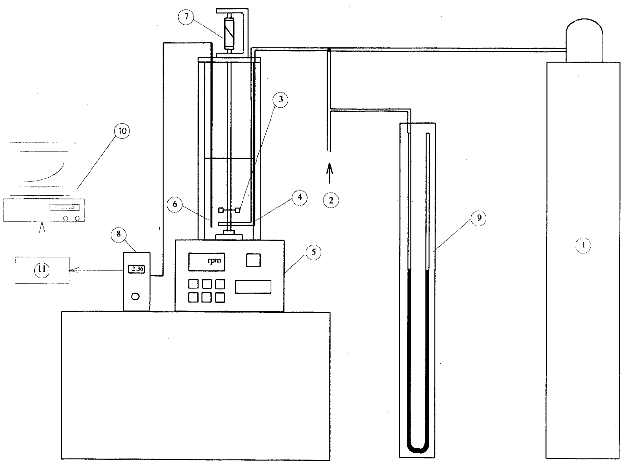

Fig. 2. Equipment set-up of <K_La> measurement.

1. Nitrogen source
2. Air inlet
3. Disc turbine impeller
4. Gas sparger
5. Magnetic driver
6. D.O. probe
7. Torque meter
8. Oxygen concentration indicator
9. Pressure manometer
10. Computer
11. AD/DA converter

to air instantaneously and recording the change of dissolved oxygen concentration with time. The K_La value can be obtained easily from the negative slope of the plot of $\ln(y^*-y)/(y^*-y_o)$ vs. t. A torque transducer with a self-balancing torque indicator was placed on the shaft to measure the power drawn by the impellers. The details of the major geometrical dimensions and the experimental equipment setup are shown in Fig. 1 and Fig. 2, respectively.

OPERATIONAL CONDITIONS

To investigate the gas dispersion capability of the various impellers, the mass transfer rate was determined and compared under the same rotational speed, the same power consumption per unit volume and the same power consumption per unit blade area conditions. Table 1 lists the operational conditions used in this study.

Table 1. The operational conditions adopted in this study

	N(rps)	Q_g(vvm)	P_g/V(W/m^3)	P_g/Vn_b(W/m^3)
Single impeller system	13.3	0.22-1.514	559.36	88.05
Multiple impeller system	13.3	0.22-1.514	1004.4	

RESULTS AND DISCUSSION

1. Effect of Blade Number and Gassing Rates on K_La for the Single Impeller System

Lu and Yang [1995] applied the LDA and modified capillary method to measure the turbulent intensity and dispersed bubble size in a stirred vessel to examine the effects of the impeller blade number on the flow pattern and gas dispersion within the stirred vessel. They pointed out that under a very low gassing condition the turbulent intensity is strongest for the 4-blade impeller, and the dispersed bubbles are also the smallest. These results indicate that the 4-blade impeller has the best gas dispersion capability and results in a better mass transfer rate. However, by comparing these results with other works in the literature, almost the contrary conclusions were found, which implies that the gassing rate plays a very important role on the mass transfer phenomenon. For single impeller systems, the volume-averaged mass transfer coefficient of the systems equipped with different impellers was compared under three different operating conditions to estimate the effects of the blade number and aerated rate on the mass transfer rate: (1) the same rotational speed; (2) the same total power consumption, and (3) the same power consumption per blade. Fig. 3 shows the overall averaged K_La for the single 2-, 4-, 6-, 8-blade disk turbine impeller

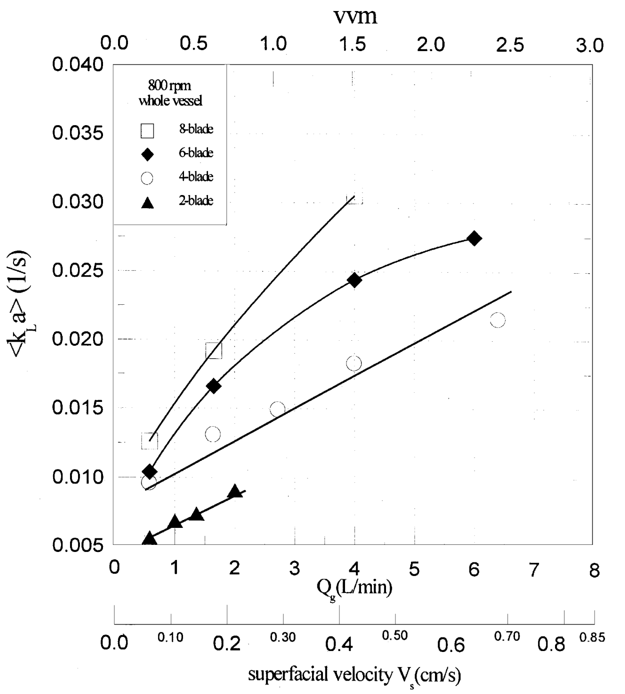

Fig. 3. Comparison of <K_La> between the impellers with various blade numbers for N=13.3 rps.

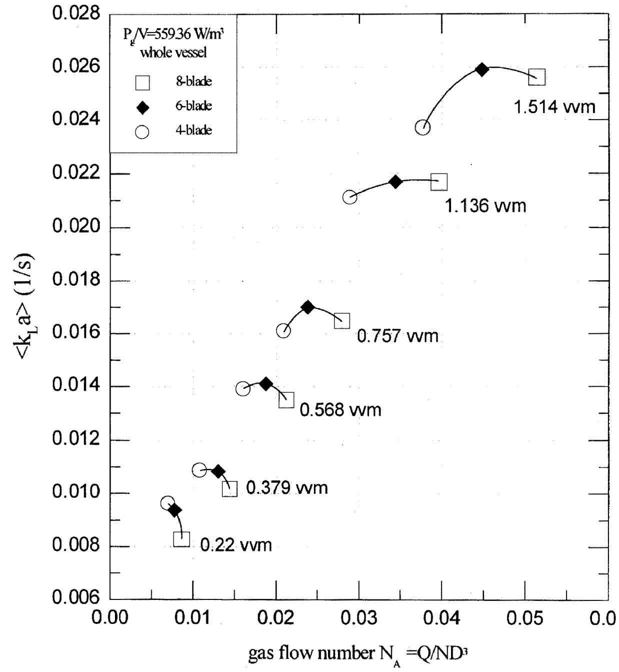

Fig. 4. Comparison of $<K_La>$ between the impellers having different blade numbers with $P_g/V=559.36\ W/m^3$.

systems under the same rotational speed N=13.3 rps. From this figure, we see two noticeable points: (1) the $<K_La>$ value for each impeller always increases monotonically with the increase of gassing rates; (2) no matter what the gassing rate is, the impeller with more blades always disperses the gas more effectively, which induces the higher value of $<K_La>$. However, under the same rotational speed the impeller having more blades always draws more power, which may not be favorable for industrial processes. In Fig. 4, the values of $<K_La>$ for the impeller having 4, 6 and 8 blades with the $P_g/V=559.36\ W/m^3$ are compared under various gas flow rates. It can be found that (1) with the same power consumption $<K_La>$ always increases with the increase in the gassing rates; (2) the 4-blade impeller can give a higher $<K_La>$ than the 6- and 8-blade impellers under a low gassing rate condition ($Q_g<0.5$ vvm), which is consistent with the results of Lu and Yang [1995]. However, with the increase in gassing rate, the 6-blade impeller demonstrates a better gas dispersion capability and results in a higher mass transfer rate. It is interesting to note that under a certain value of Q_g, the impeller equipped with 6 blades always gives a higher $<K_La>$ value than that of the 8-blade impeller.

Fig. 5 shows a comparison of the $<K_La>$ values for the 4-, 6-, 8-blade impellers under two different aerated conditions with the same power consumption per blade ($P_g/V_{nb}=88.0\ W/m^3$). From this figure, it can be found that if the gassing rate is larger than 0.5 vvm and less than 1.6 vvm, the 6-blade impeller will perform better than the other impellers. The 8-blade impeller will become the prevailing one if the gassing rate exceeds 1.6 vvm. From the above results, it can be concluded that in the single impeller system the 4-blade impeller gives the best mass transfer performance only under a low aerated condition. Under the higher power input and gassing rate, the impeller with more

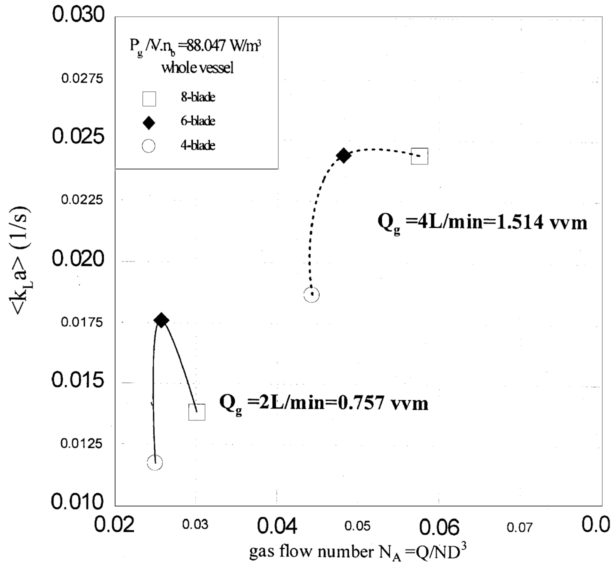

Fig. 5. Effect of blade number and aeration rate on $<K_La>$ with constant power consumption per blade (P_g/Vn_b= 88.0 W/m^3).

blades is likely to have more gas dispersion or a higher value of $<K_La>$.

2. Correlations for $<K_La>$ in the Single Impeller System

To obtain a useful correlation of $<K_La>$, the mass transfer coefficient data obtained in this study were correlated to cover the effect of n_b, N and V_s, and the correlation was given as

$$<K_La>=0.00119n_b^{0.62}N^{1.56}V_s^{0.4} \tag{2}$$

for the single disk turbine impeller system and it is plotted in Fig. 6 with the experimental data obtained. With this correlation, the $<K_La>$ value in the stirred vessel can be predicted from the original operation conditions (i. E. N, Q_g and n_b, etc.). However, in a practical scale-up design, the power consumption is always the most popular basis. In order to introduce the

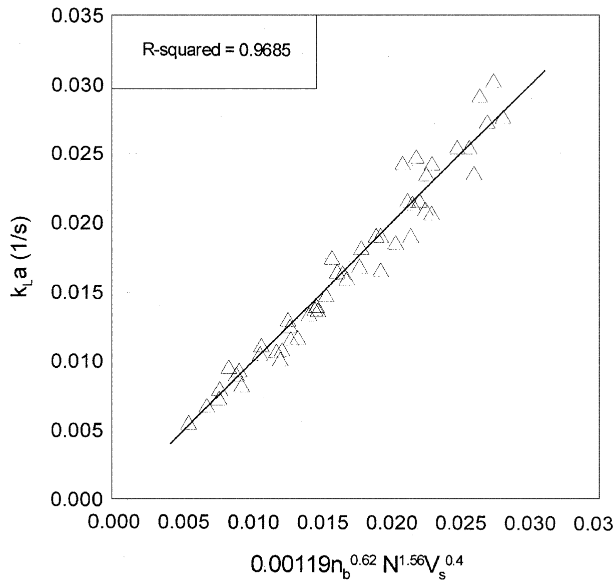

Fig. 6. $<K_La>$ regressive curve for the single impeller system based on the original operating conditions.

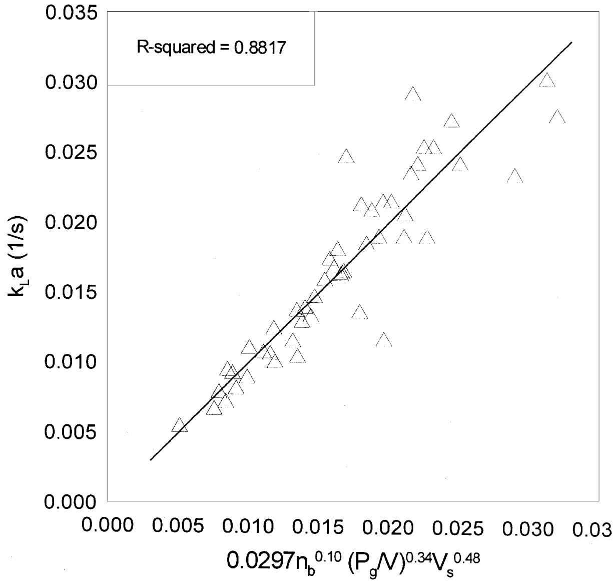

Fig. 7. $\langle K_La \rangle$ regressive curve for the single impeller system based on the power consumption of the impeller.

power drawn into this correlation, N was replaced by (P_g/V) in Eq. (2) and the results were given as :

$$\langle K_La \rangle = 0.0297 n_b^{0.1}(P_g/V)^{0.34}N^{1.56}V_s^{0.4} \quad (3)$$

The derivation of this equation is always less than 12% and the regressive result is shown in Fig. 7. From Eq. (3) one can obtain the required P_g/V for a gas-liquid contactor if the optimum value of $\langle K_La \rangle$ is known from the laboratory scale experiments.

3. K_La Values between Two Different Multiple Impeller Systems

From the results depicted above, it is interesting to compare the overall performances of gas dispersion in a system equipped with triple stages of 6-blade impellers (3×6) and a system equipped with quadruple stages of 4-blade impellers (4×4). Table 2 and Table 3 show the comparisons of the mass transfer performances between these two systems with Q_g=0.22 vvm and Q_g=0.757 vvm, respectively. In a lower gassing rate, it is surprising to notice that the 4×4 system gave 14% higher $\langle K_La \rangle$, while it drew 17.5% less power than the 3×6 system. However this trend will be reversed as the gassing rate exceeds 0.757 vvm. Although the 4×4 system drew less than 26.7% power, it gave less than 18.3% on average of K_La value. If the power for the 4×4 system is increased to the same level as the 3×6 system at the same gassing rate, the average values of K_La for both systems are nearly the same, as shown in Table 4.

Table 2. Comparison of the K_La values between 4×4 and 3×6 impeller systems under a very low aeration rate (Q_g= 1.2 L/min=0.22 vvm) and same rotational speed (N= 800 rpm=13.3 rps)

	$\langle K_La \rangle$	$\langle K_La \rangle$ ratio	Power ratio
3×6 (I)	0.0211	1	1
4×4 (II)	0.0241	1.142	0.825
(II-I)/I%	+14.2%	14.2%	−17.5%

Table 3. Comparison of the K_La values between 4×4 and 3×6 impeller systems under a higher aeration rate (Q_g= 3.97 L/min=0.757 vvm) and the same rotational speed (N=800 rpm=13.3 rps)

	$\langle K_La \rangle$	$\langle K_La \rangle$ ratio	Power ratio
3×6 (I)	0.0313	1	1
4×4 (II)	0.0256	0.817	0.733
(II-I)/I %	−18.3%	−18.3%	−26.7%

Table 4. Comparison of the K_La values between 4×4 and 3×6 impeller systems under a higher aeration rate (Q_g= 3.97 L/min=0.757 vvm) and the same power input (P_g/V=1004.4 W/m^3)

	3×6 impeller system	4×4 impeller system
$\langle K_La \rangle$	0.0313	0.0308
Ration of $\langle K_La \rangle$	1	0.982
Ratio of power consumption	1	1

The flooded impeller, which causes the 4×4 system to show a lower value of $\langle K_La \rangle$ at higher gassing rate with N=13.3 rps, was observed at the lowest impeller of the 4×4 system. If the flooded region was excluded from the calculation of $\langle K_La \rangle$, the remaining part of the 4×4 system still performed as well as the 3×6 system, as shown in Table 5. This fact implies that the increase in the blade numbers will increase the gas handling capability of the impeller, but too many blades (or too narrow blade pitch) will disturb the formation of a strong vortex, which will weaken the gas dispersion capability of the impeller.

4. Estimation of $\langle K_La \rangle$ Value for Multiple Impeller Systems

To examine whether Eq. (3), resulting from the single impeller system, can be applied to multiple impeller systems, the $\langle K_La \rangle$ data for each impeller region obtained from the 3×6 impeller system is plotted vs. $0.0297n_b^{0.1}(P_g/V)^{0.34}V_s^{0.48}$ in Fig. 8. From the results shown in this figure, it is found that no matter in which impeller region, the experimental $\langle K_La \rangle$ values are always larger than the predicted $\langle K_La \rangle$ values. Since both the recirculated gas and the sparged gas pass through the impeller region, they affect the mass transfer performance of the impeller. However, in Eq. (3), only the sparging gas rate is taken into account in the form of the superficial gas velocity, which induces an underestimation of the $\langle K_La \rangle$ values. Comparing the mass transfer performances in each impeller region, it is found that the upper

Table 5. Effect of the flooding phenomenon of the 4×4 system on $\langle K_La \rangle$ under a higher aeration rate (Q_g=3.97 L/min=0.757 vvm) and the same rotational speed (N= 800 rpm=13.3 rps)

	3×6 (I)	4×4 (II)	4×4 (III) with the flooded impeller excluded
$\langle K_La \rangle$	0.0313	0.0308	0.0318
$\langle K_La \rangle$ ratio	1	0.98	1.016

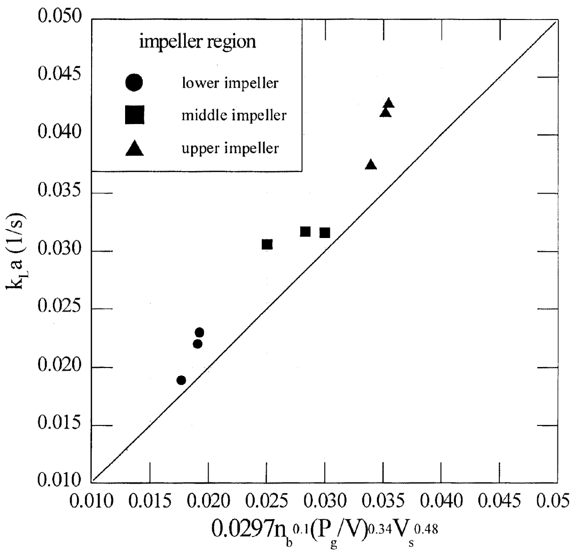

Fig. 8. The applicability of the $\langle K_La\rangle$ correlation of the single impeller system to the multiple impeller system.

impeller always gives the highest mass transfer rate, then the middle impeller, and the lowest impeller always results in the smallest $\langle K_La\rangle$ value. This result again indicates the non-uniform gas loading, which causes the non-uniform power consumption of each impeller, in multiple impeller systems. Although the deviation between the experimental and calculated $\langle K_La\rangle$ values is not so close, it still can be applied to estimate $\langle K_La\rangle$ values for each impeller region in the multiple impeller system. To confirm this viewpoint further, the $\langle K_La\rangle$ values obtained from the single 6-blade impeller system were recorrelated with P_g/V and V_s as:

$$\langle K_La\rangle=0.046(P_g/V)^{0.35}V_s^{0.52} \qquad (4)$$

Fig. 9 shows the comparison of the $\langle K_La\rangle$ value for each impeller region in the 3×6 impeller system with Eq. (4). From the results shown in this figure, it is found that they agree very well. Therefore, it can be concluded that the behavior of each impeller in any multiple system with aeration is identical as long as the (P_g/V) and V_s are the same.

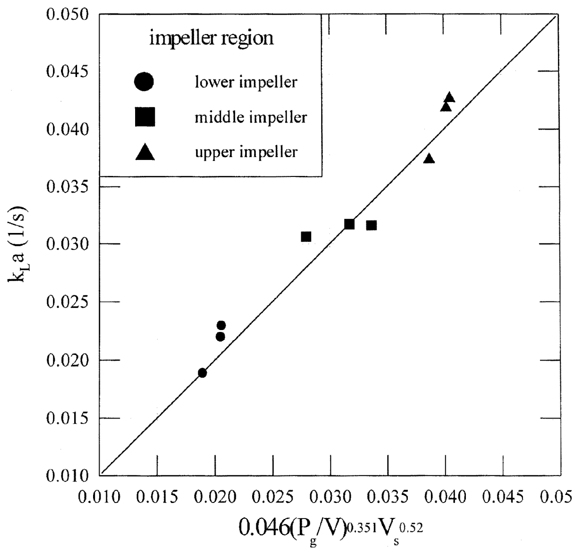

Fig. 9. The applicability of the $\langle K_La\rangle$ correlation of the single 6-blade impeller system to the multiple impeller system.

CONCLUSION

In this study, the effects of impeller blade number on the gas dispersion and mass transfer rate within the mechanically agitated vessels were investigated thoroughly. From the results obtained, it was found that under the same rotational speed condition, the impeller with more blades always disperses gas more effectively, which results in a higher value of $\langle K_La\rangle$. However, with the same power input level, the 4-blade impeller could give a higher $\langle K_La\rangle$ value than the 6- and 8-blade impellers under a gas completely dispersed condition [beyond stage (d)], but once Q_g exceeds 0.5 vvm, the 6-blade impeller performs better than the 4- and 8-blade impellers. Comparing the $\langle K_La\rangle$ values for the triple stage 6-blade impeller system (3×6) and quadruple stage 4-blade impeller system (4×4), it was seen that the 4×4 system gives a higher $\langle K_La\rangle$ value than the 3×6 system under gas completely dispersed conditions. Applying the $\langle K_La\rangle$ correlation for the single impeller systems to predict the mass transfer performance of each impeller region in the multiple impeller systems, it was found that the evaluated $\langle K_La\rangle$ value agrees with the experimental data very well.

ACKNOWLEDGEMENT

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NOMENCLATURE

a : interfacial area per unit volume [1/m]
B : baffle width [m]
C : distance between impellers [m]
D : impeller diameter [m]
H : liquid height of the stirred tank [m]
h_o : distance between the tank bottom and the lowest impeller [m]
K_L : liquid side mass transfer coefficient [m/s]
L : impeller blade length [m]
n_b : impeller blade number [-]
N : impeller rotational speed [1/s]
P_g : power drawn by the impeller with aeration [kgm^2/s^3]
Q_g : aeration rate [m^3/s]
T : tank diameter [m]
t : time [s]
V : total liquid volume [m^3]
V_s : gas superficial velocity [m/s]
vvm: the ratio of aeration rate per minute/the liquid volume in the tank [1/s]
y : concentration of the dissolved oxygen at time t [$mole/m^3$]
y_o : initial concentration of the dissolved oxygen at time t=0 [$mole/m^3$]
y^* : saturated concentration of the dissolved oxygen [$mole/m^3$]

W : impeller blade width [m]

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