

Effect of the rheological properties of aqueous xanthan gum solution on chemical absorption of carbon dioxide with diisopropanolamine

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Abstract

Absorption rate of carbon dioxide was measured in the aqueous xanthan gum (XG) solution in the range of 0~0.15 wt% containing diisopropanolamine (DIPA) of 0~2 kmol/m³ in a flat-stirred vessel with an impeller of 0.05 m and agitation speed of 50 rpm at 25°C and 101.3 kPa. The volumetric liquid-side mass transfer coefficient ($k_L a$) of CO₂, which was obtained by the measured physical absorption rate, was correlated with the viscosity and the elastic behavior of XG solution such as Deborah number as an empirical formula. The chemical absorption rate of CO₂ (R_A), which was estimated by the film theory using the measured $k_L a$ and the known kinetics of reaction between CO₂ and DIPA, was compared with the measured rate. The aqueous XG solution with elastic property of non-Newtonian liquid made $k_L a$ and R_A increased compared with Newtonian liquid based on the same viscosity of the solution.

Keywords : absorption, carbon dioxide, xanthan gum, viscoelastic liquid, diisopropanolamine

1. 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, *et al.* (Yagi and Yoshida, 1973; Ranade and Ulbrecht, 1978; Nakano and Yoshida, 1980). Variation of the volumetric liquid-phase mass transfer coefficient ($k_L a$) 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.

The apparent viscosity of non-Newtonian fluids is not sufficient to obtain a unified correlation for $k_L a$ values in the case of gas absorption into non-Newtonian fluids. Because of the complexities of gas absorption in non-Newtonian media, the correlations obtained by these studies have been 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 $k_L a$ is due to the viscoelasticity of the aqueous solution, then the extent to which data for an

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. A dimensionless number, such as Deborah number (De), which relates the elastic properties to the process parameters, is used to correlate $k_L a$ with properties of non-Newtonian liquids. Unified correlations have been proposed for $k_L a$ in Newtonian as well as non-Newtonian solutions by introducing the dimensionless term, such as $(1 + n_1 De^{n_2})^{n_3}$; which are listed in Table 1. As shown in Table 1, values in the dimensionless group are different one another, and the polymers in Table 1 act as a reduction or increment agent in the absorption rate of gas.

There is little information about the effect that elastic properties have on the absorption of gas accompanied by a chemical reaction in non-Newtonian liquid. Park and coworkers (2003, 2004) presented the effect of elasticity of PIB in the benzene solution and in the w/o(water in oil) emulsion, which is composed of an aqueous alkaline solution as the dispersed phase and a benzene solution as the continuous phase, on the absorption rate of CO₂. Park and coworkers (2005, 2006, 2007a) also measured the absorption rate of CO₂ in aqueous PEO solution with AMP, nanometer sized silica colloid solution with 2-amino-methyl-1-propanol (AMP), and PAA solution with monoethanolamine (MEA), respectively. They showed that the viscoelastic materials, such as PIB, PAA, PEO, and nanometer sized silica influenced the absorption rate of CO₂.

Xanthan gum (XG) is an extracellular heteropolysac-

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

Investigator	n_1	n_2	n_3	Substance	Contacting
Yagi and Yoshida(1975)	2	0.5	-0.67	CMC, PA	Agitated vessel
Ranade and Ulbrecht(1978)	100	1	-0.67	CMC, PAA	Stirred tank
Nakanoh and Yoshida(1980)	0.13	0.55	-1	CMC, PAA	Bubble column
Park <i>et al.</i> (2003)	100	1	-0.42	PB, PIB	Agitated vessel
Park <i>et al.</i> (2004)	2461.3	1	-0.274	PB, PIB	Agitated vessel
Park <i>et al.</i> (2005)	8.33	1.31	1	PEO	Agitated vessel
Park <i>et al.</i> (2006)	39.4	1	-0.43	silica	Agitated vessel
Park <i>et al.</i> (2007)	54.7	1	-0.45	PAA	Agitated vessel

charide produced by microorganisms of the genus *Xanthomonas*. Since its first commercial production in 1964, XG has found numerous applications in the food and chemical industries as a thickening agent, stabilizer and emulsifier (Standford and Baird, 1983). Even solutions having a low concentration of XG show high viscosity and insensitivity to changes in temperature, PH and sanitary. XG production usually has been performed in batch fermentation using the bacterium *Xanthomonas campestris*. The conditions and performance of such fermentations in stirred tank reactors (Herbst, *et al.*, 1992), bubble columns (Pons *et al.*, 1989; Suh *et al.*, 1992) and airlifts (Kessler *et al.*, 1993) have been studied by some researchers. XG fermentation is probably the most complex fermentation process in terms of rheological property variation and associated mixing problems. The changes in viscosity during culture exceed 4 orders of magnitude, which is greater even than that found in high-viscosity polymerization processes in the chemical industry. The change in rheological properties of broths during the course of a batch fermentation leads also to increasing pseudoplasticity, viscoelasticity, and yield stress values. This last characteristic, the yield stress, makes it especially difficult to achieve good mixing because, beyond certain distance from the impeller, the fluid is stagnant. In these stagnant regions where only diffusional mass and heat transfer can occur, the productivity is practically reduced to zero, and mass transfer in stirred tank reactors for XG were related to the geometry of the tank and viscosity of liquid based on the power-law liquid (Galindo and Nienow, 1992). As was reviewed in Song *et al.* (Song *et al.*, 2006), there exists a relatively large amount of literature published on the rheological properties of both diluted and semi-dilute (or moderately concentrated) XG solutions prepared from aqueous media. However, only a little attention has been given to the effect of rheological properties of XG on mass transfer of a solute in XG media (Vashitz *et al.*, 1988; Vashitz *et al.*, 1989; Gar-

cia-Ochoa and Gomez, 1998). Terasaka and Shibata (2003) presented that $k_{L,a}$ of oxygen in XG fermentation of a bubble column was a function of gas hold up, yield stress and diffusivity of oxygen.

Park and coworkers (2007b, 2008a, 2008b) also measured the absorption rate of CO₂ in aqueous XG solution with MEA, AMP, and NaOH, respectively. They explained the effect of the rheological behavior on the absorption rate of CO₂ using Deborah number and showed that the aqueous XG solution of non-Newtonian liquid made the absorption rate of CO₂ increased compared with Newtonian liquid based on the same viscosity of the solution.

In this study, the aqueous XG solution containing diisopropanolamine (DIPA) was used as a absorbent of CO₂, which is one of the series of works (2007b, 2008a, 2008b) to investigate the effect of the rheological behavior of non-Newtonian liquid on the gas absorption. The measured absorption rates of CO₂ were compared with those estimated by the mass transfer mechanism with chemical reaction based on the film theory. The volumetric mass transfer coefficient of CO₂ correlated with Deborah number was used to estimate the physical absorption rate of CO₂ in the aqueous XG solution.

2. Theory

The overall reaction between CO₂ (A) and DIPA (B) in aqueous solution is



The stoichiometric coefficients (ν) in Eq. (1) for DIPA was obtained from the reference (Versteeg and van Swaaij, 1988) and its value was 2.

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 (Versteeg and van Swaaij, 1988) as follows:

$$r_A = k_2 C_A C_B \quad (2)$$

Under the assumptions mentioned above, the mass balances of species A and B based on the film theory with chemical reaction and the boundary conditions are given as

$$D_A = \frac{d^2 C_A}{dz^2} = k_2 C_A C_B \quad (3)$$

$$D_B = \frac{d^2 C_B}{dz^2} = \nu K_2 C_A C_B \quad (4)$$

$$z = 0, C_A = C_{Ai}, \frac{dC_B}{dz} = 0 \quad (5)$$

$$z = z_L, C_A = 0, C_B = C_{Bo} \quad (6)$$

Eqs. (3)~(6) are put into the dimensionless form as follows:

$$\frac{d^2 a}{dx^2} = Mab \quad (7)$$

$$\frac{d^2 b}{dx^2} = \nu r q Mab \quad (8)$$

$$x = 0 ; a = 1, \frac{db}{dx} = 0 \quad (9)$$

$$x = 1 ; a = 0, b = 1 \quad (10)$$

where $M = D_A K_2 C_{Bo} / K_L^2$, $a = C_A / C_{Ai}$, $b = C_B / C_{Bo}$, $x = z / z_L$, $q = \nu C_{Ai} C_{Bo}$, $r = D_A / D_B$

The enhancement factor (β) here is defined as the ratio of molar flux with a chemical reaction to that without chemical reaction:

$$\beta = \left. \frac{da}{dx} \right|_{x=0} \quad (11)$$

The value of $\hat{\alpha}$ is used to predict the absorption rate (R_A) of CO_2 with chemical reaction as follows:

$$R_A = \beta R_{A0} = \beta K_1 a C_{Ai} V_L \quad (12)$$

where R_{A0} is the physical absorption rate, which is obtained by multiplying the molar flux by the specific contact area between gas and liquid (a) and the liquid volume (V_L).

3. Experimental

3.1. Chemicals

The xanthan gum sample used in this study is a com-

mercially available product supplied from the Sigma-Aldrich Corporation (St. Louis, MO, USA). An accurate determination of the molecular weight of XG is extremely difficult for several reasons including its relatively high value, the stiffness of a molecule and the presence of aggregates (Song *et al.*, 2006). The weight average molecular weight of our XG is approximately estimated to be 2×10^6 kg/kmol (Song *et al.*, 2006). XG is soluble in both cold and hot water. Like most other hydrocolloids, XG needs an intensive agitation upon introduction into an aqueous medium in order to avoid a formation of lumps. In this work, XG solutions with concentrations of 0.05, 0.1, and 0.15 wt% were prepared by slowly adding the required amount of XG powder weighed using an electric balance into a known volume of gently agitated medium filled in a glass container, which was maintained at room temperature with constant stirring using a magnetic bar for 24 hr. The preparation procedure was identical to that described elsewhere (Song *et al.*, 2006).

3.2. Absorption rate of CO_2

The agitated absorber used for measurement of the absorption rate of CO_2 was constructed of glass (0.102 m inside diameter; 0.151 m in height) with four equally spaced vertical baffles. Straight impeller with 0.05 m in length, 0.017 m in width, and 0.005 m in thickness was used as the liquid phase agitator, and were located at the middle position of the liquid phase of 0.3 dm^3 . The contact area between the gas and the liquid was measured as 43.2 cm^2 . The absorption rates of CO_2 were measured along the procedure similar to those reported elsewhere (Yu *et al.*, 1985) using a semi-batch absorber in the aqueous XG solution of 0~0.015 wt% and DIPA of 0~2.0 kmol/m³ with the impeller speed of 50 rpm at 25°C and 101.3 kPa.

4. Physicochemical and rheological properties

The physicochemical and rheological properties in the CO_2 -XG-DIPA system, which are used to solve the simultaneous differential equations of Eq. (7) and (8), are obtained as follows:

4.1. Physicochemical properties of carbon dioxide and DIPA in aqueous XG solution

Solubility (C_{AiXG}) of CO_2 in the aqueous XG solutions was obtained using the pressure measuring method, which measured the pressure difference of CO_2 before and after equilibrium in the gas and liquid phases, similar to the procedure reported elsewhere (Kennard and Meisen, 1984) at 25°C and 101.3 kPa. The detailed experimental procedure was reported in our earlier work (Park *et al.*, 2007b).

Density of the aqueous XG solution was measured within 0.1 kg/m^3 by weighing with a pycnometer (Fisher Scientific Co., USA); it was identical within experimental

accuracy to the density of water.

The apparent viscosity of aqueous XG solution was measured with Brookfield viscometer (Brookfield Eng. Lab. Inc, USA).

Diffusivity (D_A) of CO_2 in the aqueous XG solution was estimated from the following equation (Cussler, 1984) corrected with viscosity of the aqueous colloidal silica solution.

$$D_A = D_{AW}(\mu_w/\mu)^{2/3} \quad (13)$$

Diffusivity (D_B) of DIPA in aqueous amine solution was obtained from assumption that the ratio of D_B to D_A was equal to the ratio in water (Nijsing *et al.*, 1959). The diffusivity of CO_2 and DIPA in water at 25°C were taken as $1.97 \times 10^{-9} \text{ m}^2/\text{s}$ (Hikita *et al.*, 1976) and $7.71 \times 10^{-10} \text{ m}^2/\text{s}$ (Danckwerts and Sharma, 1966), respectively.

The reaction rate constant (k_2) between the reaction of CO_2 and DIPA at 25°C was taken as $2780 \text{ m}^3/\text{kmol}\cdot\text{s}$ (Versteeg and van Swaaij, 1988).

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

4.2. Rheological properties of the aqueous XG solution

We assume that a power-law model, which has been widely used for shear-dependent viscosity, can represent the non-Newtonian flow behavior of the aqueous XG solution:

$$\tau = K\dot{\gamma}^n \quad (14)$$

$$\mu = K\dot{\gamma}^{n-1} \quad (15)$$

$$N_1 = A\dot{\gamma}^b \quad (16)$$

where n , K , b , and A are material parameters that depend on the temperature. These parameters were obtained from the measurement of δ and N_1 for the change of $\dot{\gamma}$ by using a parallel disk type rheometer (Ares, Rheometrics, U.S.A.), whose diameter is 0.05 m and gap, 0.001 m.

The obtained values of K , n , A and b in the aqueous XG solution of various XG concentration are listed in Table 2. The values of A increased upon increasing the XG concentration, which means that the aqueous XG solution has

an elastic behavior (Ranade and Ulbrecht, 1978).

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

$$\lambda = \frac{N_1}{\mu\dot{\gamma}^2} \quad (17)$$

Using Eq. (14) and (16), this expression is rearranged as

$$\lambda = \frac{A}{K}\dot{\gamma}^{b-n-1} \quad (18)$$

One of dimensionless numbers, which relates the elastic properties with the process parameters, is Deborah number (De), defined as ratio of the material's characteristic relaxation time to the characteristic flow time. The characteristic flow time is measured against a characteristic process time (t), which is related to the reciprocal of the agitation speed (N) of impeller in case of stirred tanks, and De is derived as follows:

$$De = \lambda/t = \frac{A}{K}\dot{\gamma}^{b-n-1}N \quad (19)$$

where shear rate ($\dot{\gamma}$) is obtained in case of the agitation of liquid in a cylindrical vessel as follows (Metzner and Otter, 1957):

$$\dot{\gamma} = 4\pi N/n \quad (20)$$

5. Results and discussion

5.1. Empirical correlation of volumetric liquid-Side mass transfer coefficient of CO_2

To observe the effect of XG concentration on the physical absorption rate (R_{A0}) and volumetric mass transfer coefficient ($k_{L,a}$) of CO_2 , R_{A0} were measured in the aqueous XG solutions in the range of XG concentrations of 0~0.15 wt%, and $k_{L,a}$ were obtained using R_{A0} and $C_{A,i}$ in Table 2. R_{A0} and $k_{L,a}$ were plotted against the XG concentrations as circles in Fig. 1 and 2, respectively.

As shown in Fig. 1 and 2, R_{A0} and $k_{L,a}$ decrease with

Table 2. Physicochemical and rheological properties of CO_2 and aqueous XG solution

XG (wt%)	Viscosity (Ns/m ²)	Diffusivity (m ² /s)x10 ⁹	Solubility (kmol/m ³)	Density (kg/m ³)	Rheological properties			
					n	K (Ns ⁿ /m ²)	b	A (Ns ⁿ /m ²)
0	0.0009	1.95	0.035	1000.0	1.0	0.001		
0.05	0.0331	1.92	0.032	1468.0	0.622	0.0372	0.112	2.81
0.10	0.0777	1.91	0.030	1468.3	0.520	0.1050	0.138	10.20
0.15	0.1571	1.89	0.023	1468.6	0.458	0.2094	0.181	23.13

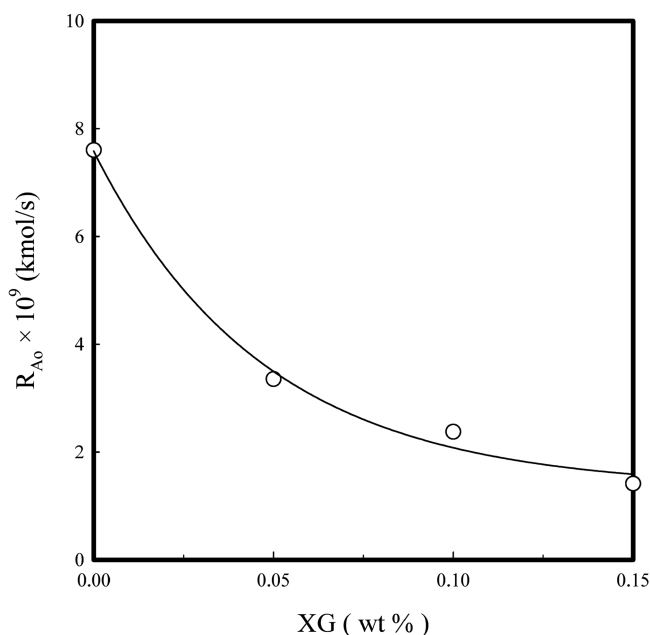


Fig. 1. Effect of XG concentration on R_{A0} .

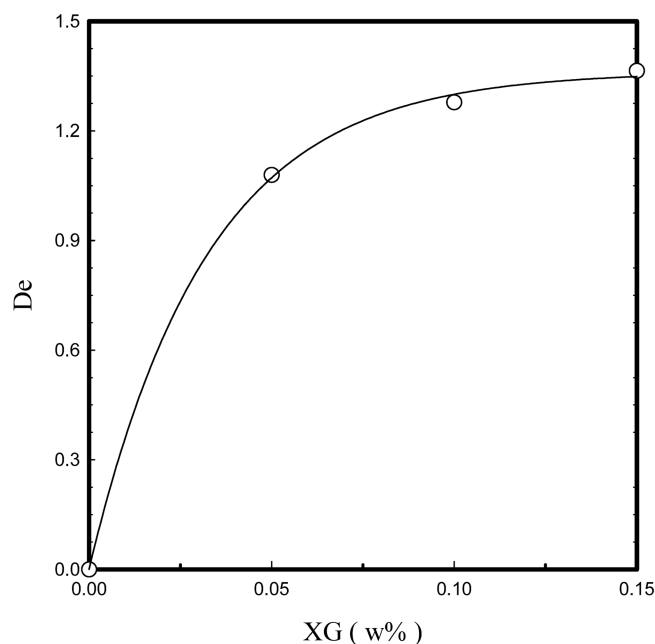


Fig. 3. Effect of XG concentration on De .

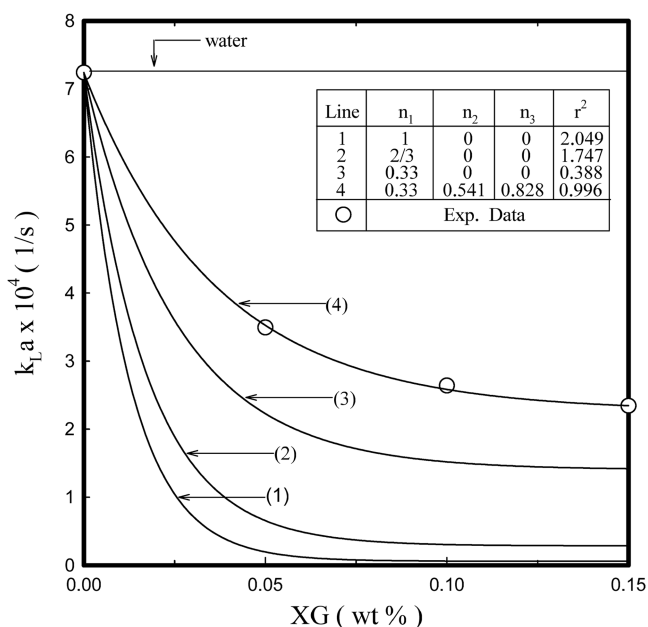


Fig. 2. Effects of XG concentration on k_{La} with variation of coefficient of viscosity and Deborah number.

increasing XG concentration. These results may be due to increase of viscosity by increase of XG concentration. The solid line 4 in Fig. 2 was the k_{La} , which was obtained using an empirical formula correlated with the rheological behavior of XG solution, which will be shown later. The solid line in Fig. 1 was the R_{A0} obtained using the k_{La} calculated from the empirical formula.

It is customary to express the influence that the viscosity has upon the mass transfer coefficient in terms of the 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 XG solution did 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 aqueous XG solution to that of water (Sandall and Patel, 1970) was used to correlation with k_{La} , because the viscosity in the agitated vessel depends on the rheological properties, as shown in Eq. (14) through Eq. (20).

Based on the literature (Cussler, 1984), which shows that an increase in the viscosity of liquid results in a reduction of k_{La} , one is suggested to correlate k_{La} in aqueous XG solution with that in water as follows:

$$k_{La} = k_{L,w} a \left(\frac{\mu_w}{\mu} \right)^{n_1} \quad (21)$$

where 1 or 2/3 is frequently used as n_1 of a Newtonian liquid.

The values of k_{La} are calculated from Eq. (21) against various XG concentrations for n_1 of 1 and 2/3, respectively, and plotted as solid line 1 and 2 in Fig. 2. As shown in Fig. 2, there is a great difference between the calculated k_{La} (line 1 and 2) and measured k_{La} , respectively; correlation coefficient of line 1 compared with the measured k_{La} is 2.049, and that of line 2, 1.747. This means that the aqueous XG solution in this study does not follow the behavior of a Newtonian liquid.

To investigate the effect of the XG solution on the k_{La} , the values of De , which were obtained using Eq. (19) and the rheological properties in Table 2, were plotted against the XG concentration in Fig. 3.

As shown in Fig. 3, De increase with increasing XG con-

centration. This means that the aqueous XG solution has a rheological behavior and the viscoelasticity of XG solution increases with increasing the XG concentration. Therefore, to reduce the deviation of $k_L a$ for line 1 and 2 from the measured $k_L a$ as shown in Fig. 2, new terms, corrected with viscosity and De , were used as follows:

A simple multiple regression exercise using De in Fig. 3 was tried for the plots of $k_L a$ combined with the new terms such as $(\mu/\mu_w)^{n_1}(1+n_2De^{n_3})$ against XG concentration, which gave the values of n_1 , n_2 and n_3 of 0.33, 0.541, and 0.828, respectively. A multiple regression analysis provides the following correlation:

$$k_L a = k_{Lw} a \left(\frac{\mu_w}{\mu} \right)^{0.33} (1 + 0.541 De^{0.828}) \quad (22)$$

The values of $k_L a$ are calculated by Eq. (22) and shown as line 4 in Fig. 2. As shown in Fig. 2, the agreement between the measured $k_L a$ and calculated $k_L a$ from Eq. (22) is very good with correlation coefficient of 0.996. Also, as shown in Eq. (22), $k_L a$ is affected by both viscosity and elasticity, and it is decreased upon increasing XG concentration. From the work of Yagi and Yoshida (1975), Ranade and Ulbrecht (1978), and Moo-Young and Kawase (1987), it may be concluded that the exponent m in the relationship $k_L a \propto \mu^{-m}$ for stirred tanks is between 0.35 and 0.6. When our data were analyzed by Eq. (22) for the overall effect of viscosity on the $k_L a$, it comes out as $k_L a \propto \mu^{-0.33}$, which compares well with the findings of Yagi and Yoshida (1975) of $\mu^{-0.4}$ and Ranade and Ulbrecht (1978) of $\mu^{-0.41}$, and Moo-Young and Kawase (1987) of $\mu^{-0.38}$. As a result in Fig. 2, the deviation of plots of $k_L a$ against XG concentration can be eliminated by incorporating De into the correlation.

5.2. Effect of Rheological Properties on the $k_L a$ of CO_2

Because $k_L a$ is affected by both of viscosity and elasticity of the aqueous XG solution as shown in Eq. (22), $k_L a$ are estimated according to the kinds of the solutions, *i.e.*, water, the aqueous XG solution without elasticity, and solution with elasticity, and presented as water line, line 3, and line 4 as shown in Fig. 2, respectively. Water line has μ of μ_w and De of 0, line 3 has μ of that in aqueous XG solution and De of 0, and line 4 has μ of that in aqueous XG solution with elasticity and De of some value > 0 . The aqueous XG solution without elasticity ($De=0$) is an imaginary solution, which is assumed to be a Newtonian liquid with the same viscosity as that of the actual XG solution with elasticity. As shown in Fig. 2, the $k_L a$ decreases in water line, line 4, and line 3 order. In general, the mass transfer coefficient in the solution is inversely proportional to the viscosity. The viscosity of water is smaller than that of the aqueous XG solution as listed in Table 2, and then, $k_L a$ in water is larger than that in the aqueous XG solution. If the aqueous XG solution in this study would have only viscous behavior, the $k_L a$ should be the $k_L a$ represented as

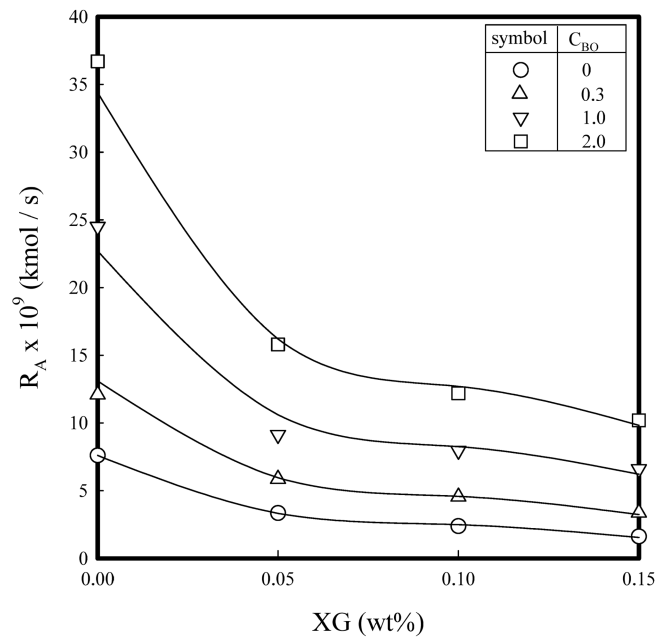


Fig. 4. Effect of XG concentration on R_A for various DIPA concentrations.

the line 3. But, the actual $k_L a$ of the line 4 is larger than that of the line 3. The increase of $k_L a$ from the line 3 to the line 4 might be attributed to the elasticity of the aqueous XG solution. In other words, the aqueous XG solution used in this study might play the part of increasing agent of $k_L a$ based on the same viscosity of the solution.

5.3. Effect of Rheological Properties on the chemical absorption of CO_2

To investigate the effect of elasticity of XG solution on the chemical absorption rate of CO_2 , the absorption rate (R_A) of CO_2 into aqueous XG solution containing DIPA was measured against XG concentration in the range 0~0.15 wt% at DIPA concentration in the range of 0~2 kmol/m³ at the agitation speed of 50 rev/min and the impeller size of 0.05 m. Fig. 4 shows the plots of the absorption rate of CO_2 against XG concentration for various DIPA concentrations.

As shown in Fig. 5, R_A increases with increasing DIPA concentration and decreases with increasing XG concentration. Increase of R_A with increasing DIPA concentration is due to the reactant of DIPA in reaction of CO_2 . Decrease of R_A with increasing XG concentration is explained from the dependences of $k_L a$, β , and C_{Ai} on XG concentration as flows:

Because $k_L a$ decrease with increasing XG concentration as shown in Fig. 2, R_A decrease with increasing XG concentration.

The values of C_{Ai} in the aqueous XG solution decrease with increasing XG concentration, but, they do not vary significantly from that in water, as shown in Table 2.

The measured and calculated values of k_L were obtained

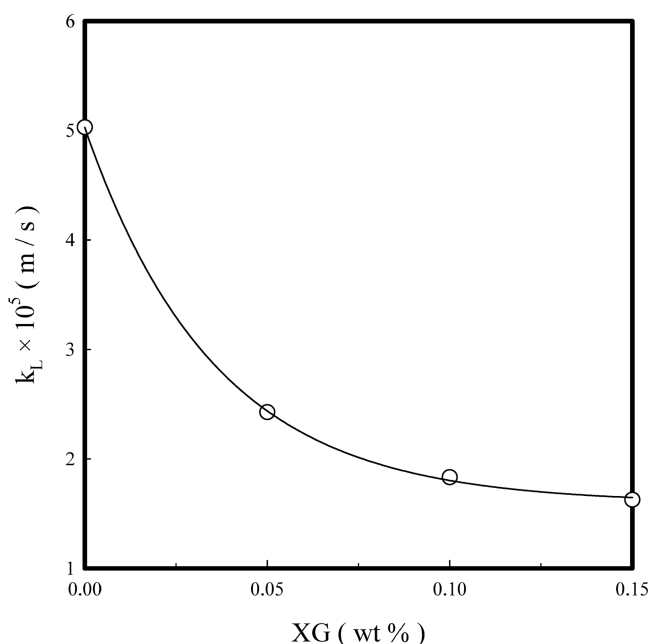


Fig. 5. Effect of XG concentration on k_L .

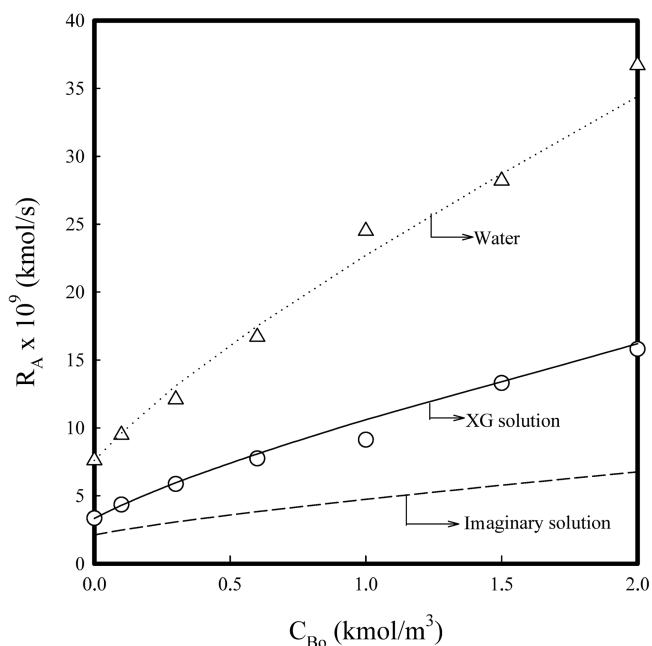


Fig. 7. Effect of C_{B0} on R_A at aqueous XG solution of 0.1 wt%.

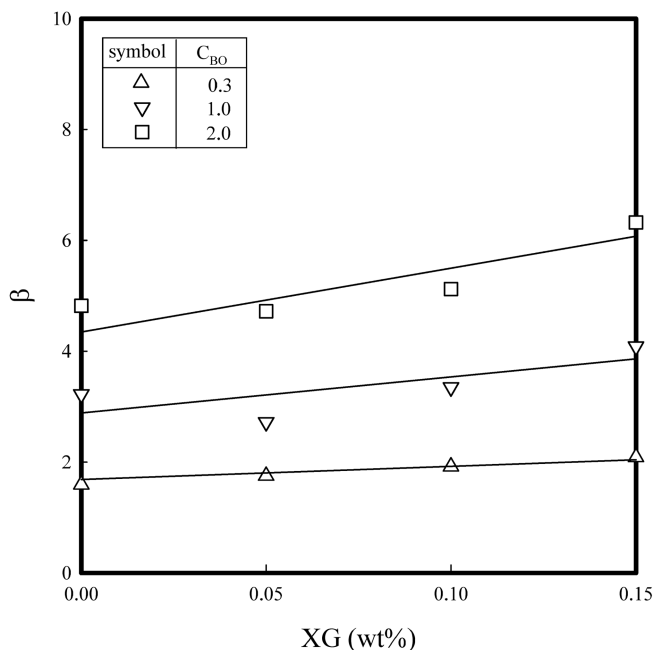


Fig. 6. Effect of XG concentration on enhancement factor for various DIPA concentrations.

using the measured $k_{L,a}$ and calculated $k_{L,a}$ from the empirical formula of Eq. (22), respectively, and plotted against the XG concentration as circle and solid line in Fig. 5.

As shown in Fig. 5, k_L decreases with increasing XG concentration. The calculated value of β was obtained from Eq. (11) and solutions of Eq. (7) and (8) with the known parameters, such as, k_L , D_A , D_B , k_2 , and C_{Ai} at given concentrations of XG and DIPA. Eq. (7) and (8) were solved by the finite element method of FEMLAB[®]. The measured values

of β were obtained as the ratio of R_A to R_{A0} . The measured and calculated values of β were plotted against the XG concentration in Fig. 6 as marks and solid lines, respectively.

As shown in Fig. 6, β increase with increasing concentrations of DIPA and XG. This result coincides with the fact (Danckwerts, 1970) that β increases with increasing M , which is defined as a dimensionless parameter of $D_A k_2 C_{B0} / k_L^2$ in Eq. (7) and (8). R_A should increase with increasing XG concentration due to the result of Fig. 6, but, R_A decrease actually with increasing XG concentration as shown in Fig. 4. Therefore, decrease of R_A was affected mainly by decrease of $k_{L,a}$ rather than b and C_{Ai} , *i.e.*, reduction of $k_{L,a}$ by the elastic properties of the aqueous XG solution causes decrease of chemical absorption rate of CO_2 .

The values of R_A in water, the imaginary and actual solution of aqueous XG solution, which are obtained from Eq. (12) using $k_{L,a}$ of water line, line 3, and line 4 in Fig. 2, respectively, are plotted as a dotted, solid, and dashed line against DIPA concentration at a typical XG concentration of 0.1 wt% in Fig. 7. The triangle and circle are the measured values in water and XG solution.

As shown in Fig. 7, R_A increase in water, XG solution, and imaginary solution order. Same trends were obtained in the other two XG concentrations of 0.05 and 0.15 wt%. If the aqueous XG solution in this study would have only viscous behavior, R_A should be R_A represented as the dashed line. But, the actual R_A of the solid line is larger than that of the dashed line. The increase of R_A from the dashed line to the solid line might be attributed to the elasticity of the aqueous XG solution, whose trend is as same as the trend of $k_{L,a}$ as shown in Fig. 2.

6. Conclusions

The physical and chemical absorption rates of carbon dioxide were measured into the aqueous XG solution of 0~0.15 wt% with DIPA of 0~2 kmol/m³ in a flat-stirred vessel with 0.05 m size and 50 rpm of agitation speeds of impeller at 25°C and 101.3 kPa.

The value of $k_L a$ was correlated with an empirical formula having the rheological behavior of XG solution such as Deborah number as follow:

$$k_L a = k_{L,w} a \left(\frac{\mu_w}{\mu} \right)^{0.33} (1 + 0.541 De^{0.828})$$

The chemical absorption rate was estimated from the mass balance accompanied by chemical reaction based on the film theory using the value of $k_L a$. Acceleration of $k_L a$ and the absorption rate according to increase of XG concentration was explained by the elastic properties of the aqueous XG solution.

Nomenclature

- a : specific gas-liquid area(m²/m³)
 C_i : concentration of species, i (kmol/m³)
 d : diameter of impeller(m)
 D_i : diffusivity of species, i (m²/s)
 k₂ : reaction rate constant in reaction (1) (m³/kmol·s)
 k_L : liquid-side mass transfer coefficient of CO₂ in absorbent (m/s)
 N₁ : primary normal stress difference(kg/m·s²)
 V_L : volume of the liquid phase(m³)
 r_A : reaction rate in Equation (2)(kmol/m³·s)
 R_A : chemical absorption rate of CO₂(kmol/s)
 R_{Ao} : physical absorption rate of CO₂(kmol/s)
 T : temperature(°K)
 XG : xanthan gum
 z : diffusion coordinate of CO₂ (m)
 z_L : film thickness(m)

Greek letters

- β : enhancement factor of absorption rate by the chemical reaction
 γ : shear rate(1/s)
 μ : viscosity of liquid(N·s/m²)
 μ_w : viscosity of water(N·s/m²)
 ρ : density of liquid(kg/m³)
 τ : shear stress(N/m²)

Subscripts

- A : CO₂
 B : DIPA
 i : gas-liquid interface

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