I&EC research
Industrial & Engineering Chemistry Research

Article

Mass Transfer in a Rotating Packed Bed with Various Radii of the Bed

Yu-Shao Chen, Chia-Chang Lin, and Hwai-Shen Liu

Ind. Eng. Chem. Res., **2005**, 44 (20), 7868-7875 • DOI: 10.1021/ie048962s

GENERAL RESEARCH

Mass Transfer in a Rotating Packed Bed with Various Radii of the Bed

Yu-Shao Chen,† Chia-Chang Lin,‡ and Hwai-Shen Liu*,†

Department of Chemical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China, and Department of Chemical and Materials Engineering, Chang-Gung University, Tao-Yuan, Taiwan, Republic of China

This work examined the mass transfer efficiency of a rotating packed bed with various radii of the packed bed. Experimental results showed that k_La increased with decreasing volume of the packed bed. This may contribute to the significant end effects as the volume of the packed bed is reduced. A correlation which takes end effects into consideration for k_La in a rotating packed bed was proposed and is valid for different sizes of the rotating packed bed and for viscous Newtonian and non-Newtonian liquid systems. In addition, it was also found that the correlation could reasonably estimate most of the k_La data in the Higee literature.

Introduction

A rotating packed bed (i.e., RPB or Higee system), which replaced gravity with centrifugal force up to several hundred gravitational force, was first introduced as a novel gas/liquid contactor to enhance mass transfer in 1981.[1] This system can be operated at a higher gas/liquid ratio because of its lesser tendency of flooding. Under a significant centrifugal field, thin liquid films and tiny liquid droplets can be generated, thus decreasing mass transfer resistance and, meanwhile, increasing gas/liquid interfacial area. A 1−2 orders of magnitude enhancement in mass transfer could be obtained in an RPB. Consequently, the size and the capital of the processing system would be extremely reduced. The enhancement of mass transfer on gas/liquid and liquid/solid systems has been experimentally demonstrated in the literature.[1−5]

The characteristics of mass transfer in a traditional packed column have been well-studied. For example, Onda et al.[6] proposed a correlation, shown as eq 1, to predict the mass transfer coefficient (k_L) in a packed column.

$$k_L\left(\frac{\rho}{\mu g}\right)^{1/3} = 0.0051\left(\frac{L}{a\mu}\right)^{2/3}\left(\frac{\mu}{\rho D}\right)^{-0.5}(a_td_p)^{0.4} \quad (1)$$

According to the correlation, it is expected that the mass transfer coefficient should be independent of the packed height. In 1985, Munz[7] performed experiments of stripping oxygen and VOCs from water in a packed column. He also found that the packed height has little effect on the mass transfer coefficients.

However, in an RPB, the effects of the radial position and the thickness of the packing on mass transfer could be quite complicated. In 1985, Tung and Mah[8] theoretically analyzed an RPB and proposed a correlation for the mass transfer coefficient.

$$k_L = \frac{D}{d_P}\frac{2\times 3^{1/3}}{\pi}\left(\frac{\mu}{\rho D}\right)^{1/2}\left(\frac{L}{a_t\mu}\right)^{1/3}\left(\frac{a_t}{a}\right)^{1/3}\left(\frac{d_p{}^3\rho^2a_c}{\mu^2}\right)^{1/6} \quad (2)$$

In 1989, Munjal et al.[9] also proposed a correlation for predicting k_L in the RPB theoretically.

$$k_L = 2.6\frac{\pi L}{2a\rho X}\left(\frac{\mu}{\rho D}\right)^{-1/2}\left(\frac{2\pi L}{a\mu}\right)^{-2/3}\left(\frac{X^3\rho^2a_c}{\mu^2}\right)^{1/6} \quad (3)$$

In 2005, Chen et al.[10] reported an empirical correlation for k_La which is valid for mass transfer in Newtonian and non-Newtonian fluids in an RPB.

$$\frac{k_Lad_p}{Da_t} = 0.9\left(\frac{\mu}{\rho D}\right)^{0.5}\left(\frac{L}{a_t\mu}\right)^{0.24}\left(\frac{d_p{}^3\rho^2a_c}{\mu^2}\right)^{0.29}\left(\frac{L^2}{\rho a_t\sigma}\right)^{0.29} \quad (4)$$

The liquid mass flux (L) decreases because of the change of cross-sectional area, while the centrifugal acceleration (a_c) increases with increasing radial distance. It is noted in eqs 2−4 that these two parameters compete with each other as the radial distance increases. In 2000, Burns et al.[11] experimentally measured the liquid holdup in an RPB with a method of electrical resistance. They found that the radial dependence of liquid holdup is mainly due to its influence on centrifugal acceleration and liquid velocity. In 1992, Singh et al.[12] performed experiments of stripping VOCs from groundwater in an RPB. The dependence of the mass transfer coefficient on the outer radius of the packed bed was investigated. A liquid sampling tube was installed near the outer radius of the bed to minimize end effects (mass transfer outside the packing) in their study. The results showed that the relationship between the mass transfer coefficient and the outer radius of the bed was dependent

* Corresponding author. Tel.: +886-2-3366-3050. Fax: +886-2-2362-3040. E-mail: hsliu@ntu.edu.tw.
† National Taiwan University.
‡ Chang-Gung University.

10.1021/ie048962s CCC: $30.25
Published on Web 09/02/2005

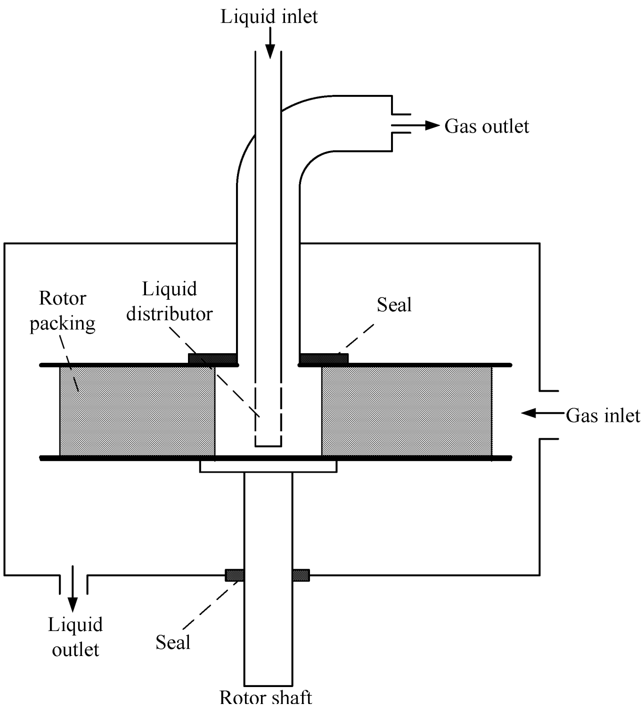

Figure 1. Main structure of an RPB.

on the rotor speed. At low rotational speed, the mass transfer coefficient decreased with increasing outer radius of the bed, and the decrease was relatively minor at high rotational speed.

On the other hand, there may be obvious end effects in an RPB. In fact, the regions for mass transfer in an RPB include the region inside the packed bed, the region between the liquid distributor and the inner edge of the packed bed, and the region between the outside edge of the bed and the static housing. In 1989, Munjal et al.[2] reported the experimental measurements of gas−liquid interfacial area based on chemical absorption of CO_2 in NaOH solutions. The results showed that obvious end effects did exist in an RPB, especially for a smaller bed. Because the experimental measurements include the end effects, the mass transfer coefficient calculated based on the volume of the packed bed will be overestimated. Therefore, the contribution of the end effects has to be determined to develop a realistic correlation for the mass transfer coefficient in an RPB.

In this study, the influence of the radius of the packed bed on mass transfer was experimentally investigated. In addition, to develop a consistent correlation for the liquid-side mass transfer coefficient in an RPB, experimental data of various liquid-phase control systems available in the literature were also included and evaluated.

Experiments

The main structure of RPB-1 is shown in Figure 1. The liquid enters the packed bed from a liquid distributor and sprays onto the inner edge of the packed bed. The liquid distributor has two vertical sets of holes in the opposite direction, and each set has three 0.5-mm-diameter holes. Inside the bed, the liquid moves outward through the packing as a result of the centrifugal force. The liquid is then splashed on the stationary housing and is collected at the bottom. The gas is introduced from the stationary housing, flows inward through the packing, and leaves the rotor through the center pipe.

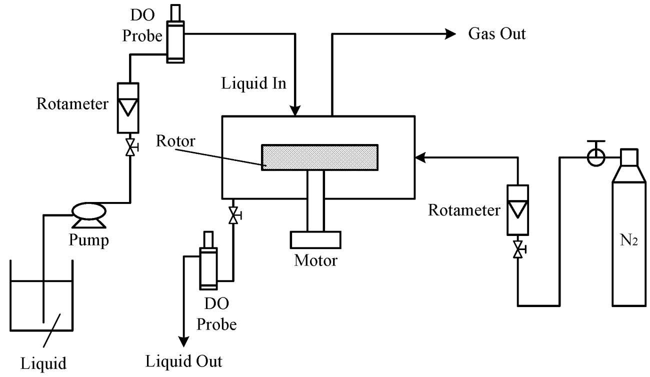

Figure 2. Diagram of the experimental setup.

Table 1. Physical Properties of Water and Oxygen in Water

density of liquid (ρ)	viscosity of liquid (μ)	diffusion coefficient (D)	Henry's constant (H)
996 kg/m^3	0.001 Pa·s	2.1×10^{-9} m^2/s	34.0 (mol/L)/(mol/L)

Thus, the gas and the liquid contact countercurrently in the RPB. The bed can be operated in the range of 600−1500 rpm. The packing used in this study is 0.22-mm-diameter stainless steel wire mesh, with porosity and interfacial area of 0.954 and 829 1/m, respectively. The sphericity of wire mesh was found to be 0.11.[13] The axial height of the bed is 2 cm. The packing support used in this study was a stainless steel ring with 5-mm-diameter holes on it, and the open ratio of the ring was ∼61%. The packing support can be set in the radial direction at 1, 2, 3, 4, 5, and 6 cm, respectively. As the result, the influence of the inner radius, the outer radius, and the thickness of the packed bed on mass transfer can be investigated. The radius of the stationary housing is 7.5 cm.

Figure 2 shows a diagram of the experimental setup. Fresh water at a temperature of 30 °C was pumped into the RPB. A nitrogen stream with a flow rate of 1 L/min was introduced into the bed and contacted countercurrently with water. The concentration of dissolved oxygen (DO) in the inlet liquid stream was controlled at 2.48×10^{-4} mol/L, and the concentration in the outlet liquid stream was measured by a DO probe (Ingold type 170). The physical properties of water and oxygen in water were listed in Table 1.

To derive the design equation for an RPB, first consider a differential volume with cross-sectional area $2\pi rz$ and thickness dr. Assuming that the gas-side mass transfer resistance can be neglected for the process of deoxygenation, then the mass balance of solute in this volume for a dilute system is

$$Q_L dC_L = k_L a(C_L{}^* - C_L) 2\pi rz dr \quad (5)$$

where C_L is the concentration of solute (oxygen) in the liquid phase and k_La is the mass transfer coefficient. $C_L{}^*$ is the equilibrium concentration associated with the gas concentration. The overall mass balance is

$$Q_L(C_L - C_{L,o}) = Q_G(C_G - C_{G,i}) = Q_G(HC_L{}^* - 0) \quad (6)$$

i.e.,

$$C_L{}^* = \frac{1}{S}(C_L - C_{L,o}) \quad (7)$$

where Q_G is the gas flow rate, H is Henry's constant,

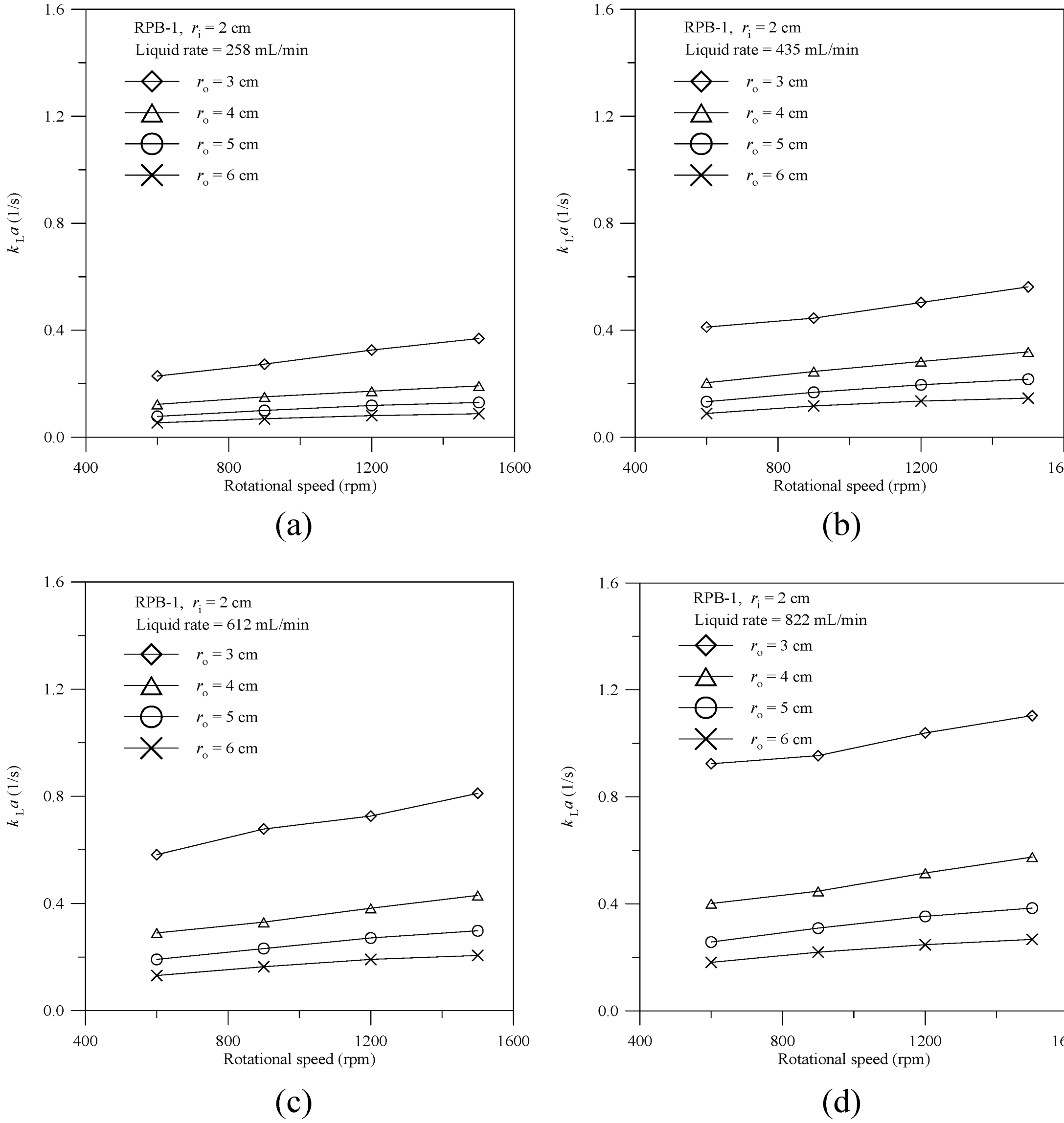

Figure 3. Dependence of k_La on rotational speed at different outer radii of the packed bed; liquid flow rate = (a) 258 mL/min, (b) 435 mL/min, (c) 612 mL/min, and (d) 822 mL/min.

$C_{L,o}$ is the outlet dissolved oxygen concentration in the liquid, $C_{G,i}$ is the inlet oxygen concentration in the gas, and S is the stripping factor defined as follows:

$$S = \frac{HQ_G}{Q_L} \tag{8}$$

Then the mass transfer coefficient can be obtained by substituting eq 7 into eq 5 and integrating the equation from $r = r_i$ to $r = r_o$ with the boundary conditions $C_L = C_{L,i}$ and $C_L = C_{L,o}$, respectively.

$$k_La = \frac{Q_L}{\pi(r_o^2 - r_i^2)z} \frac{\ln\left[\left(1 - \frac{1}{S}\right)\frac{C_{L,i}}{C_{L,o}} + \frac{1}{S}\right]}{1 - \frac{1}{S}} \tag{9}$$

Results and Discussion

Figure 3 shows the dependence of k_La on rotational speed at different outer radii of the packed bed for four liquid flow rates. As shown in eq 9, the mass transfer coefficient, k_La, was calculated based on the volume of the packed bed. Four outer radii of 3, 4, 5, and 6 cm were investigated, while the inner radius was set at 2 cm. First, as expected, it is found in the figure that k_La increased with increasing rotational speed, indicating that centrifugal force could enhance mass transfer. Besides, it is also noted that k_La increased with an increase in liquid flow rate. These characteristics have been observed and discussed in previous research. In addition, from Figure 3, it is clearly seen that k_La increased as the outer radius of the bed decreased. It is suggested that the dependence of mass transfer coefficients in the radial direction is due to the variation of centrifugal acceleration and liquid flux. In eqs 2 and 3, it is found that mass transfer coefficients increase with centrifugal acceleration and liquid flux to the power of $1/6$ and $1/3$, respectively. Therefore, it is expected that the mass transfer coefficients would decrease with increasing radial distance. In addition, it should be noted that, with decreasing the outer radius of the bed, the volume of the bed decreases and, at the same time, the volume between the outer radius of the bed and the stationary housing increases. As a result, the end effects in an RPB would become more significant, and an

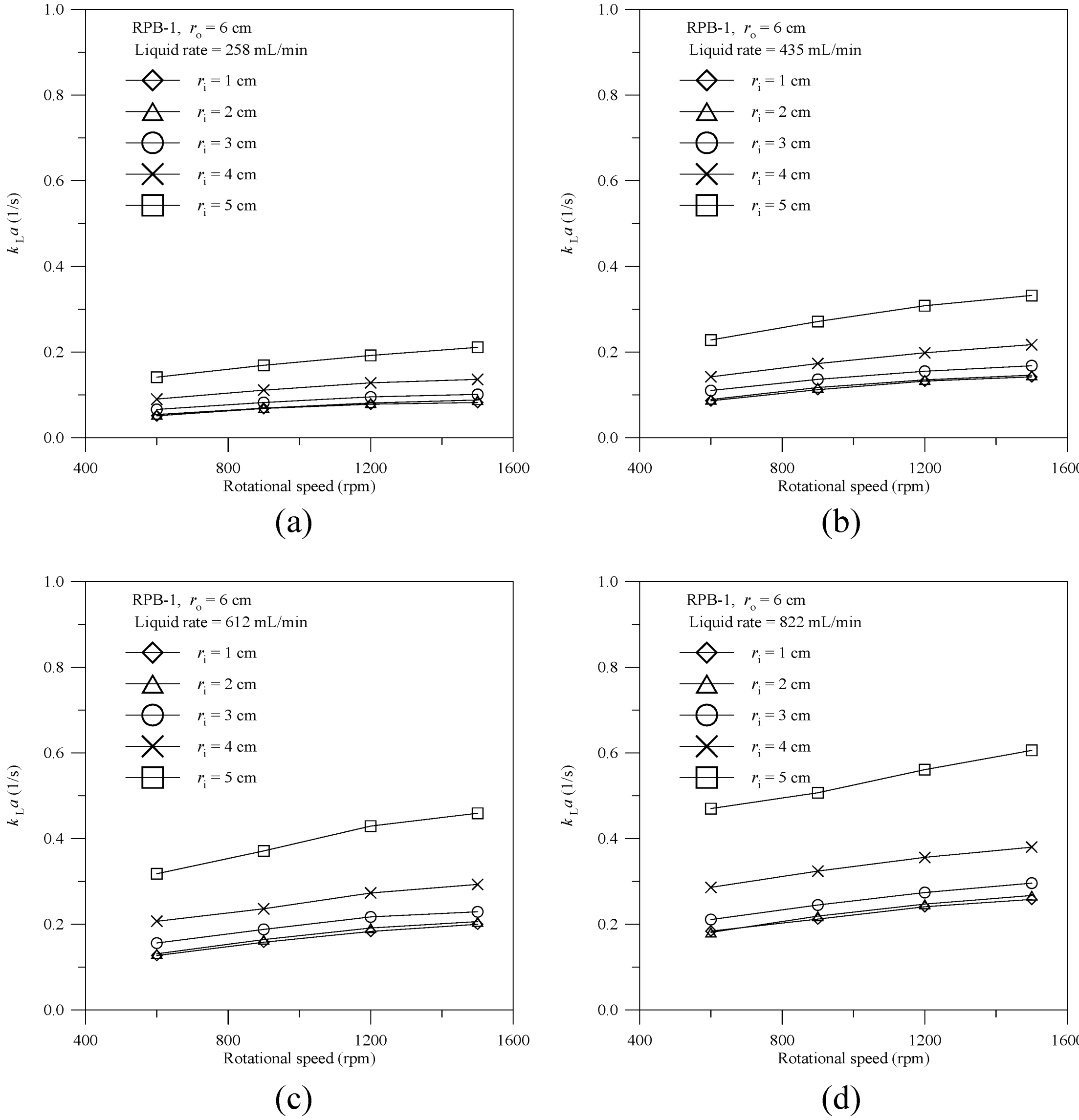

Figure 4. Dependence of k_La on rotational speed at different inner radii of the packed bed; liquid flow rate = (a) 258 mL/min, (b) 435 mL/min, (c) 612 mL/min, and (d) 822 mL/min.

overestimated value of k_La, which is calculated based on the volume of the packed bed, was obtained.

The effect of rotational speed on k_La at various inner radii of the packed bed was shown in Figure 4. Inner radii of 1, 2, 3, 4, and 5 cm were investigated while the outer radius was kept at 6 cm. As shown in the figure, k_La increased as the inner radius of the bed increased. Though, by the effect of centrifugal acceleration and liquid flux, the mass transfer coefficient may decrease as the inner radius of the bed increases, the end effects would become more significant because of the smaller volume of the bed. Thus, k_La increased with increasing inner radius of the bed. Figure 5 shows the dependence of k_La on rotational speed for different radial positions of the packed bed whose thickness was set to 1 cm. It is found that k_La increased as the radial distance of the bed decreased. As discussed previously, increasing the radial distance of the bed provides higher centrifugal acceleration, but the liquid flux would decrease because of the larger cross-sectional area. This would lead to a decrease of the mass transfer coefficient. Besides, the volume of the bed would decrease when reducing the radial distance of the bed, and k_La may be overestimated by the end effects. It can be concluded that the mass transfer coefficients may be affected by centrifugal acceleration, liquid flux, and end effects for different radii of the bed. However, from the results shown in Figures 3−5, the intrinsic influence of centrifugal acceleration and liquid flux may probably be hindered by the end effects.

A correlation was developed to predict the liquid-side mass transfer coefficient in an RPB. Since the end effects obviously influence k_La, they should be included in the correlation. The end effects in an RPB depend on the volume inside the inner radius of the bed (V_i), the volume between the outer radius of the bed and the stationary housing (V_o), and the total volume of the RPB (V_t). V_i, V_o, and V_t can be expressed as

$$V_i = \pi r_i^2 z \tag{10}$$

$$V_o = \pi(r_s^2 - r_o^2)z \tag{11}$$

$$V_t = \pi r_s^2 z \tag{12}$$

From a regression of the experimental data shown in

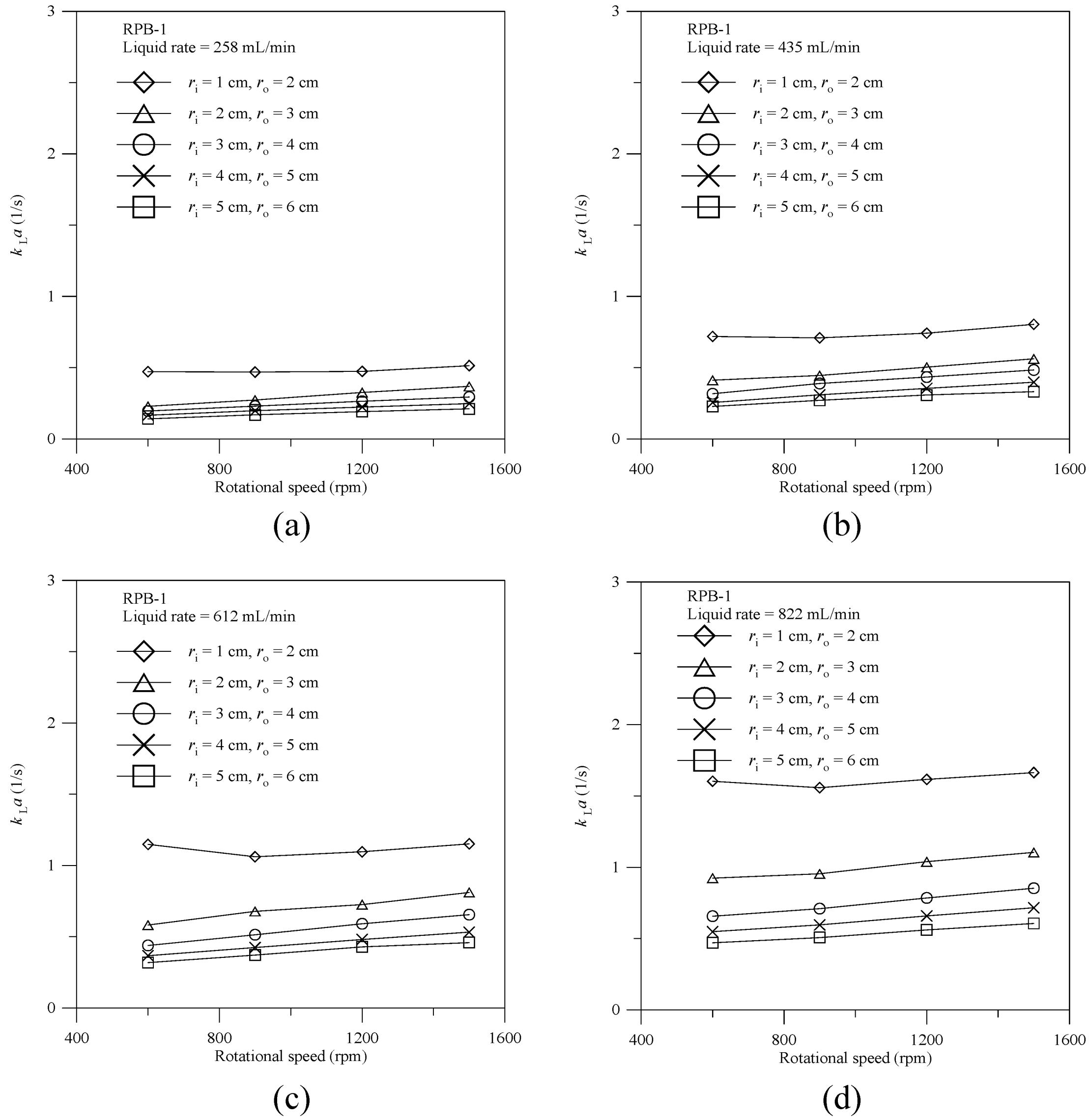

Figure 5. Dependence of k_La on rotational speed at different radial positions of the packed bed; liquid flow rate = (a) 258 mL/min, (b) 435 mL/min, (c) 612 mL/min, and (d) 822 mL/min.

Figures 3−5, a correlation, which takes end effects into consideration, can be expressed as

$$\frac{k_Lad_p}{Da_t}\left(1 - 0.93\frac{V_o}{V_t} - 1.13\frac{V_i}{V_t}\right) = 0.65\left(\frac{\mu}{\rho D}\right)^{0.5}\left(\frac{L}{a_t\mu}\right)^{0.17}\left(\frac{d_p{}^3\rho^2a_c}{\mu^2}\right)^{0.3}\left(\frac{L^2}{\rho a_t\sigma}\right)^{0.3} \quad (13)$$

To verify the correlation obtained above, more experiments of deoxygenation in RPB-1 with viscous glycerol solutions (Newtonian fluids) and CMC (carboxymethyl cellulose) solutions (non-Newtonian fluids) were employed.[10] The inner and outer radii of the bed were set at 1 and 6 cm, respectively. The packing used was also 0.22-mm-diameter stainless steel wire mesh, whose porosity and interfacial area were 0.954 and 829 1/m, respectively. Furthermore, experiments of deoxygenation in RPB-2 packed with 2-mm-diameter plastic beads were also included. For RPB-2, the radii of the inner and outer edge of the bed and the stationary housing were 2, 4, and 6 cm, respectively, while the axial height of the bed was 2 cm. The porosity and the interfacial area of the packing were 0.6 and 1200 1/m, respectively. These experimental results are listed in Table 2. In Figure 6a, it is found that the experimental values of k_La can be predicted well by the empirical correlation of eq 13. This indicates that the correlation is valid for different sizes of RPBs (RPB-1 and RPB-2) and for viscous Newtonian (glycerol solutions) and non-Newtonian (CMC solutions) media. The ranges of the dimensionless groups in eq 13 are $9.12 \leq k_Lad_p/Da_t \leq 2.54 \times 10^3$, $0.116 \leq (1 - 0.93(V_o/V_t) - 1.13(V_i/V_t)) \leq 0.645$, $5.0 \times 10^2 \leq \mu/\rho D \leq 1.2 \times 10^5$, $2.3 \times 10^{-3} \leq L/a_t\mu \leq 8.7$, $1.2 \times 10^2 \leq (d_p{}^3\rho^2a_c)/\mu^2 \leq 7.0 \times 10^7$, and $3.7 \times 10^{-6} \leq L^2/\rho a_t\sigma \leq 9.4 \times 10^{-4}$. Also, it is noted in the correlation that the value of k_La depends on centrifugal acceleration to the power of 0.3, which is close to the exponent (0.3−0.38) proposed by Munjal et al.[2] and the exponent (0.3−0.35) reported by Keyvani and Gardner.[14]

Furthermore, the k_La data available in the open literature are compared with the values calculated by eq 13. In 1981, Ramshaw and Mallinson[1] reported the results of a water-oxygen system in an RPB packed with 1-mm glass beads and copper gauze, respectively. The inner and outer radii of the bed were 4 and 9 cm, respectively, but the axial height of the bed was not reported. In 1989, Munjal et al.[2] studied the mass

Table 2. Experimental Results of Glycerol and CMC Solutions in RPB-1 and Water in RPB-2[a]

RPB used	exp. systems	liquid flow rate (mL/min)	liquid viscosity (mPa·s)	rotat. speed (rpm)	$C_{L,o}$ (mol/L)	k_La (1/s)
RPB-1	O_2−glycerol solutions	143	1.95	600	2.44×10^{-5}	0.0251
				900	1.43×10^{-5}	0.0309
				1200	1.09×10^{-5}	0.0339
				1500	8.14×10^{-6}	0.0371
		258	1.95	600	2.64×10^{-5}	0.0439
				900	1.58×10^{-5}	0.0540
				1200	9.87×10^{-6}	0.0632
				1500	6.91×10^{-6}	0.0702
		143	3.98	600	6.09×10^{-5}	0.0150
				900	3.47×10^{-5}	0.0211
				1200	2.40×10^{-5}	0.0251
				1500	1.48×10^{-5}	0.0304
		258	3.98	600	6.11×10^{-5}	0.0270
				900	3.78×10^{-5}	0.0365
				1200	2.28×10^{-5}	0.0464
				1500	1.33×10^{-5}	0.0570
		143	9.32	600	9.05×10^{-5}	0.0103
				900	4.60×10^{-5}	0.0177
				1200	3.17×10^{-5}	0.0217
				1500	1.76×10^{-5}	0.0281
		258	9.32	600	8.58×10^{-5}	0.0197
				900	4.93×10^{-5}	0.0306
				1200	3.17×10^{-5}	0.0393
				1500	1.78×10^{-5}	0.0506
		143	14.4	600	9.87×10^{-5}	0.0090
				900	5.50×10^{-5}	0.0153
				1200	3.52×10^{-5}	0.0202
				1500	2.55×10^{-5}	0.0237
		258	14.4	600	1.14×10^{-4}	0.0133
				900	6.69×10^{-5}	0.0238
				1200	4.06×10^{-5}	0.0336
				1500	2.46×10^{-5}	0.0435
RPB-1	O_2−glycerol solutions	143	25.1	600	1.08×10^{-4}	0.0082
				900	8.85×10^{-5}	0.0104
				1200	5.88×10^{-5}	0.0148
				1500	4.80×10^{-5}	0.0170
		258	25.1	600	1.07×10^{-4}	0.0150
				900	8.76×10^{-5}	0.0189
				1200	6.09×10^{-5}	0.0260
				1500	4.80×10^{-5}	0.0307
		143	40.5	600	1.13×10^{-4}	0.0063
				900	1.08×10^{-4}	0.0068
				1200	8.20×10^{-5}	0.0099
				1500	7.24×10^{-5}	0.0112
		258	40.5	600	1.09×10^{-4}	0.0122
				900	1.01×10^{-4}	0.0138
				1200	7.49×10^{-5}	0.0196
				1500	6.72×10^{-5}	0.0217
	O_2−CMC solutions	200	1.22	600	1.21×10^{-5}	0.0459
			1.20	900	6.13×10^{-6}	0.0563
			1.19	1200	4.47×10^{-6}	0.0611
			1.19	1500	3.97×10^{-6}	0.0629
		200	1.38	600	1.38×10^{-5}	0.0439
			1.32	900	6.29×10^{-6}	0.0559
			1.27	1200	4.39×10^{-6}	0.0614
			1.23	1500	4.31×10^{-6}	0.0617
RPB-1	O_2−CMC solutions	200	1.72	600	1.76×10^{-5}	0.0402
			1.55	900	9.00×10^{-6}	0.0504
			1.43	1200	5.40×10^{-6}	0.0582
			1.35	1500	4.97×10^{-6}	0.0595
		200	5.76	600	2.82×10^{-5}	0.0330
			5.07	900	1.99×10^{-5}	0.0383
			4.64	1200	1.27×10^{-5}	0.0452
			4.32	1500	8.30×10^{-6}	0.0517
RPB-1	O_2−CMC solutions	200	19.08	600	6.69×10^{-5}	0.0199
			16.92	900	4.58×10^{-5}	0.0257
			15.53	1200	3.25×10^{-5}	0.0309
			14.54	1500	2.18×10^{-5}	0.0370
		200	34.07	600	7.19×10^{-5}	0.0188
			29.34	900	4.71×10^{-5}	0.0253
			26.39	1200	3.46×10^{-5}	0.0299
			24.31	1500	2.91×10^{-5}	0.0326
		200	204.36	600	1.15×10^{-4}	0.0117
			166.92	900	8.35×10^{-5}	0.0166
			144.59	1200	5.76×10^{-5}	0.0222
			129.35	1500	3.80×10^{-5}	0.0285
RPB-2	O_2−water	149	1	300	5.27×10^{-5}	0.0510
			1	600	2.56×10^{-5}	0.0748
			1	900	1.34×10^{-5}	0.0960
			1	1200	1.07×10^{-5}	0.1035
			1	1500	8.94×10^{-6}	0.1094
			1	2100	7.45×10^{-6}	0.1154
		258	1	300	6.96×10^{-5}	0.0786
			1	600	3.23×10^{-5}	0.1263
			1	900	1.84×10^{-5}	0.1498
			1	1200	1.07×10^{-5}	0.1693
			1	1500	7.45×10^{-6}	0.1873
			1	2100	4.72×10^{-6}	0.2069
		435	1	300	7.65×10^{-5}	0.1137
			1	600	4.17×10^{-5}	0.1724
			1	900	2.73×10^{-5}	0.2135
			1	1200	1.84×10^{-5}	0.2520
			1	1500	1.37×10^{-5}	0.2808
			1	2100	9.69×10^{-6}	0.3142
RPB−2	O_2−water	612	1	300	9.84×10^{-5}	0.1259
			1	600	5.22×10^{-5}	0.1866
			1	900	3.63×10^{-5}	0.2623
			1	1200	2.53×10^{-5}	0.3115
			1	1500	1.76×10^{-5}	0.3611
			1	2100	1.17×10^{-5}	0.4177
		822	1	300	1.07×10^{-4}	0.1539
			1	600	6.46×10^{-5}	0.2300
			1	900	4.10×10^{-5}	0.3307
			1	1200	2.93×10^{-5}	0.3927
			1	1500	2.38×10^{-5}	0.4308
			1	2100	1.44×10^{-5}	0.5240

[a] Some of the k_La data were presented in our previous study.[10]

transfer characteristics by absorption of CO_2 from air into NaOH. Two outer radii of the bed of 7 and 8.7 cm were investigated, while the inner radius was set at 3.8 cm. Keyvani and Gardner[14] obtained mass transfer coefficients with various surface areas of aluminum foam metal as packing in a CO_2−water system. In 1990, Kumar and Rao[15] performed experiments of absorption of CO_2 from air into NaOH solutions in an RPB packed with wire meshes. In 1992, Singh et al.[12] evaluated the performance of an RPB with various outer radii of the bed for air stripping of VOCs from groundwater. A liquid sampling tube was installed near the outer radius of the bed to minimize end effects. In 2004, Chen et al.[16] investigated the mass transfer coefficient by absorption of oxygen into water. The specifications of the RPBs and the packings used in the above studies are shown in Table 3. However, the radius of the stationary housing was not reported in these works. In the studies of Ramshaw and Mallinson[1] and Munjal et al.,[2] liquid left the packed bed through a liquid seal lip, instead of splashing onto the stationary housing. As a result, the end effect in the outer region could be insignificant, and the radius of the stationary housing was assumed to be the same as the outer radius of the bed. Singh et al.[12] installed a liquid sampling tube near the outer radius of the bed, and therefore, the end effect in the outer region could be ignored. In other works, estimated ranges of the stationary housing are given, and these are listed in Table 3.

In Figure 6b, the errors bars of the calculated values are the estimated ranges of the unknown parameters listed in Table 3. It is seen in Figure 6b that, with the

Table 3. Experimental Systems and the Specifications of the RPBs Used in the Literature

		specifications of RPB (cm)				packing used		
authors	experimental systems	r_i	r_o	z_b	r_s	type	a_t (1/m)	ϵ
Ramshaw and Mallinson[1]	O_2-H_2O	4	9	$(1-5)^a$	$(9)^a$	glass beads	3300	0.45
						wire gauze	1650	$(0.9)^a$
Munjal et al.[2]	CO_2-NaOH	3.8	7, 8.7	2.54	$(8.7)^a$	glass beads	1132	0.434
Keyvani and Gardner[14]	CO_2-H_2O	12.7	22.85	4.4	$(25-30)^a$	foam metal	656−2952	0.92
Kumar and Rao[15]	CO_2-NaOH	3	15.5	2.5	$(17-23)^a$	wire mesh	4000	0.95
Singh et al.[12]	VOCs$-H_2O$	12.7	22.9	12.7	$(r_o)^a$	foam metal	2500	0.95
			38.1			wire gauze	2067	0.934
Chen et al.[16]	O_2-H_2O	3.85	8.25	2	$(10-15)^a$	wire mesh	840	0.954
present work	O_2-H_2O	1−5	2−6	2	7.5	wire mesh	829	0.954
		2	4	2	6	plastic beads	1200	0.6

^{a} Values or range estimated.

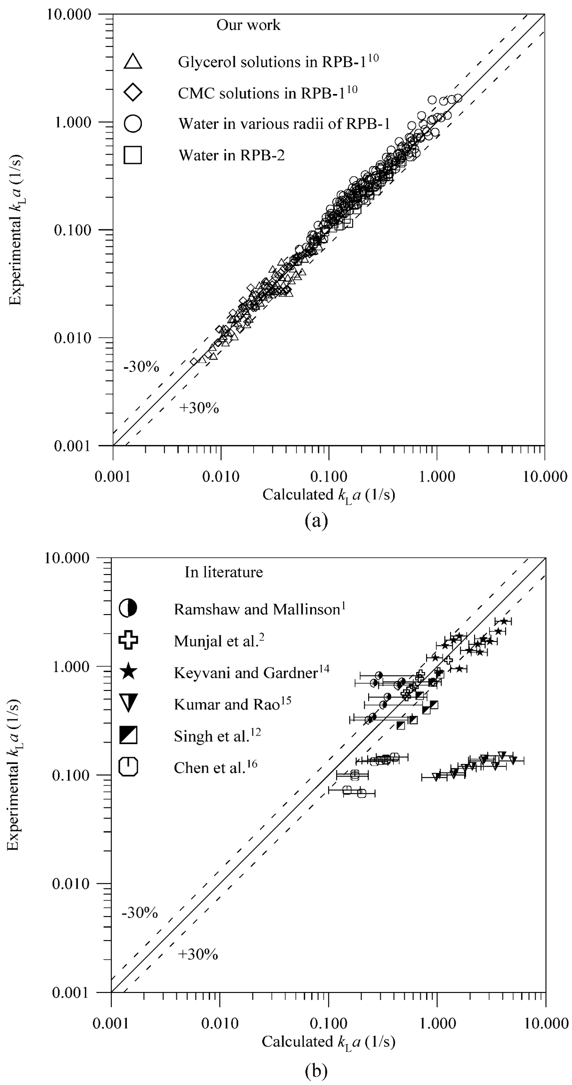

Figure 6. Comparison of experimental values of k_La with results calculated using eq 13. Experimental data from (a) our work and (b) literature.

exception of the data of Kumar and Rao,[15] eq 13 can reasonably estimate most of the liquid-side mass transfer coefficients in previous Higee studies.

Conclusion

In this study, the mass transfer efficiency of an RPB with various inner and outer radii has been examined. The mass transfer coefficients were investigated as a function of rotational speed, liquid flow rate, inner radius of the packed bed, outer radius of the packed bed, and radial position of the bed. Experimental results showed that k_La increased with increasing rotational speed and liquid flow rate. Besides, a smaller bed showed a higher value of k_La. This is mainly due to the fact that the contribution of the end effects may be more significant as the volume of the packed bed is reduced. A correlation, which takes end effects into consideration, was developed to predict k_La in an RPB. Results showed that this correlation was valid for various sizes of the RPBs and for viscous Newtonian and non-Newtonian liquid systems. The mass transfer coefficient increased with centrifugal acceleration to the power of 0.3, which was close to the exponent proposed by Munjal et al.[2] and Keyvani and Gardner.[14] Besides, it was found that the correlation could reasonably estimate most of the k_La data in the Higee literature.

Acknowledgment

The support from Ministry of Economic Affairs, Taiwan, Republic of China, is greatly appreciated.

Nomenclature

a = gas−liquid interfacial area (1/m)
a_t = surface area of the packing (1/m)
a_c = centrifugal acceleration (m^2/s)
C_G = concentration of solute in the gas stream (mol/L)
$C_{G,i}$ = concentration of solute in the inlet gas stream (mol/L)
C_L = concentration of solute in liquid stream (mol/L)
C_L^* = equilibrium concentration associated with the gas concentration (mol/L)
$C_{L,i}$ = concentration of solute in the inlet liquid stream (mol/L)
$C_{L,o}$ = concentration of solute in the outlet liquid stream (mol/L)
D = diffusion coefficient (m^2/s)
d_p = spherical equivalent diameter of the packing = $[6(1 - \epsilon)/a_t\psi]$ (m)
g = gravitational force (m/s^2)
H = Henry's law constant [(mol/L)/(mol/L)]
k_L = liquid-side mass transfer coefficient (m/s)
k_La = volumetric liquid-side mass transfer coefficient (1/s)
L = liquid mass flux [kg/(m^{2}s)]
Q_G = gas flow rate (m^3/s)
Q_L = liquid flow rate (m^3/s)
r_i = inner radius of the packed bed (m)
r_o = outer radius of the packed bed (m)
r_s = radius of the stationary housing (m)
S = stripping factor defined as eq 8
V_i = volume inside the inner radius of the bed (m^3)
V_o = volume between the outer radius of the bed and the stationary housing (m^3)
V_t = total volume of the RPB (m^3)

X = surface renewal parameter (m)
z = axial height of the packing (m)

Greek Letters

ϵ = porosity of the packing
μ = viscosity of liquid (Pa·s)
ρ = density of liquid (kg/m^3)
ψ = sphericity of packing

Literature Cited

(1) Ramshaw, C.; Mallinson, R. H. Mass Transfer Process. U.S. Patent 4,283,255, 1981.

(2) Munjal, S.; Dudukovic, M. P.; Ramachandran, P. Mass-Transfer in Rotating Packed Beds. II. Experimental Results and Comparison with Theory and Gravity Flow. *Chem. Eng. Sci.* **1989**, *44*, 2257.

(3) Lin, C. C.; Liu, H. S. Adsorption in a Centrifugal Field: Basic Dye Adsorption by Activated Carbon. *Ind. Eng. Chem. Res.* **2000**, *39*, 161.

(4) Chen, Y. S.; Liu, H. S. Absorption of VOCs in a Rotating Packed Bed. *Ind. Eng. Chem. Res.* **2002**, *41*, 1583.

(5) Lin, C. C.; Ho, T. J.; Liu, W. T. Distillation in a Rotating Packed Bed. *J. Chem. Eng. Jpn.* **2002**, *35*, 1298.

(6) Onda, K.; Takeuchi, H.; Okumoto, Y. Mass Transfer Coefficients between Gas and Liquid Phases in Packed Columns. *J. Chem. Eng. Jpn.* **1968**, *1*, 56.

(7) Munz, C. Air−Water Phase Equilibria and Mass Transfer of Volatile Organic Solutes. Ph.D. Dissertation, Stanford University, Stanford, CA, 1985.

(8) Tung, H. H.; Mah, R. S. H. Modeling Liquid Mass Transfer in Higee Separation Process. *Chem. Eng. Commun.* **1985**, *39*, 147.

(9) Munjal, S.; Dudukovic, M. P.; Ramachandran, P. Mass-Transfer in Rotating Packed Beds. I. Development of Gas−Liquid and Liquid−Solid Mass-Transfer Correlations. *Chem. Eng. Sci.* **1989**, *44*, 2245.

(10) Chen, Y. S.; Lin, C. C.; Liu, H. S. Mass Transfer in a Rotating Packed Bed with Viscous Newtonian and Non-Newtonian Fluids. *Ind. Eng. Chem. Res.* **2005**, *44*, 1043.

(11) Burns, J. R.; Jamil, J. N.; Ramshaw, C. Process Intensification: Operating Characteristics of Rotating Packed Beds—Determination of Liquid Hold-up for a High-Voidage Structured Packing. *Chem. Eng. Sci.* **2000**, *55*, 2401.

(12) Singh, S. P.; Wilson, J. H.; Counce, R. M.; Villiersfisher, J. F.; Jennings, H. L.; Lucero, A. J.; Reed, G. D.; Ashworth, R. A.; Elliott, M. G. Removal of Volatile Organic-Compounds from Groundwater Using a Rotary Air Stripper. *Ind. Eng. Chem. Res.* **1992**, *31*, 574.

(13) Brown, G. G. *Unit Operations*; Wiley: New York, 1950.

(14) Keyvani, M.; Gardner, N. C. Operating Characteristics of Rotating Beds. *Chem. Eng. Prog.* **1989**, *85*, 48.

(15) Kumer, M. P.; Rao, D. P. Studies on a High-Gravity Gas−Liquid Contactor. *Ind. Eng. Chem. Res.* **1990**, *29*, 917.

(16) Chen, Y. H.; Chang, C. Y.; Su, W. L.; Chen, C. C.; Chiu, C. Y.; Yu, Y. H.; Chiang, P. C.; Chiang, S. I. M. Modeling Ozone Contacting Process in a Rotating Packed Bed. *Ind. Eng. Chem. Res.* **2004**, *43*, 228.

Received for review October 26, 2004
Revised manuscript received July 19, 2005
Accepted August 1, 2005

IE048962S