Research Note

Packing Characteristics for Mass Transfer in a Rotating Packed Bed

Yu-Shao Chen, Fang-Yi Lin, Chia-Chang Lin, Clifford Yi-Der Tai, and Hwai-Shen Liu

Ind. Eng. Chem. Res., **2006**, 45 (20), 6846-6853 • DOI: 10.1021/ie060399l

Packing Characteristics for Mass Transfer in a Rotating Packed Bed

Yu-Shao Chen,[†] Fang-Yi Lin,[†] Chia-Chang Lin,[‡] Clifford Yi-Der Tai,[†] and Hwai-Shen Liu*,[†]

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

This work investigated the mass transfer of a rotating packed bed (RPB) with emphasis on the effects of the packing's size, shape, material, and surface property. Experimental results show that there is no obvious relationship between a_t and k_La. Among the various shapes of the packings, the mass transfer coefficients of Raschig rings and Intalox saddles are lower than those of the others, while the k_La of the wire meshes is the highest. As to materials, the mass transfer coefficients are similar for acrylic, glass, ceramic, and stainless steel beads. Besides, the k_La values of the hydrophobically treated packings are 8−27% lower than those of the original glass and ceramic packings. A modified correlation of k_La, which includes the effects of various packings, is proposed based on our RPB experimental results. Further, this correlation can also reasonably estimate most of the k_La data in the Higee literature.

Introduction

A rotating packed bed (RPB), which generates a centrifugal force up to several hundred times greater than gravitational force, was introduced as a novel gas−liquid contactor to increase mass transfer rates. This equipment consists of a rotor driven by a motor and a static housing. Under a rigorous centrifugal field, thin liquid films and tiny liquid droplets are generated and flow chaotically in the packing, resulting in a dramatic increase in gas−liquid interfacial area and mixing efficiency.[1,2] Moreover, due to the reduced tendency of flooding, the system can be operated within a wider range of gas and liquid flow rates. Therefore, an order of magnitude enhancement in mass transfer can frequently be observed in an RPB and the size of the equipment would be greatly reduced as compared with a conventional packed column. The enhancement of mass transfer on gas−liquid systems, such as absorption,[3−5] stripping,[6−9] and distillation;[10,11] liquid−liquid systems, such as mixing;[1,2] and liquid−solid systems, such as adsorption,[12,13] has been demonstrated in the literature.

In 1981, Ramshaw and Mallinson[3] first conducted a water−oxygen absorption system in an RPB and found that the mass transfer coefficient was 27−44 times higher than that in conventional packed columns. In 1985, Tung and Mah[14] theoretically proposed a correlation for the mass transfer coefficient in an RPB.

$$k_L = \frac{D}{d_p}\frac{2 \times 3^{1/3}}{\pi}Sc^{1/2}Re^{1/3}\left(\frac{a_t}{a}\right)^{1/3}Gr^{1/6} \qquad (1)$$

With the correlation of gas−liquid interfacial area for a conventional packed column proposed by Onda et al.,[15]

$$\frac{a_t}{a} = 1 - \exp\left[-1.45\left(\frac{\sigma_c}{\sigma}\right)^{0.75}Re^{0.1}Fr^{-0.05}We^{0.2}\right] \qquad (2)$$

they[14] found that eqs 1 and 2 could reasonably predict the experimental results reported by Ramshaw and Mallinson.[3] In 1989, Munjal et al.[16,17] proposed a correlation for predicting k_L in an RPB theoretically and experimentally studied for the absorption of CO_2 from air into NaOH. Keyvani and Gardner[18] obtained mass transfer coefficients in an RPB packed with aluminum foam metal of various specific surface areas in a CO_2−water system. The surface area of the packing ranged from 656 to 2952 1/m. They found that k_La depended on centrifugal acceleration to the power of 0.3−0.35. In addition, their results showed that the k_La for 656 1/m packing was comparable to that for 1476 1/m packing. They attributed this to the more even liquid spread in the tangential direction because the 656 1/m packing has a larger pore size. In 1990, Kumar and Rao[19] performed experiments of absorption of CO_2 from air into NaOH solutions in an RPB and found that k_La increased with increasing liquid rates and rotation speeds. In 1992, Singh et al.[6] investigated the mass transfer in an RPB for air stripping of volatile organic compounds (VOCs) from groundwater. In 2004, Chen et al.[20] evaluated the mass transfer coefficient of an oxygen−water absorption system, and they found that k_La was dependent on rotation speed to the power of 0.31. In 2005, Chen et al.[8] investigated the influence of liquid viscosity on the mass transfer rate for both Newtonian and non-Newtonian fluids in an RPB. They proposed a correlation of k_La valid for both Newtonian and non-Newtonian fluids. Further, Chen et al.[9] evaluated the end effects of an RPB by varying the radii of the packed bed. They proposed a correlation of k_La which took end effects into consideration in an RPB.

$$\frac{k_L a d_p}{D a_t}\left(1 - 0.93\frac{V_o}{V_t} - 1.13\frac{V_i}{V_t}\right) = 0.65Sc^{0.5}Re^{0.17}Gr^{0.3}We^{0.3} \qquad (3)$$

The correlation was found to be valid for different sizes of the RPBs and for viscous Newtonian and non-Newtonian fluids. In addition, the correlation could reasonably estimate most of the k_La data in the Higee literature (see Table 3 of ref 9).

In conventional packed columns, various types of packings are developed to enhance mass transfer. In 1968, Onda et al.[15] provided correlations for a and k_L for several types and

* To whom correspondence should be addressed. Tel.: +886-2-3366-3050. Fax: +886-2-2362-3040. E-mail: hsliu@ntu.edu.tw.
[†] National Taiwan University.
[‡] Chang-Gung University.

10.1021/ie060399l CCC: $33.50
Published on Web 09/06/2006

sizes of the packings, shown as eqs 2 and 4.

$$k_L\left(\frac{\rho}{\mu g}\right)^{1/3} = 0.0051\left(\frac{L}{a\mu}\right)^{2/3} Sc^{-1/2}(a_t d_p)^{0.4} \qquad (4)$$

According to the correlations, it is noted that the mass transfer coefficient would increase while increasing the specific surface area and the critical surface tension of the packing. Coughlin[21] and Sahay and Sharma[22] reported that ceramic packing showed higher mass transfer efficiency than plastic packing due to the higher critical surface tension of ceramic packing. In 1983, ASHRAE[23] reported that mass transfer coefficients would increase clearly as the specific surface area of the packing increased.

According to the previous studies in conventional packed columns, it is generally considered that increasing the specific surface area and the critical surface tension of the packing could enhance mass transfer efficiency. However, according to the experimental results of Keyvani and Gardner,[18] the dependence of mass transfer in an RPB on the specific surface area of the packing may be different from that in a conventional packed column. Therefore, it is reasonable to expect that the characteristics of mass transfer are different between an RPB and a packed column for different kinds of packing. Therefore, a systematical study on the effects of the size, shape (bead, Raschig ring, Intalox saddle, and wire mesh), material (acrylic, glass, ceramic, and stainless steel), and surface property (critical surface tension) of the packings on mass transfer was performed in an RPB. Consequently, a correlation of $k_L a$ modified from eq 3 was presented with good agreement for both our current experimental data and most results from previous literature.

Experiments

Figure 1 shows the main structure of an RPB. The liquid is introduced into the inner edge of the packed bed from a liquid distributor consisting of a six-hole tube, three holes on each side. The liquid flows outward from the inner edge of the bed by means of the centrifugal force. Then, it sprays onto the stationary housing and is collected at the bottom. The gas is introduced from the stationary housing, flows inward through the bed, and leaves the rotor through the center pipe. As a result, the gas and the liquid contact countercurrently in the RPB. The axial height of the bed is 2 cm. The inner radius and the outer radius of the bed are 1 and 6 cm, respectively. The radius of the stationary housing is 7.5 cm. The bed can be operated from 600 to 1800 rpm, which provides a 14 to 127-fold gravitational force on the basis of the arithmetic mean radius. In this study, 11 kinds of packing were used. The size, specific surface area, porosity, and critical surface tension of the packings are listed in Table 1. The sphericities of the Raschig ring, Intalox saddle, and wire mesh are 0.56, 0.48, and 0.11, respectively.[24] The critical surface tension of the packings can be found in the literature.[25−27] The hydrophobically treated ceramic beads and glass beads were obtained by treating them with octadecyltrichlorosilane and isooctane for 4 h, and a hydrophobic layer was therefore coated on the packing surface.[27]

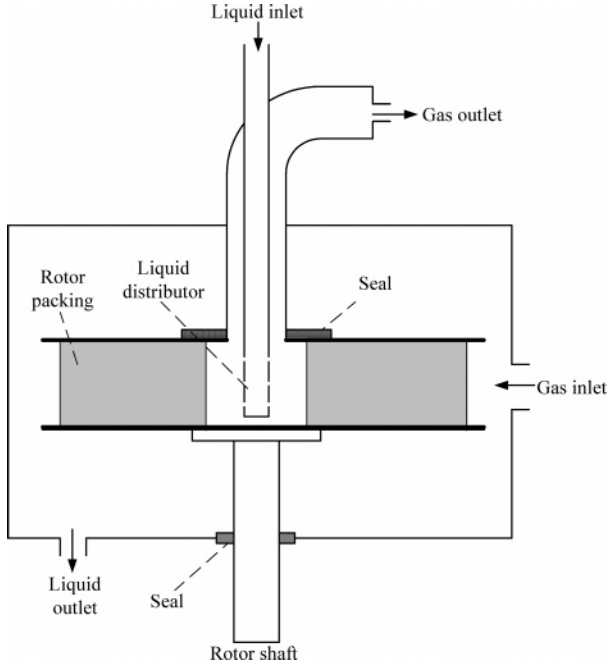


Figure 1. Main structure of an RPB.

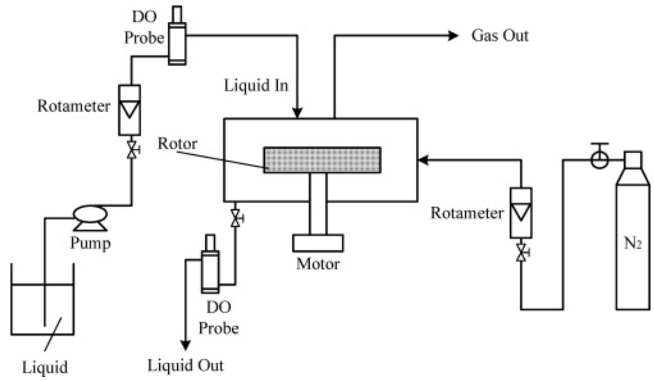


Figure 2. Diagram of the experimental setup.

Table 1. Specifications of the Packings

packing	d_p (10^{-3} m)	a_t (1/m)	ϵ (−)	σ_c (10^{-3} kg/s^2)
2-mm acrylic bead	2	2074	0.309	47[25]
3-mm acrylic bead	3	1255	0.372	47[25]
5-mm acrylic bead	5	720	0.400	47[25]
glass bead	5	707	0.411	61[26]
ceramic bead	5	677	0.436	55[26]
stainless steel bead	5	688	0.427	75[26]
ceramic Raschig ring	5.9	789	0.573	55[26]
ceramic Intalox saddle	5.5	850	0.633	55[26]
hydrophobically treated ceramic bead	5	683	0.431	22[27]
hydrophobically treated glass bead	5	715	0.404	22[27]
stainless steel wire mesh	3	825	0.950	75[26]

Figure 2 shows a diagram of the experimental setup. Freshwater at a temperature of 30 °C was pumped into the RPB, with the flow rate ranging from 310 to 1030 mL/min. A nitrogen stream of 2 L/min was introduced into the bed and contacted with water countercurrently. The concentrations of dissolved oxygen (DO) of inlet and outlet liquid streams were measured by a DO probe (Ingold type 170). The error bounds on the experimental data were estimated within ±10%. The detailed experimental measurements and data were given by Lin.[28]

The mass transfer coefficient in an RPB can be calculated as follows:

$$k_L a = \frac{Q_L}{\pi(r_o^{\,2} - r_i^{\,2})z}\,\frac{\ln\left[\left(1 - \frac{1}{S}\right)\frac{C_{L,i}}{C_{L,o}} + \frac{1}{S}\right]}{1 - \frac{1}{S}} \qquad (5)$$

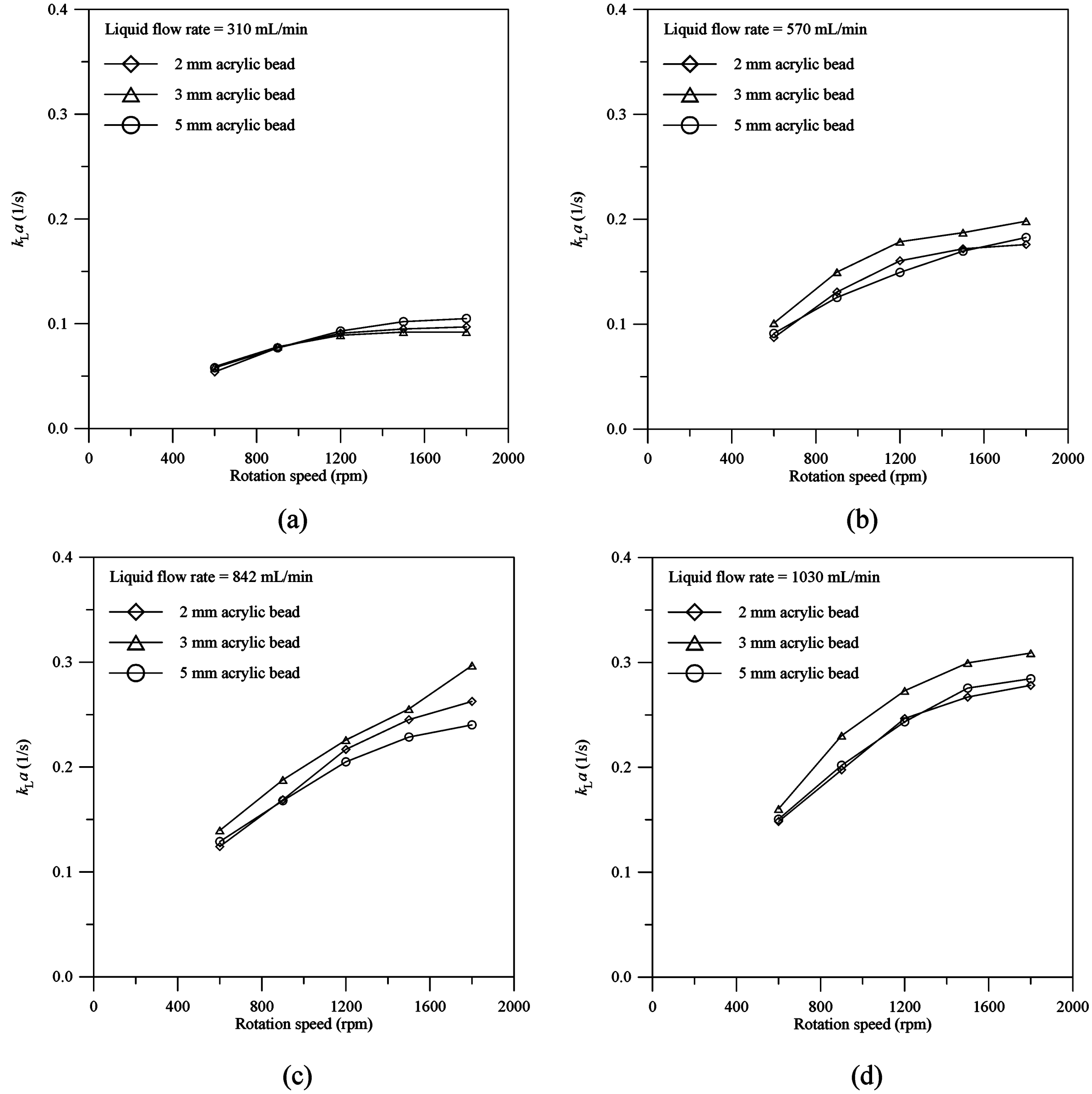


Figure 3. Dependence of k_La on rotation speed for different sizes of the packings: liquid flow rate = (a) 310, (b) 570, (c) 842, and (d) 1030 mL/min.

In eq 5, S is the stripping factor defined as follows:

$$S = \frac{HQ_G}{Q_L} \quad (6)$$

A detailed derivation of eq 5 can be found in our previous work.[9]

Results and Discussion

Figure 3 shows the dependence of k_La on rotation speed for the bed packed with acrylic beads. The diameters of the acrylic beads used were 2, 3, and 5 mm, respectively. First, it is seen in the figure that k_La increased with increasing rotation speed and liquid flow rate. Similar results have been observed and discussed in many previous reports related to Higee studies. In addition, it is noteworthy that the diameter of the acrylic beads had no effect on the mass transfer coefficient at lower liquid flow rates; however, a higher k_La appeared for the bed packed with the 3-mm beads when the liquid flow rate was beyond 570 mL/min. The dependence of k_La on a_t in an RPB was shown in Figures 4, including data from this work and Keyvani and Gardner.[18] It is clear from the figure that the influence of the specific surface area of the packing in a Higee system is different from that in a conventional packed column. In a conventional packed column, the results of ASHRAE[23] show that the mass transfer coefficient would clearly increase while increasing the specific surface area of the packing. In an RPB, it is found that there is no such clear dependence between the specific surface area and the experimental values of k_La as suggested by Keyvani and Gardner[18] as well as this work. The difference could be probably attributed to the different liquid flow patterns in an RPB and in a conventional packed column. According to the visual study of the liquid flow in an RPB by Burns and Ramshaw,[29] they found that the liquid flows very fast through the packing in the radial direction and hardly disperses laterally in comparison to the radial motion. When the specific surface area of the packing increases, the liquid would disperse more difficultly in the tangential direction due to lower voids in the packed bed. Therefore, maldistribution of liquid becomes

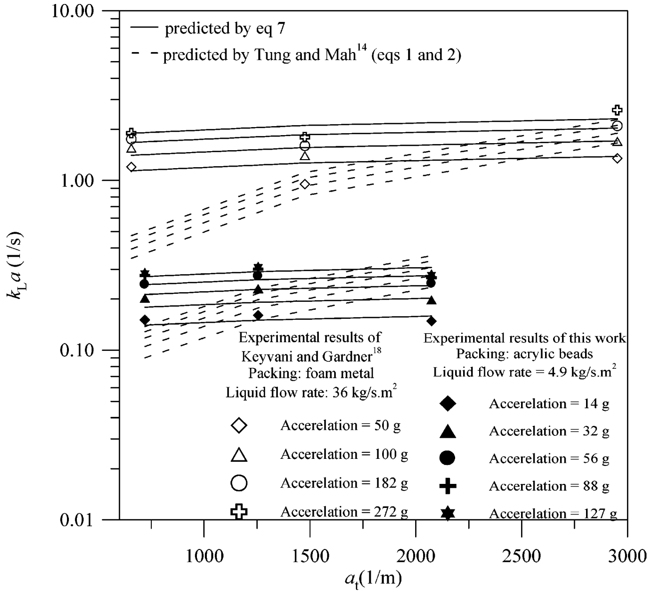


Figure 4. Dependence of k_La on a_t in an RPB.

significant and reduces mass transfer efficiency. In addition, Burns and Ramshaw[29] also reported that significant amount of droplets would be generated in the packed bed when liquid impinged on to the fast rotating packing and mass transfer would occur on the droplets as well as on the liquid films on the surface of the packing. It is suggested that the liquid droplets would not be strongly influenced by the size of the packing. As a result, reducing the size of the packing or increasing the specific area of the packing may not show obvious effects on the mass transfer efficiency in an RPB. In addition, it is found in Figure 4 that the correlation of k_La provided by Tung and Mah[14] is not applicable for estimating the relationship between k_La and the specific area of the packing in a Higee system.

Figure 5 shows the mass transfer coefficient in an RPB for various shapes of the packing, including beads, Raschig rings, Intalox saddles, and wire meshes. The result shows that wire meshes provide the highest mass transfer efficiency among these packings, while Raschig rings and Intalox saddles show lower efficiency. In a conventional packed column, Raschig rings and Intalox saddles are mainly developed to increase the specific

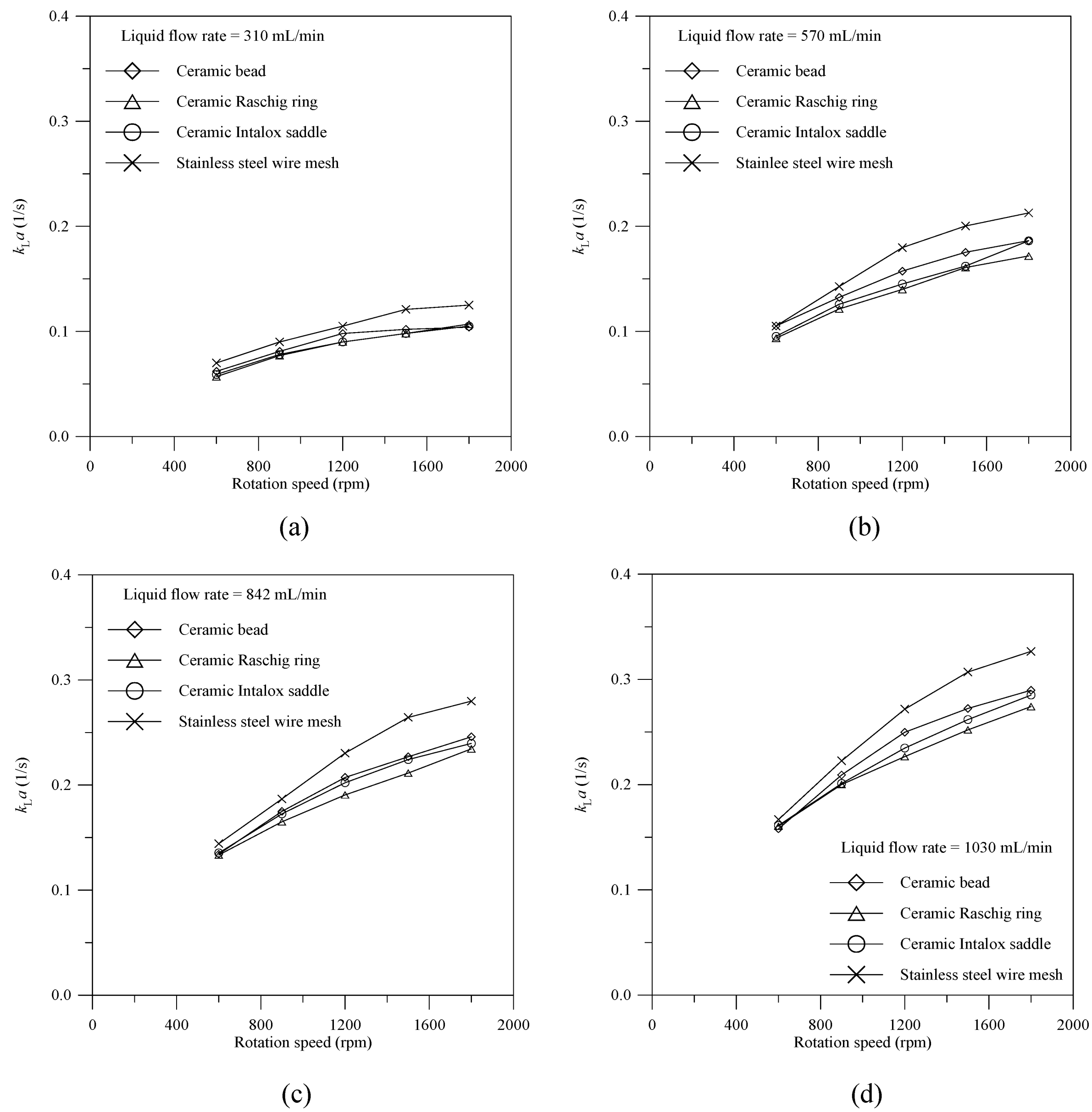


Figure 5. Dependence of k_La on rotation speed for different shapes of the packings: liquid flow rate = (a) 310, (b) 570, (c) 842, and (d) 1030 mL/min.

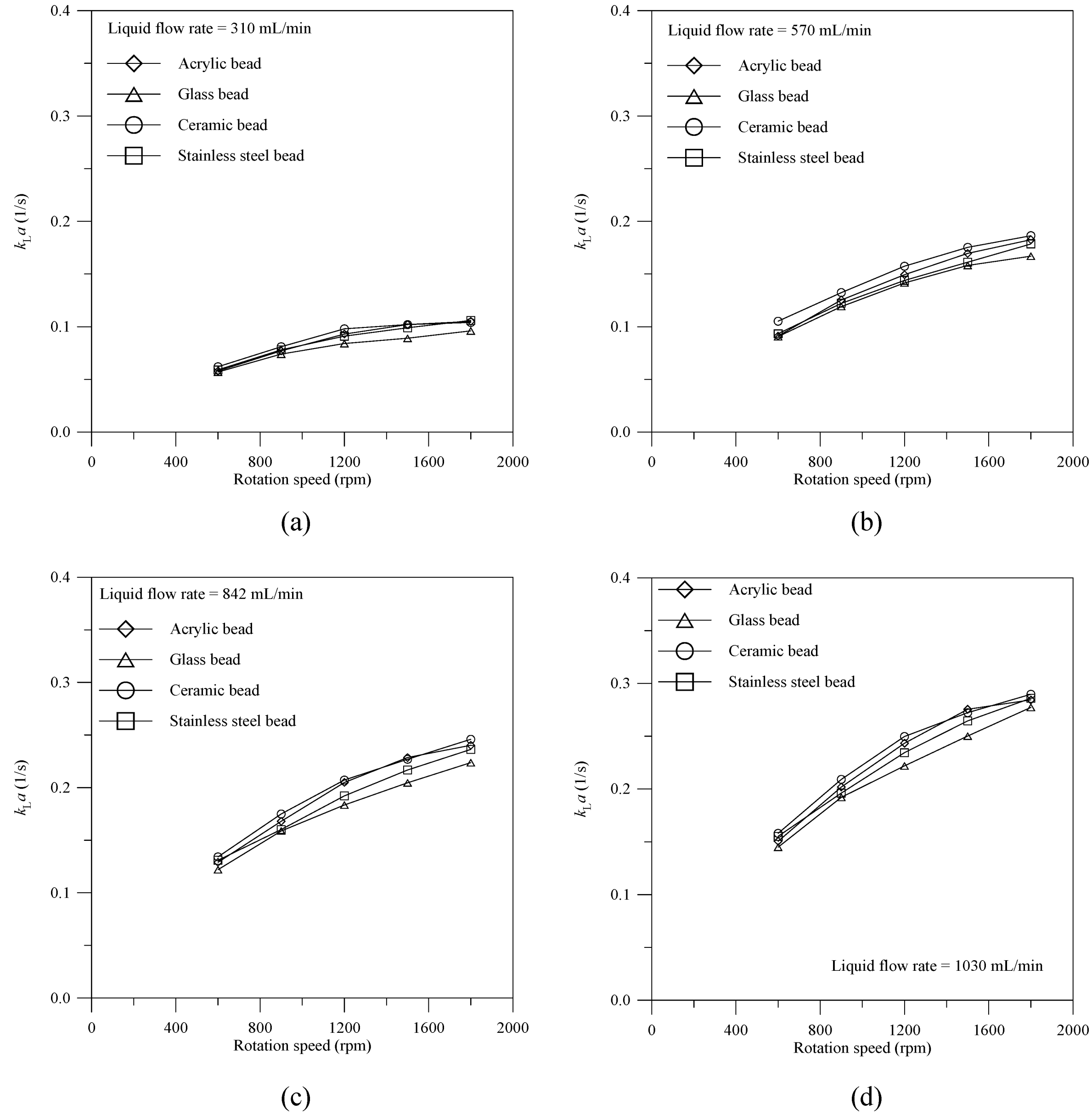


Figure 6. Dependence of k_La on rotation speed for different materials of the packings: liquid flow rate = (a) 310, (b) 570, (c) 842, and (d) 1030 mL/min.

area of the packing. However, in an RPB, these types of packing are not effective in enhancing the mass transfer efficiency probably because the shape of Raschig rings and Intalox saddles hinders the dispersion of the liquid, especially in the radial direction. A part of the packing's surface is difficult to wet when liquid flows very fast.

Figure 6 shows the mass transfer coefficients in an RPB for various materials of the packings. It is found that the mass transfer coefficients in an RPB are similar for various materials of the packings. This characteristic is different from the results obtained in a conventional packed column by Coughlin[21] and Sahay and Sharma.[22] To further investigate the influence of the surface property of the packing on mass transfer, the ceramic beads and the glass beads were treated with octadecyltrichlorosilane and isooctane and a hydrophobic layer was coated on the packing surface.[27] Figure 7 shows the mass transfer coefficient in an RPB packed with the original and the hydrophobically treated packings, respectively. The result shows that the hydrophobically treated packings provide lower mass transfer efficiency than the original packings. The mass transfer coefficient of the glass beads is 8−17% lower after being coated with a hydrophobic layer, and the mass transfer coefficient of the ceramic beads with a hydrophobic layer is 15−27% lower compared to the original beads. In addition, as the liquid flow rate increases, the difference between the hydrophobically treated and the original packings becomes larger. This is mainly because the surface of the hydrophobically treated packing is not easily wetted, resulting in a lower gas−liquid interfacial area and thicker liquid films. Consequently, lower mass transfer efficiency was obtained.

Figure 8 shows a comparison between the current experimental results and the calculated values of k_La by using the correlations given in the Higee literature.[9,14] In Figure 8a, the Tung and Mah[14] model gives a clear discrepancy between the calculated and experimental values of k_La for different packings, and the discrepancy is relatively small by the correlation (eq 3) of Chen et al.,[9] shown as Figure 8b. The correlation of eq 3 seems to fit data with good traits (slope), but with relatively significant deviation. This may be due to the fact that the correlation was obtained with limited packings. To further

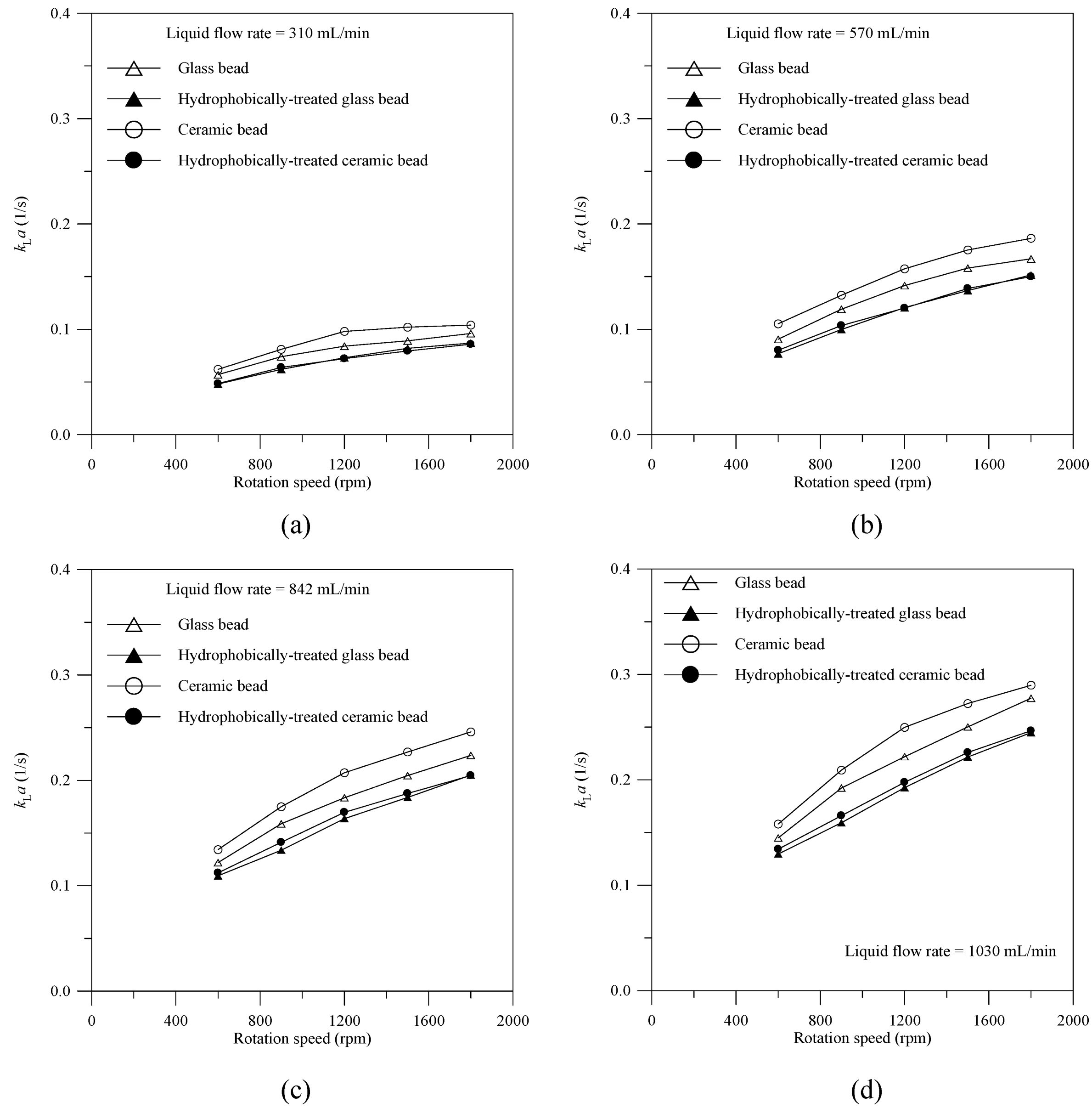


Figure 7. Dependence of $k_L a$ on rotation speed for the original and the hydrophobically treated packings: liquid flow rate = (a) 310, (b) 570, (c) 842, and (d) 1030 mL/min.

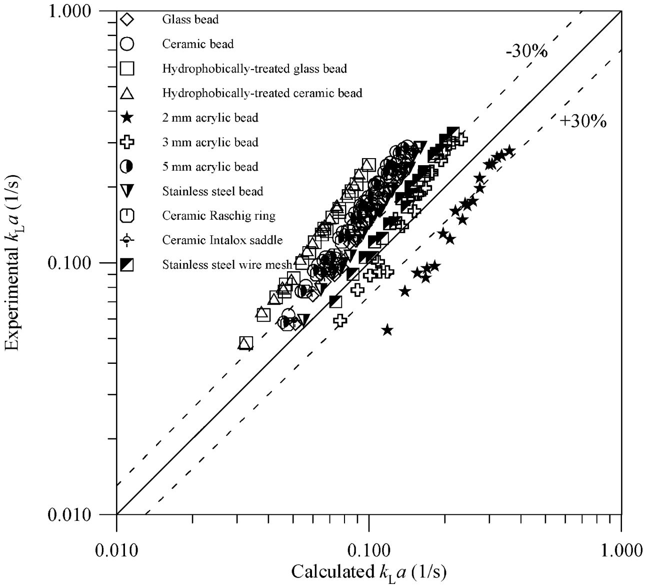
improve the applicability of eq 3 by including various kinds of packing, a modified correlation was proposed as follows:

$$\frac{k_L a d_p}{D a_t}\left(1 - 0.93\frac{V_o}{V_t} - 1.13\frac{V_i}{V_t}\right) = 0.35 Sc^{0.5} Re^{0.17} Gr^{0.3} We^{0.3} \left(\frac{a_t}{a_p'}\right)^{-0.5} \left(\frac{\sigma_c}{\sigma_w}\right)^{0.14} \quad (7)$$

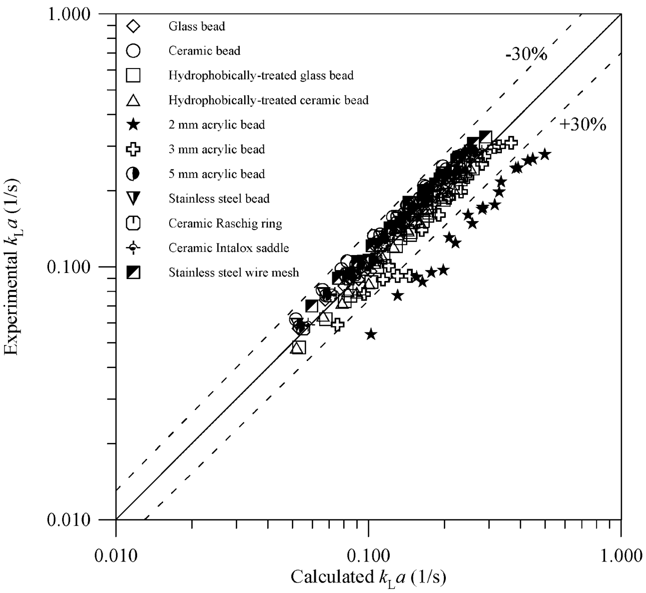
In the right-hand side of eq 7, the surface area of the packing per unit volume of the bed, a_t, and the critical surface tension, σ_c, are added to reduce the discrepancy between eq 3 and experimental data, and a_p' and σ_w are the surface area of the 2-mm diameter bead per unit volume of the bead and the surface tension of water at 25 °C, whose values are 3000 1/m and 0.072 kg/s^2, respectively. As shown in Figure 9, the $k_L a$ data collected in this experiment can be predicted well with this modified empirical correlation by including the packing effect. In addition, Figure 10 shows the comparison between the calculated results of eq 7 and experimental values of $k_L a$ from various papers published previously. The detailed description of the experimental systems and the specifications of the RPBs used in these studies can be found in our previous work.[9] It is seen in Figure 10 that eq 7 could reasonably estimate most of the mass transfer coefficients reported in previous Higee studies.

Conclusion

In this study, the mass transfer efficiency of an RPB packed with various types of packing has been examined. The packings include acrylic beads, glass beads, ceramic beads, stainless steel beads, Raschig rings, Intalox saddles, wire meshes, and hydrophobically treated beads with emphases on their size, shape, material, and surface property. The mass transfer coefficients were obtained using an oxygen−water system and evaluated as a function of rotation speed and liquid flow rate. Experimental results show that $k_L a$ increases with an increase in rotation speed and liquid flow rate. There is no obvious relationship between a_t and $k_L a$. This could be attributed to the fast flowing liquid



(a)



(b)

Figure 8. Comparison of experimental values of k_La with results calculated by the correlation provided by (a) Tung and Mah[14] (eqs 1 and 2) and (b) Chen et al.[9] (eq 3).

films and significant amount of droplets in the radial direction induced by high rotation speeds in an RPB. In addition, probably because a part of the surface of Raschig rings and the Intalox saddles is difficult to wet, the mass transfer coefficients of these two packings are lower than those of the others, while the k_La of the wire mesh is the highest. As for materials, the mass transfer coefficients are similar for acrylic, glass, ceramic, and stainless steel beads. Besides, the k_La values for hydrophobically treated packings are 8−27% lower than those of the original packings. In light of the above results, the effect of packing on the mass transfer obtained in an RPB is different from that obtained in a conventional packed column, and the existing correlations for Higee systems need to be improved by including the packing effect. Therefore, a modified correlation for k_La in an RPB is proposed. It is noted that the correlation is valid not only for the various packings investigated in this work but also for most of the k_La data in the Higee literature.

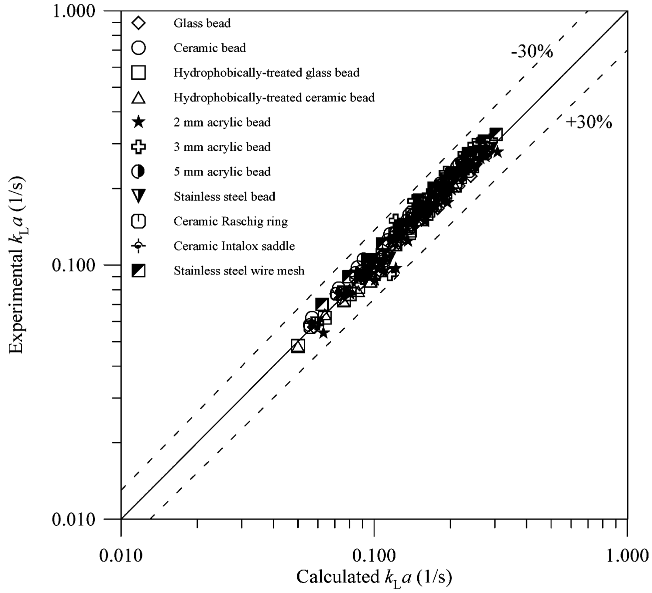


Figure 9. Comparison of experimental values of k_La with results calculated using eq 7.

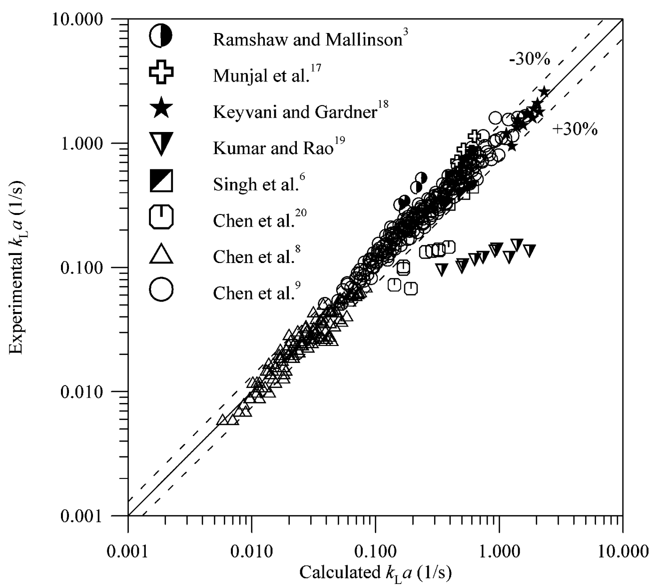


Figure 10. Comparison of experimental values of k_La in the Higee literature with results calculated using eq 7.

Acknowledgment

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

Nomenclature

a = gas−liquid interfacial area (1/m)
a_p' = surface area of the 2-mm diameter bead per unit volume of the bead (1/m)
a_t = surface area of the packing per unit volume of the bed (1/m)
a_c = centrifugal acceleration (m/s^2)
$C_{L,i}$ = 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)
$k_L a$ = 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 6 (−)
V_i = volume inside the inner radius of the bed = $\pi r_i^2 z$ (m^3)
V_o = volume between the outer radius of the bed and the stationary housing = $\pi(r_s^2 - r_o^2)z$ (m^3)
V_t = total volume of the RPB = $\pi r_s^2 z$ (m^3)
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 (−)
σ = surface tension (kg/s^2)
σ_c = critical surface tension of packing (kg/s^2)
σ_w = surface tension of water (kg/s^2)

Dimensionless Groups

Fr = Froude number = $L^2 a_t/\rho^2 a_c$
Gr = Grashof number = $d_p^3 a_c \rho^2/\mu^2$
Re = Reynolds number = $L/a_t\mu$
Sc = Schmidt number = $\mu/\rho D$
We = Weber number = $L^2/\rho a_t \sigma$

Literature Cited

(1) Chen, Y. S.; Liu, H. S.; Lin, C. C.; Liu, W. T. Micromixing in a Rotating Packed Bed. *J. Chem. Eng. Jpn.* **2004**, *37*, 1122.

(2) Chen, Y. S.; Tai, C. Y.; Chang, M. H.; Liu, H. S. Characteristics of Micromixing in a Rotating Packed Bed. *J. Chin. Inst. Chem. Eng.* **2006**, *37*, 63.

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

(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.; Liu, W. T.; Tan, C. S. Removal of Carbon Dioxide by Absorption in a Rotating Packed Bed. *Ind. Eng. Chem. Res.* **2003**, *42*, 2381.

(6) 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.

(7) Liu, H. S.; Lin, C. C.; Wu, S. C.; Hsu, H. W. Characteristics of a Rotating Packed Bed. *Ind. Eng. Chem. Res.* **1996**, *35*, 3590.

(8) 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.

(9) Chen, Y. S.; Lin, C. C.; Liu, H. S. Mass Transfer in a Rotating Packed Bed with Various Radii of the Bed. *Ind. Eng. Chem. Res.* **2005**, *44*, 7868.

(10) Kelleher, T.; Fair, J. R. Distillation Studies in a High-Gravity Contactor. *Ind. Eng. Chem. Res.* **1996**, *35*, 4646.

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

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

(13) Lin, C. C.; Chen, Y. S.; Liu, H. S. Adsorption of Dodecane from Water in a Rotating Packed Bed. *J. Chin. Inst. Chem. Eng.* **2004**, *35*, 531.

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

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

(16) 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.

(17) 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.

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

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

(20) 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.

(21) Coughlin, R. W. Effect of Liquid-Packing Surface Interaction on Gas Absorption and Flooding in a Packed Column. *AIChE J.* **1969**, *15*, 654.

(22) Sahay, B. N.; Sharma, M. M. Effective Interfacial Area and Liquid and Gas Side Mass Transfer Coefficients in a Packed Column. *Chem. Eng. Sci.* **1973**, *28*, 41.

(23) ASHRAE. *Equipment, 1983 ASHRAE Handbook*; American Society Heating Refrigerating and Air-Conditioning Engineers: Atlanta, 1983.

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

(25) Kwok, M. P.; Neumann, A. W. Contact Angle Measurement and Contact Angle Interpretation. *Adv. Colloid Interface Sci.* **1999**, *81*, 167.

(26) Perry, R. H.; Green, D. W. *Chemical Engineers' Handbook*, 6th ed.; McGraw-Hill: New York, 1984.

(27) Ulman, A. Formation and Structure of Self-Assembled Monolayers. *Chem. Rev.* **1996**, *96*, 1533.

(28) Lin, F. Y. The Effect of Packing on Mass Transfer in a Rotating Packed Bed. Master's Thesis, National Taiwan University, Taiwan, 2005.

(29) Burns, J. R.; Ramshaw, C. Process Intensification: Visual Study of Liquid Maldistribution in Rotating Packed Beds. *Chem. Eng. Sci.* **1996**, *51*, 1347.

Received for review March 30, 2006
Revised manuscript received July 26, 2006
Accepted August 17, 2006

IE060399L