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Abstract: Carbon dioxide was absorbed into aqueous polyacrylamide (PAA) solution containing NaOH in a flat-stirred vessel to investigate the effect of non-Newtonian rheological behavior of PAA on the rate of chemical absorption of CO_2, where the reaction between CO_2 and NaOH was assumed to be a first-order reaction with respect to the molar concentration of CO_2 and NaOH, respectively. The liquid-side mass transfer coefficient (k_L), which was obtained from the dimensionless empirical equation containing the properties of viscoelasticity of the non-Newtonian liquid, was used to estimate the enhancement factor due to chemical reaction. PAA with elastic property of non-Newtonian liquid made the rate of chemical absorption of CO_2 accelerate compared with Newtonian liquid.

Keywords: Chemical absorption, carbon dioxide, PAA, NaOH, non-Newtonian liquid

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INTRODUCTION

Gas-liquid mass transfer in non-Newtonian liquid is an important example of gas absorption in pseudoplastic flow of industrial processes such as a fermentation broth, slurry, and fluidized bed Variation of the volumetric liquid-phase mass transfer coefficient (k_La) in gas-dispersed systems consists of the mass transfer coefficient (k_L) and the specific gas-liquid interfacial area (a). The former could be correlated with Reynolds and Schmidt numbers including liquid viscosity. It is likely that the latter varies not only with Newtonian liquid properties such as surface tension but also with some non-Newtonian and/or viscoelastic fluid properties.

Only use of the apparent viscosity of non-Newtonian fluids was not sufficient to obtain a unified correlation for k_La values. Due to the complexities of gas absorption in non-Newtonian media, the correlations obtained by these studies were limited to just a few kinds of non-Newtonian fluids such as Carbopol, carboxymethylcellulose (CMC), polyacrylate (PA), polyethylene oxide (PEO), polyacrylamide (PAA), and polyisobutylene (PIB) solutions. If a considerable reduction of k_La is due to the viscoelasticity of the aqueous solution, then the extent to which data for the viscoelastic solution such as PAA deviate from those for the inelastic solution such as CMC should correlate with some measure of the solution's elasticity. The dimensionless number such as Deborah number (De), which relates the elastic properties with the process parameters, is used to correlate k_La with properties of non-Newtonian liquids. Unified correlations have been proposed for k_La in Newtonian as well as non-Newtonian solutions by introducing the dimensionless terms such as $(1 + n_1De^{n_2})^{n_3}$, which are listed in Table 1. As shown in Table 1, values of in the dimensionless group are different from one another.

There is little information about the effect of elastic properties on chemical absorption of gas in non-Newtonian liquid. Park et al. (6) presented the effect of elasticity of polyisobutylene (PIB) in the benzene solution of polybutene (PB) and PIB on chemical absorption of CO_2 in w/o emulsion composed of aqueous alkaline solution as dispersed phase and

Table 1. Coefficients of dimensionless group for gas-liquid mass transfer correlation

Investigator	n_1	n_2	n_3	Polymer	Contactor
Yagi and Yoshida (1)	2	0.5	−0.67	CMC, PA	Agitated vessel
Ranade and Ulbrecht (2)	100	1	−0.67	CMC, PAA	Stirred tank
Nakanoh and Yoshida (3)	0.13	0.55	−1	CMC, PA	Bubble column
Park et al. (4)	100	1	−0.42	PB, PIB	Agitated vessel
Park et al. (5)	2461.3	1	−0.274	PB, PIB	Agitated vessel

benzene solution of PB and PIB as continuous phase in an agitation vessel. They showed that PIB accelerated the absorption rate of CO_2. It is worthwhile to investigate the effect of non-Newtonian rheological behavior on the rate of chemical absorption of a gas, where a reaction between CO_2 and reactant occurs in the aqueous phase.

In this study, the chemical absorption mechanism of CO_2 into an aqueous PAA solution with NaOH is presented to observe the effect of rheological property on the chemical absorption, and the measured absorption rates of CO_2 are compared with those obtained from the model based on the penetration theory with chemical reaction. The volumetric mass transfer coefficient obtained from the empirical formula is used to estimate the enhancement factor due to chemical reaction.

THEORY

The problem to be considered is that a gaseous species A (CO_2) dissolves into the liquid phase and then reacts irreversibly with species B according to

$$A + \nu B \rightarrow P \tag{1}$$

The stoichiometric coefficients (ν) in Eq. (1) for NaOH were obtained from the reference (7) and its value was 1.

Species B is a nonvolatile solute, which has been dissolved into the liquid phase prior to its introduction into the gas absorber. It is assumed that gas phase resistance to absorption is negligible by using pure species A, and thus the concentration of species A at the gas-liquid corresponds to equilibrium with the partial pressure of species A in the bulk gas phase.

The chemical reaction of Eq. (1) is assumed to be second-order as follows:

$$r_A = k_2 C_A C_B \tag{2}$$

Under the assumptions mentioned above, the conservation equations of species A and B are given as

$$D_A \frac{\partial^2 C_A}{\partial z^2} = \frac{\partial C_A}{\partial t} + k_2 C_A C_B \tag{3}$$

$$D_B \frac{\partial^2 C_B}{\partial z^2} = \frac{\partial C_B}{\partial t} + \nu k_2 C_A C_B \tag{4}$$

Boundary and initial conditions to be imposed are

$$z = 0,\ t > 0;\ C_A = C_{Ai} \tag{5}$$

$$z > 0,\ t = 0;\ C_A = 0 \tag{6}$$

$$z = \infty,\ t > 0;\ C_A = 0 \tag{7}$$

Eqs. (3)–(7) are put into the dimensionless form as follows:

$$\frac{\partial^2 a}{\partial x^2} = \frac{\partial a}{\partial \theta} + ab \tag{8}$$

$$\frac{\partial^2 b}{\partial x^2} = r\frac{\partial b}{\partial \theta} + vrq\ ab \tag{9}$$

$$x = 0,\ \theta > 0;\ a = 1,\ \frac{\partial b}{\partial \theta} = 0 \tag{10}$$

$$x > 0,\ \theta = 0;\ a = 0,\ b = 1 \tag{11}$$

$$x = \infty,\ \theta > 0;\ a = 0,\ b = 1 \tag{12}$$

where $a = C_A/C_{Ai}$, $b = C_B/C_{Bo}$, $x = z\sqrt{k_2 C_{Bo}/D_A}$, $\theta = k_2 C_{Bo} t$, $r = D_A/D_B$, $q = C_{Ai}/C_{Bo}$.

The molar flux (N_A) of CO_2 with chemical reaction at any contact time t is defined as

$$N_A = -D_A \left.\frac{\partial C_A}{\partial z}\right|_{z=0} \tag{13}$$

The mean molar flux ($\bar{N}_A$) of CO_2 during contact time, t is written as

$$\bar{N}_A = \frac{1}{t}\int_0^t N_A dt \tag{14}$$

The mean molar flux ($\bar{N}_A^o$) without chemical reaction based on the penetration model during contact time has been derived as follows (8):

$$\bar{N}_A^o = 2C_{Ai}\sqrt{\frac{D_A}{\pi t}} \tag{15}$$

From comparison of the penetration model with the film model, the relation between t and k_L is derived as follows (9):

$$k_L = 2\sqrt{\frac{D_A}{\pi t}} \tag{16}$$

The enhancement factor (β) here defined as the ratio of molar flux with chemical reaction to that without chemical reaction ($\bar{N}_A/\bar{N}_A^o$) is described by using Eqs. (14) and (15) as follows:

$$\beta = -\frac{\pi}{4H_A}\int_0^\theta \left.\frac{\partial a}{\partial x}\right|_{x=0} d\theta \tag{17}$$

where $H_A = \sqrt{D_A k_2 C_{Bo}/k_L}$.

The absorption rate of CO_2 (R_A) is expressed as follow:

$$R_A = \beta R_{Ao} = \beta k_L a\, C_{Ai} \tag{18}$$

where R_{Ao} is the absorption rate multiplied by the mean molar flux ($\bar{N}_A^o$) by the contact area of gas and liquid (a). The value of β in Eq. (18) is estimated from Eq. (17) by using a numerical solution with FEMLAB at the contact time of $4D_A/\pi k_L^2$ calculated from Eq. (16).

EXPERIMENTAL

Chemicals

All chemicals in this study were reagent grade, and used without further purification. Purity of both CO_2 and N_2 was more than 99.9%. The polymers used in this study were polyacrylamide (PAA) with the mean molecular weight of 10,000 (by Aldrich Chemical Company, USA). NaOH (Aldrich, USA) was used as reagent grade without purification.

Rate of Absorption

An agitated vessel used for measurement of absorption rate of CO_2 was constructed of glass of 0.102 m inside diameter and of 0.151 m in height with four equally spaced vertical baffles. A straight impeller with 0.034, 0.05, and 0.07 m in length and 0.011 m in width was used as the liquid phase agitator, and located at the middle position of the liquid phase. The gas and liquid in the vessel were agitated in the range of 50 to 400 rev/min. The absorption rate of CO_2 was measured in the aqueous solution of PAA of $0\sim100\,kg/m^3$ and NaOH of $0\sim2\,kmol/m^3$ under the experimental conditions such as an impeller speed of 50–400 rev/min along the procedure similar to those reported elsewhere (4) at 1 atm and 25°C.

PHYSICOCHEMICAL AND RHEOLOGICAL PROPERTIES

Solubility of CO_2 in Aqueous PAA Solution

The pressure measuring method in this study was used by measuring the pressure difference of CO_2 between before and after equilibrium between gas and liquid phase similar to the procedure reported elsewhere (10) to get the solubility (C_{APi}) of CO_2 in the aqueous solutions of PAA at 25°C and 0.101 MPa. The experimental procedure was duplicated as reported in the

published research (4) in detail. The solubility (C_{Ai}) of CO_2 in aqueous NaOH (7) solution was estimated as follows:

$$\log(C_{Ai}/C_{APi}) = -0.138\ C_{Bo}$$

Density and Apparent Viscosity of Aqueous PAA Solution

The density of the aqueous solution of PAA was measured at 25°C within $0.1\,kg/m^3$ by weighing with a pycnometer (Fisher Scientific Co., USA) and were found to be identical within experimental accuracy to the density of water. The apparent viscosity of aqueous solution of PAA was measured at 25°C with Brookfield viscometer (Brookfield Eng. Lab. Inc., USA).

Reaction Rate Constant

In the reaction of CO_2 with NaOH (7), the reaction rate constant (k_2) was estimated as follows.

$$\log k_2 = 10.99 - \frac{2152}{T}$$

Diffusivities of CO_2 and NaOH

The diffusivity (D_{ANaOH}) of CO_2 in aqueous NaOH (11) solution was estimated as follows:

$$D_{ANaOH} = D_{AW}(1 - 0.129C_{Bo})$$

Diffusivity (D_{BNaOH}) of NaOH in aqueous NaOH solution was obtained from the assumption that the ratio of D_{BNaOH} to D_{ANaOH} was equal to the ratio in water (12). The diffusivity of CO_2 and NaOH in water at 25°C were taken as $1.97 \times 10^{-9}\,m^2/s$ (11) and $3.24 \times 10^{-9}\,m^2/s$ (12), respectively.

The diffusivity of a solute of a small size such as CO_2, O_2, or CH_4 in a polymer solution depends on the viscosity of the solution and the molecular weight of the polymer. The diffusivity (D_A) of CO_2 and that (D_B) of NaOH in the aqueous PAA solution were obtained from the following equations suggested by Lohse et al. (13), which were modified from the Stoke-Einstein equation, and correlated with the molecular weight of the polymer in the solution, respectively.

$$D_A/D_{ANaOH} = (\mu_W/\mu)^{3.7\sqrt{M_W/M_P}}$$

$$D_B/D_{BNaOH} = (\mu_W/\mu)^{3.7\sqrt{M_W/M_P}}$$

where M_w and M_p are molecular weight of water and polymer, respectively.

The values of solubility, diffusivity of CO_2, density, and apparent viscosity of aqueous PAA solution are given in Table 2.

Rheological Properties of Aqueous PAA Solution

We assume that a power-law model, which has been widely used for shear-dependent viscosity, can be represented by the non-Newtonian flow behavior of aqueous PAA solutions.

$$\tau = K\gamma^{n} \tag{19}$$

$$\mu = K\gamma^{n-1} \tag{20}$$

$$N_1 = A\gamma^{b} \tag{21}$$

where n, K, b, and A are material parameters depending on temperature. These parameters were obtained from the measurement of τ and N_1 for the change of γ by the parallel disk type rheometer (Ares, Rheometrics, USA) of the diameter of 0.05 m and the gap of 0.001 m.

The obtained values of K, n, A, and b in the aqueous solution of various concentration of PAA are give in Table 2. As shown in Table 2, the values of A increased with increasing of the concentration of PAA, which means that PAA has an elastic behavior (2).

One of the parameters used frequently to represent the characteristics of viscoelasticity is known as the material's characteristic relaxation time (λ) of the liquid defined as

$$\lambda = \frac{N_1}{\mu\gamma^2} \tag{22}$$

Using Eqs. (20) and (21), λ is rearranged as

$$\lambda = \frac{A}{K}\gamma^{b-n-1} \tag{23}$$

One of the dimensionless numbers, which relate the elastic properties with the process parameters, is Deborah number (De), defined as the ratio of the material's characteristic relaxation time to the characteristic flow time. The characteristic flow time is measured against a characteristic process time, which is related to the reciprocal of the impeller speed in case of stirred tanks, and De is derived as follows:

$$De = \lambda/t = \frac{A}{K}\gamma^{b-n-1}N \tag{24}$$

Table 2. The physicochemical and rheological properties of CO_2 and PAA aqueous solution

PAA (kg/m^3)	Viscosity (Ns/m^2) $\times 10^3$	Diffusivity (m^2/s) $\times 10^9$	Solubility ($kmol/m^3$)	Density (kg/m^3)	Rheological property			
					n	K $\times 10^3$	b	A $\times 10^3$
0	1	1.970	0.039	1000	1.0	1.0	—	—
0.1	1.002	1.9694	0.039	1000	0.99	1.07	0.1	27.3
0.5	1.004	1.9688	0.039	1003	0.94	1.25	0.11	28.5
1	1.011	1.9666	0.038	1005	0.92	1.34	0.13	30.9
5	0.172	1.9486	0.038	1008	0.89	1.71	0.18	46.5
10	2.155	1.7463	0.036	1010	0.86	3.71	0.25	57.6
50	2.811	1.6750	0.036	1016	0.78	6.16	0.38	188.2
100	3.451	1.6219	0.035	1032	0.76	7.15	0.43	294.8

where shear rate (γ) is obtained in case of agitation of liquid in a cylindrical vessel as follows (14):

$$\gamma = 4\pi N/n \tag{25}$$

RESULTS AND DISCUSSION

Empirical Correlation of Liquid-Side Mass Transfer Coefficient of CO_2

To observe the effect of the concentration of PAA with the impeller speed and size as parameters on the volumetric mass transfer coefficient (k_La), the measured k_La in the aqueous solution of PAA concentration in the range of $0.1\sim100\,kg/m^3$ was plotted against PAA concentration in Fig. 1. As shown in Fig. 1, k_La increases with the increase of the agitation speed of the impeller and decreases with the increase of PAA concentration.

In analyzing the relationship between k_La and the experimental variables such as the PAA concentration, and the speed and size of the impeller, the following influences may be considered: diffusivity, viscosity, and rheological properties of the liquid phase.

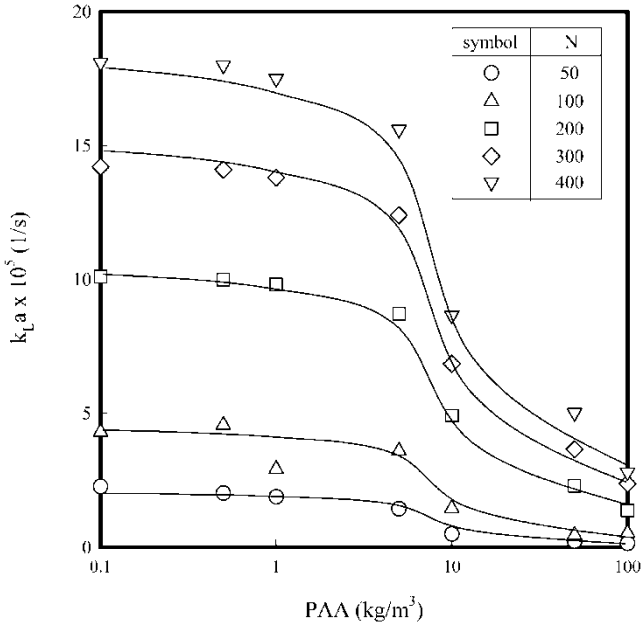

Figure 1. Effect of PAA concentration on k_La of CO_2 at $d = 0.034\,m$.

It is customary to express the influence of viscosity upon the mass transfer coefficient in terms of Schmidt number defined as $\mu/\rho D_A$, in which the viscosity is related to the diffusion coefficient. As shown in Table 2, the diffusivity of CO_2 in the aqueous PAA solution does not vary significantly from that in water, and thus the use of a dimensionless Schmidt number is not warranted. Instead, the ratio of viscosity of PAA solution to that of water (15) was used to correlate with k_La, because the viscosity in the agitated vessel depends on the speed of impeller and the rheological properties as shown in Eq. (20) through Eq. (25).

To correlate k_La with the experimental variables such as the PAA concentrations and the speed and size of the impeller, the dimensionless groups such as Sherwood number (Sh) and Reynolds number (Re) are used, and they are defined as follows, respectively:

$$Sh = k_L a d^2/D_A \tag{26}$$

$$Re = d^2 N\rho/\mu \tag{27}$$

Figure 2 shows logarithmic plots of Sh against Re in case of water as absorbent of CO_2. As shown in Fig. 2, the plots are linear, and the slope and intercept from the straight line of the plots by a least-squares method

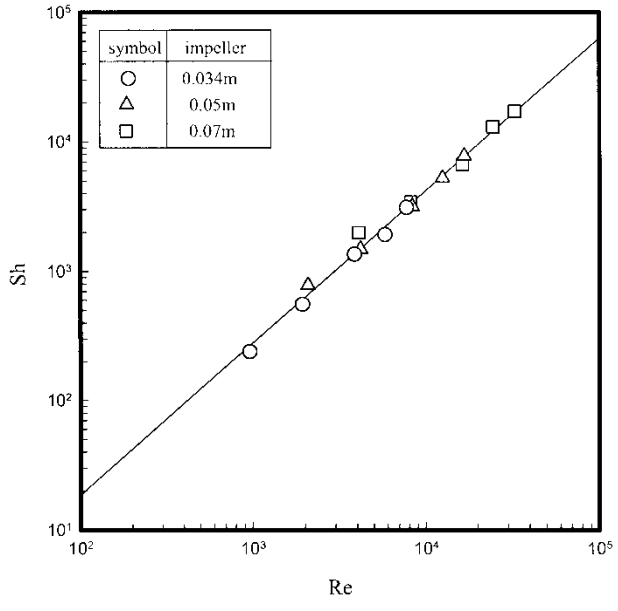

Figure 2. Sh vs. Re in water at various impeller size.

were obtained, which were used to get an empirical equation between Sh and Re as follows:

$$\mathrm{Sh} = 0.082\,\mathrm{Re}^{1.17} \tag{28}$$

The calculated values of Sh from Eq. (28) approached the measured Sh very well with a standard deviation (SD) of 0.81% and a mean deviation (MD) of 6.37%.

Figure 3 shows logarithmic plots of Sh against Re for the aqueous PAA solutions, and the solid line in Fig. 3 presents the Sh calculated from Eq. (28). As shown in Fig. 3, the plots were scattered from the straight line with SD of 33.75% and MD of 56.93%. This may be due to non-Newtonian behavior of the aqueous PAA solution.

The new terms corrected with viscosity and De were used to lessen the deviation of the plots for the PAA solution from the plots for water as shown in Fig. 2. A simple multiple regression exercise was used for the plots of Sh combined with $(\mu/\mu_w)^{c_1}$ $(1 + c_2\mathrm{De})^{c_3}$ against Re, which gave the values of c_1, c_2, and c_3 are 0.68, 54.7, and -0.45, respectively, with SD of 8.07% and MD of 22.49% as shown in Fig. 4.

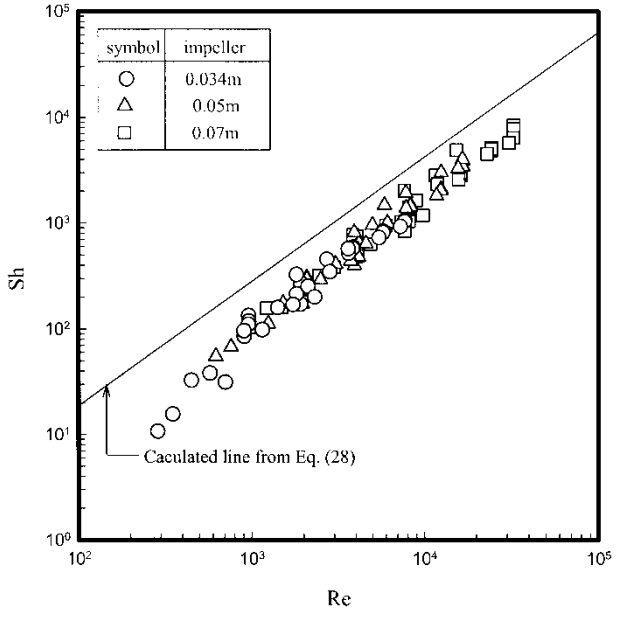

Figure 3. Dimensionless correlation of volumetric mass transfer coefficient of CO_2 in PAA aqueous solution at various impeller size.

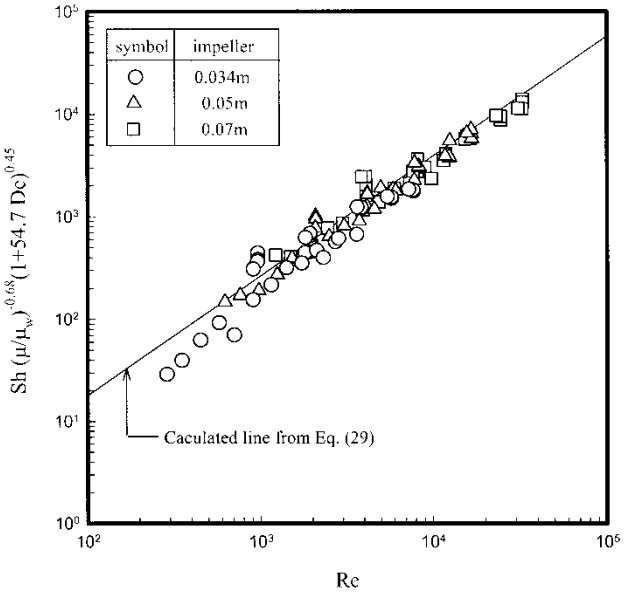

Figure 4. Dimensionless correlation of volumetric mass transfer coefficient of CO_2 in PAA aqueous solution with corrected specific viscosity and Deborah number at various impeller size.

Using a total of 105 data points, a multiple regression analysis came up with a correlation as follows:

$$k_L a d^2/D_A = 0.082(d^2 N\rho/\mu)^{1.17}(\mu/\mu_w)^{0.68}(1 + 54.7De)^{-0.45} \qquad (29)$$

Effect of Rheological Properties on the Rate of Chemical Absorption

To observe the effect of rheological properties of aqueous PAA solution on the rate of chemical absorption, the absorption rate of CO_2 into aqueous PAA solution with NaOH was measured according to change of NaOH concentration in the range of $0\sim2\,kmol/m^3$. Figures 5 and 6 show the typical plots of the absorption rate of CO_2 against the concentration of NaOH at PAA concentration of 1 and $100\,kg/m^3$, respectively, under the experimental conditions of the agitation speed of 50 rev/min with the impeller size of 0.034 m. The triangle and circle in Fig. 5 and 6 represent the measured values of absorption rate of CO_2 in water with NaOH and aqueous PAA solution with NaOH, respectively. The three lines in both the figures represent the estimated absorption rate of CO_2 according to the kind of the

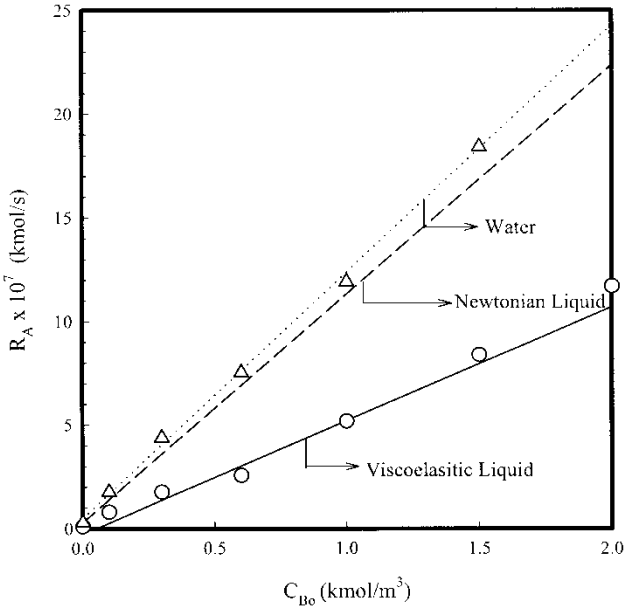

Figure 5. Effect of C_{Bo} on R_A at aqueous solution of PAA of 1 kg/m^3. (d = 0.034 m, N = 50 rev/min).

absorbents, i.e., k_La. The value of k_La used to get the solid line, dashed line, and dotted line comes from Eq. (29), Eq. (29) without De, and Eq. (28), respectively. The value of k_La in the solid line is affected by both of viscosity and elasticity, that in the dashed line by viscosity of aqueous PAA solution, and that in the dotted line by viscosity of water. As shown in Figs. 5 and 6, R_A increases with increasing NaOH concentration, and R_A in the solid line is smaller than that in the dashed line in Fig. 5, on the other hand, R_A of the solid line is larger than that in the dashed line in Fig. 6. From comparison of R_A of Fig. 5 with that of Fig. 6, the effect of the elasticity of the aqueous solution with PAA of 100 kg/m^3 on R_A is stronger than that of 1 kg/m^3, on the other hand, the effect of the viscosity of that of 1 kg/m^3 on R_A is stronger than that of 100 kg/m^3.

CONCLUSIONS

Rates of the chemical absorption of CO_2 in the aqueous solution of PAA at 0.1∼100 kg/m^3 with NaOH at 0∼2 kmol/m^3 were measured in a flat-stirred vessel to get the influence of the rheological properties of PAA on the absorption rate under the experimental conditions such as the impeller

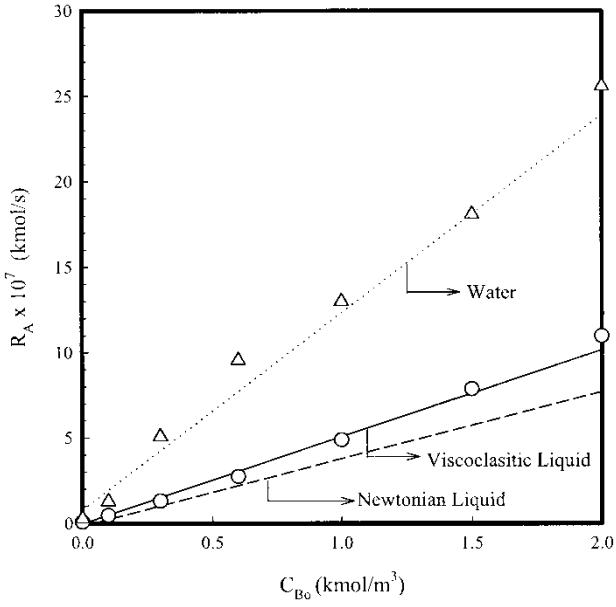

Figure 6. Effect of C_{Bo} on R_A at aqueous solution of PAA of 100 kg/m^3. (d = 0.034 m, N = 50 rev/min).

size of 0.034, 0.05, and 0.07 m and the agitation speed of 0∼400 rev/min at 25°C and 0.101 MPa. The elastic property such as Deborah number of the aqueous PAA solution was considered to get an empirical correlation of the volumetric mass transfer coefficient in the non-Newtonian liquid, which is used to estimate the enhancement factor for the chemical absorption. There are concentration ranges of PAA which make the mass transfer coefficient and absorption rate increase due to the comparison of the relative magnitude of viscosity and elasticity of the aqueous PAA solution. Deborah numbers of aqueous solution with 1 and 100 kg/m^3 PAA concentration were obtained at impeller size with 0.034 m and agitation speed with 50 rev/min using Eq. (24), and their values were 0.247 and 1.05, respectively. The larger value of De in PAA solution with 100 kg/m^3 than that in 1 kg/m^3 may make the absorption rate of CO_2 in 100 kg/m^3 PAA solution larger.

NOMENCLATURE

C_A	concentration of CO_2 (kmol/m^3)
C_B	concentration of NaOH (kmol/m^3)
d	diameter of impeller (m)

N	speed of impeller (1/s)
N_1	primary normal stress difference (N/m^2)
t	Time (s)
T	Temperature (K)
z	coordinate in film thickness direction in benzene phase (m)

Greek letters

γ	shear rate (1/s)
μ	viscosity of liquid (Ns/m^2)
μ_w	viscosity of water (Ns/m^2)
ρ	density of liquid (kg/m^3)
τ	shear stress (N/m^2)

Subscripts

A	CO_2
B	NaOH
i	gas-liquid interface
o	bulk body

REFERENCES

1. Yagi, H. and Yoshida, F. (1975) Gas absorption by Newtonian and non-Newtonian fluids in sparged agitated vessel. *Ind. Eng. Chem. Process Des. Dev.*, 14 (4): 488–493.
2. Ranade, V.R. and Ulbrecht, J.J. (1978) Influence of polymer additives on the gas-liquid mass transfer in stirred tanks. *AIChE J.*, 24 (5): 796–803.
3. Nakanoh, M. and Yoshida, F. (1980) Gas absorption by Newtonian and non-Newtonian liquids in a bubble column. *Ind. Eng. Chem. Process Des. Dev.*, 19 (1): 190–195.
4. Park, S.W., Sohn, I.J., Park, D.W., and Oh, K.J. (2003) Absorption of carbon dioxide into non-Newtonian liquid. I. Effect of Viscoelasticity. *Sep. Sci. Technol.*, 38 (6): 1361–1384.
5. Park, S.W., Sohn, I.J., Sohn, S.G., and Kumazawa, H. (2003) Absorption of carbon dioxide into non-Newtonian liquid. II. Effect of w/o emulsion. *Sep. Sci. Technol.*, 38 (6): 3983–4007.
6. Park, S.W., Sohn, I.J., Sohn, S.G., and Kumazawa, H. (2004) Absorption of carbon dioxide into non-Newtonian liquid. III. Effect of chemical reaction. *Sep. Sci. Technol.*, 39 (10): 2323–2350.
7. Hikita, H., Asai, S., and Takatsuka, T. (1976) Absorption of carbon dioxide into aqueous sodium hydroxide and sodium carbonate-bicarbonate solutions. *Chem. Eng. J.*, 11: 131–141.
8. Higbie, R. (1935) The rate of absorption of a pure gas into a still liquid during short periods of exposure. *Trans. Am. Inst. Chem. Eng.*, 31: 365–389.
9. Danckwerts, P.V. (1970) *Gas-Liquid Reactions*; McGraw-Hill Book Co.: New York, 101.

10. Kennard, M.L. and Meisen, A. (1984) Solubility of carbon dioxide in aqueous diethanolamine solutions at elevated temperature and pressures. *J. Chem. Eng. Data*, 29: 309–312.
11. Danckwerts, P.V. and Sharma, M.M. (1966) The absorption of carbon dioxide into solutions of alkalis and amines. *Chem. Eng.*, 44: 244–280.
12. Nijsing, R.A.T.O., Hendriksz, R.H., and Kramers, H. (1959) Absorption of CO_2 in jet and falling films of electrolyte solutions, with and without chemical reaction. *Chem. Eng. Sci.*, 10: 88–104.
13. Lohse, M., Quicker, G., and Deckwer, D.-W. (1981) Diffusivity and solubility of carbon dioxide in diluted polymer solutions. *AIChE J.*, 27 (4): 626–631.
14. Metzner, A.B. and Otter, R.E. (1957) Agitation of non-Newtonian fluids. *AIChE J.*, 3: 3–10.
15. Sandall, O.C. and Patel, K.G. (1970) Heat transfer to non-Newtonian pseudoplastic fluids in agitated vessels. *Ind. Eng. Chem. Process Des. Dev.*, 9 (1): 139–144.