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Abstract: Carbon dioxide was absorbed into the aqueous xanthan gum (XG) solution in the range of 0–0.151 wt% containing monoethanolamine (MEA) of 0–2 kmol/m^3 in a flat-stirred vessel with the impeller of 0.05 m and agitation speed of 50 rpm at 25°C and 0.101 MPa to measure the absorption rate of CO_2. The volumetric liquid-side mass transfer coefficient (k_La_L) of CO_2 decreased with increasing XG concentration, and was correlated with the empirical formula having the rheological behavior of XG solution. The chemical absorption rate of CO_2 was estimated by the film theory using the values of k_La_L and physicochemical properties of CO_2 and MEA. The aqueous XG solutions made the rate of absorption of CO_2 accelerated compared with the Newtonian liquid based on the same viscosity of the solution.

Keywords: Absorption, monoethanolamine, carbon dioxide, xanthan gum, viscoelastic liquid

INTRODUCTION

Gas-liquid mass transfer in non-Newtonian liquid is an important example of gas absorption in the pseudoplastic flow of industrial processes such as a

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fermentation broth, slurry, and fluidized bed, etc. (1–3). Variation of the volumetric liquid-phase mass transfer coefficient (k_La_L) in gas-dispersed systems consists of the mass transfer coefficient (k_L) and the specific gas-liquid interfacial area (a_L). The former could be correlated with the Reynolds and the 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_La_L 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_La_L 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_La_L with properties of non-Newtonian liquids. Unified correlations have been proposed for k_La_L in Newtonian as well as non-Newtonian solutions by introducing the dimensionless term, such as $(1 + n_1De^{n_2})^{n_3}$; which are listed in Table 1. As

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

Investigator	n_1	n_2	n_3	Substance	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	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
Park et al. (6)	54.7	1	-0.45	PAA	Agitated vessel
Park et al. (7)	8.33	1.31	1	PEO	Agitated vessel
Park et al. (8)	39.4	1	-0.43	Silica	Agitated vessel

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 some 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 (4, 5) 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 CO_2. Park and coworkers (6–8) also measured the absorption rate of CO_2 in aqueous PAA solution with NaOH, PEO solution with triethanolamine, and nanometer sized silica colloid solution with diethanolamine, respectively. They showed that the viscoelastic materials, such as PIB, PAA, PEO, and nanometer sized silica influenced the absorption rate of CO_2.

Xanthan gum (XG) is an extracellular heteropolysaccharide 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 (9). Even solutions having a low concentration of XG show high viscosity and insensitivity to changes in temperature, pH, and sanitation. XG production usually has been performed in batch fermentation using the bacterium Xanthomonas compestris. The conditions and performance of such fermentations in stirred tank reactors (10), bubble columns (11, 12) and airlifts (13) 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 (14), 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 a 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 (14). As was reviewed in Song et al. (14), 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 (16–18). Terasaka and Shibata (19) presented that k_La_L of oxygen in XG fermentation of a bubble column was a function of gas hold up, yield stress and diffusivity of oxygen.

To investigate the effect of the rheological behavior of non-Newtonian liquid on the gas absorption as, XG was used as a viscoelastic material in this study, which was one of the series works. The absorption rates of CO_2 were measured in aqueous XG solution containing monoethanolamine (MEA) and they were compared with those estimated by the mass transfer with chemical reaction based on the film theory. Deborah number, which was obtained from a power-law model of the relationship between the measured shear stress and primary normal stress difference against the shear rate of XG solution, was used to obtain a unified correlation between the values of k_La_L in water and that in XG solutions.

THEORY

The overall reaction between CO_2 (A) and MEA (B) in aqueous solution is

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

The stoichiometric coefficients (ν) in Eq. (1) for MEA was obtained from the reference (20) and its value was 2.

Species B is assumed to be a nonvolatile solute, because its vapor pressure is very small as 0.2 mmHg at 20°C. 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 (20) as follows:

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

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

$$D_A \frac{d^2C_A}{dz^2} = k_2 C_A C_B \tag{3}$$

$$D_B \frac{d^2C_B}{dz^2} = \nu k_2 C_A C_B \tag{4}$$

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

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

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

$$\frac{d^2a}{dx^2} = \mathrm{Mab} \tag{7}$$

$$\frac{d^2b}{dx^2} = \mathrm{rqMab} \tag{8}$$

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

$$x = 1; \quad a = 0, \quad b = 1 \tag{10}$$

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:

$$\beta = -\left.\frac{da}{dx}\right|_{x=0} \tag{11}$$

The value of β is used to predict the absorption rate (R_A) of CO_2 with chemical reaction as follows:

$$R_A = \beta R_{Ao} = \beta k_L a_L C_{Ai} V_L \tag{12}$$

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

EXPERIMENTAL

Chemicals

The xanthan gum sample used in this study is a commercially available product supplied from the Sigma-Aldrich Corporation (CAS: 11138-66-2, 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 (14). The weight average molecular weight of our XG is approximately estimated to be 2×10^6 kg/kmol (14). XG is completely soluble in water. Like most other hydrocolloids, XG needs an intensive agitation upon introduction into an aqueous medium in order to avoid a clotted state at initial dissolution of XG. The XG concentrations used in this study were 0.05, 0.1, and 0.15 wt.%. The XG solution was made at room temperature with constant stirring using a magnetic bar for 24 hr. The preparation procedure was identical to that described elsewhere (14).

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 effect of dead stagnant zones was assumed to be negligible and to be plain, because of the baffles. The contact area between the gas and the liquid was calculated from the ratio of the volume of added water to the measured height of the water in the absorber, and its value was $43.2\ cm^2$. The absorption rates of CO_2 were measured along the procedure similar to those reported elsewhere (21) using a semi-batch absorber in the aqueous XG solution of 0–0.015 wt% and MEA of $0{\sim}2\ kmol/m^3$ with the impeller speed of 50 rpm at 25°C and 0.101 MPa.

A sketch of the experimental set up is presented in Fig. 1. A typical experimental run was carried out as follows: The vent valve A is initially closed and the purge value B is open. CO_2 is made to continuously through the absorber C, so as to make sure that the latter is filled with CO_2 at the start of the experiment. During this initial period, the water bath temperature is brought up to the desired value, and the liquid batch is kept in bottle D inside the water bath. At the start of the experiment, the liquid batch is poured into funnel E and the agitator H in C is started. The liquid feed valve F is closed, the purge value B is closed, and the vent valve A is opened, as simultaneously as possible. Measurements are started at the soap film meter G taking care that there are always two soap films in the meter so that a continuous reading of the cumulative volume of CO_2 which has flowed through the soap film meter (V) can be recorded as a function of time. CO_2 absorption rate was obtained as a slope of the plots of V vs. time at an initial time.

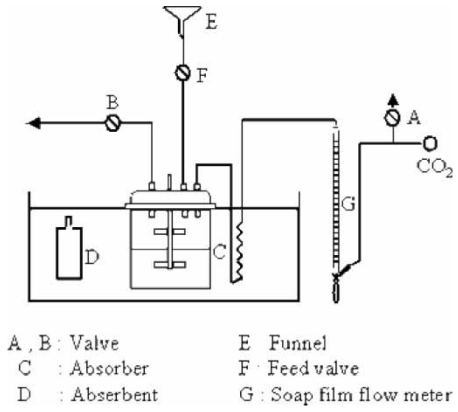

Figure 1. Schematic diagram of the agitated vessel.

PHYSICOCHEMICAL AND RHEOLOGICAL PROPERTIES

The physicochemical and rheological properties in the CO_2-XG-MEA system, which are used to obtain the theoretical values of β, are obtained as follows:

Physicochemical Properties of Carbon Dioxide and MEA in Aqueous XG Solution

Solubility (C_{Ai}) 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 (22) at 25°C and 0.101 MPa. The detailed experimental procedure was reported in our earlier work (8).

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 the aqueous XG solution was measured with a Brookfield viscometer (Brookfield Eng. Lab. Inc, USA).

Diffusivity (D_B) of MEA in aqueous amine solution was obtained from assumption that the ratio of D_B to D_A was equal to the ratio in water (23). The diffusivities of CO_2 and MEA in water at 25°C were taken as $1.97 \times 10^{-9}\ m^2/s$ (24) and $1.1 \times 10^{-9}\ m^2/s$ (25), respectively.

Diffusivity (D_{AB}) of CO_2 in aqueous MEA (25) solution was estimated as follows:

$$D_{AB} = (1.9686 - 0.184C_{Bo} - 0.0429C_{Bo}^2) \times 10^{-9} \tag{13}$$

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. Diffusivity (D_A) of CO_2 in the aqueous XG solution were obtained from the following equation suggested by Lohse et al. (26), which was modified from the Stoke-Einstein equation, and correlated with the molecular weight of the polymer in the solution, respectively.

$$D_A = D_{AB}\left(\frac{\mu_W}{\mu}\right)^{3.7\sqrt{M_W/M_P}} \tag{14}$$

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

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

The overall reaction rate constant (k_2) in the reaction of CO_2 with MEA was estimated as follows (20):

$$\log k_2 = 10.99 - \frac{2152}{T} \tag{15}$$

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

					Rheological propertie			
XG (wt.%)	Viscosity (Ns/m^2)	Diffusivity (m^2/s) $\times 10^9$	Solubility ($kmol/m^3$)	Density (kg/m^3)	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

Rheological Properties of the Aqueous XG Solution

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

$$\tau = \mathrm{K}\gamma^{\mathrm{n}} \tag{16}$$

$$\mu = \mathrm{K}\gamma^{\mathrm{n}=1} \tag{17}$$

$$\mathrm{N}_1 = \mathrm{A}\gamma^{\mathrm{b}} \tag{18}$$

where n, K, b, and A are material parameters that depend on the temperature. These parameters were obtained from the measurement of τ and N_1 for the change of γ 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 (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

$$\lambda = \frac{\mathrm{N}_1}{\mu\gamma^2} \tag{19}$$

Using Eqs. (18) and (19), this expression is rearranged as

$$\lambda = \frac{\mathrm{A}}{\mathrm{K}}\gamma^{\mathrm{b-n-1}} \tag{20}$$

One of dimensionless numbers, which relates the elastic properties with the process parameters, is Deborah number (De), defined as a 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:

$$\mathrm{De} = \lambda/\mathrm{t} = \frac{\mathrm{A}}{\mathrm{K}}\gamma^{\mathrm{b-n-1}}\mathrm{N} \tag{21}$$

where shear rate (γ) is obtained in case of the agitation of the liquid in a cylindrical vessel as follows (27):

$$\gamma = 4\pi\mathrm{N}/\mathrm{n} \tag{22}$$

RESULTS AND DISCUSSION

Empirical Correlation of Volumetric Liquid-Side Mass Transfer Coefficient of CO_2

To observe the effect of XG concentration on the absorption rate (R_{Ao}) and volumetric mass transfer coefficient (k_La_L) of CO_2, R_{Ao} were measured in the aqueous XG solutions in the range of XG concentrations of 0–0.15 wt.%, and k_La_L were obtained using R_{Ao} and C_{Ai} in Table 2. R_{Ao} and k_La_L were plotted against the XG concentrations as circles in Figs. 2 and 3, respectively. As shown in Figs. 2 and 3, R_{Ao} and k_La_L decrease with increasing XG concentration. These results may be due to increase of viscosity by increase of XG concentration. The solid line 4 in Fig. 3 was the calculated k_La_L, 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. 2 was the R_{Ao} obtained using the calculated k_La_L,

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 (28) was used to correlation with k_La_L,

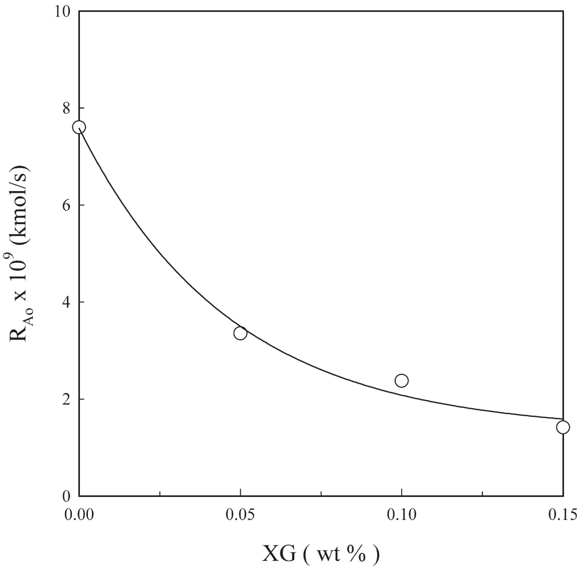

Figure 2. Effect of XG concentration on R_{Ao}.

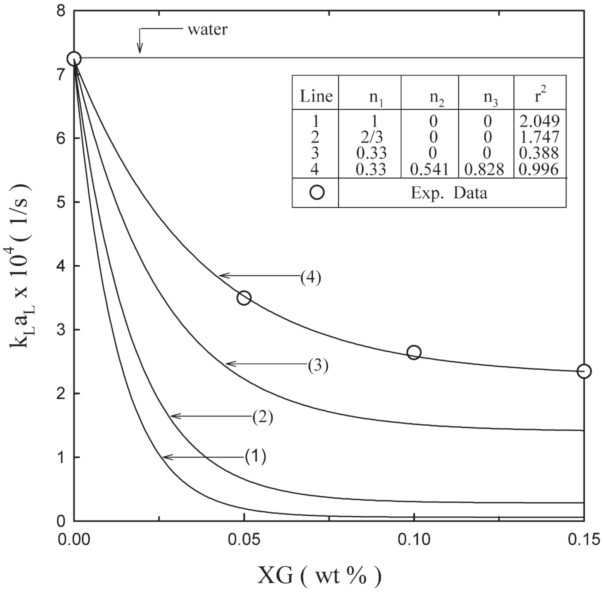

Figure 3. Coefficients of dimensionless group for $k_La_L = k_{Lw}a_L \ (\mu_w/\mu)^{n1} (1 + n_2De^{n3})$.

because the viscosity in the agitated vessel depends on the rheological properties, as shown in Eq. (16) through (22).

D_A is inversely proportional to μ in Stokes-Einstein equation, and k_L is directly proportional to D_A^n, where n=1 in the film theory, 0.5 in the penetration model, and 2/3 (12, 30) in case of a Newtonian liquid. Based on the results mentioned above, one is suggested to correlate k_La_L in aqueous XG solution with that in water as follows:.

$$k_La_L = k_{LW}a_L\left(\frac{\mu_W}{\mu}\right)^{n_1} \tag{23}$$

The values of k_La_L are calculated from Eq. (23) against various XG concentrations for n_1 of 1 and 2/3, respectively, and plotted as solid line 1 and 2 in Fig. 3. As shown in Fig. 3, there is a great difference between the calculated k_La_L (line 1 and 2) and measured k_La_L, respectively; correlation coefficient of line 1 compared with the measured k_La_L 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 reduce the deviation of k_La_L for line 1 and 2 from the measured k_La_L as shown in Fig. 3, new terms, corrected with viscosity and De, were used as follows:

The values of De, which were obtained using Eq. (21) and the rheological properties in Table 2, were plotted against the XG concentration in Fig. 4. As

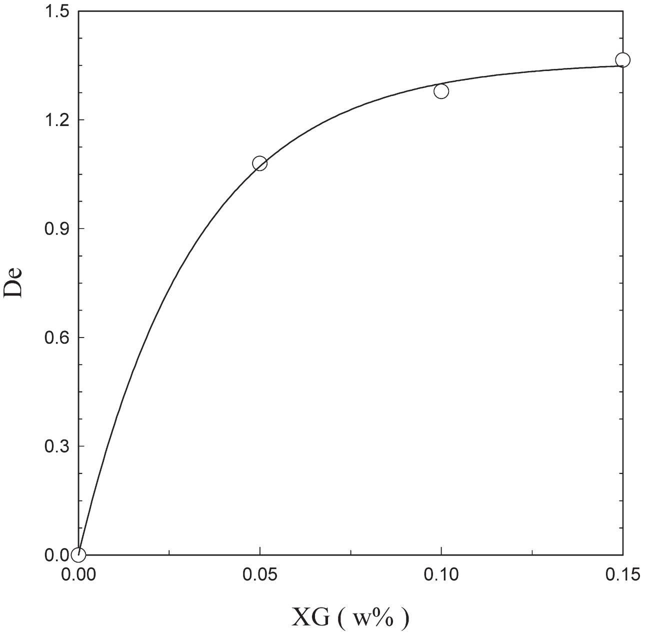

Figure 4. Effect of XG concentration on De.

shown in Fig. 4, De increase with increasing XG concentration. This means that the viscoelasticity of XG solution increases with increasing the XG concentration.

A simple multiple regression exercise using De in Fig. 4 was tried for the plots of k_La_L 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 0.330, 0.541, and 0.828, respectively. A multiple regression analysis provides the following correlation:

$$k_La_L = k_{LW}a_L\left(\frac{\mu_W}{\mu}\right)^{0.33}(1 + 0.541De^{0.828}) \tag{24}$$

The values of k_La_L are calculated by Eq. (24) and shown as line 4 in Fig. 3. As shown in Fig. 3, the agreement between the measured k_La_L and those predicted by Eq. (24) is very good with correlation coefficient of 0.996. Also, as shown in Eq. (24), k_La_L is affected by both the viscosity and the elasticity, and it is decreased upon increasing XG concentration. From the work of Yagi and Yoshida (1), Ranade and Ulbrecht (2), and Moo-Young and Kawase (30), it may be concluded that the exponent m in the relationship $k_La_L \propto \mu^{-m}$ for stirred tanks is between 0.35 and 0.6. When our data were analyzed by Eq. (24) for the overall effect of viscosity on the

k_La_L, it comes out as $k_La_L \propto \mu^{-0.33}$, which compares well with the findings of Yagi and Yoshida (1) of $\mu^{-0.4}$ and Ranade and Ulbrecht (2) of $\mu^{-0.41}$, and Moo-Young and Kawase (31) of $\mu^{-0.38}$. As a result in Fig. 3, the deviation of plots of k_La_L against XG concentration can be eliminated by incorporating De into the correlation.

The measured k_L was obtained using the measured k_La_L and a_L. The calculated k_L was obtained from the empirical formula of Eq. (24). The measured and calculated values of k_L were plotted against the XG concentration as circle and solid line in Fig. 5, respectively. As shown in Fig. 5, k_L decreases with increasing XG concentration. These results may be due to increase of viscosity and elasticity of the XG solution by increase of XG concentration. The calculated k_L was used to estimate the theoretical β in section 3.

Effect of Rheological Properties on the k_La_L of CO_2

The value of k_La_L is affected by both viscosity and elasticity of the aqueous XG solutions as shown in Eq. (24). Figure 3 presented plots of k_La_L vs. XG concentration for water, the aqueous XG solution without elasticity (line 3), and solution with elasticity (line 4), respectively. The 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

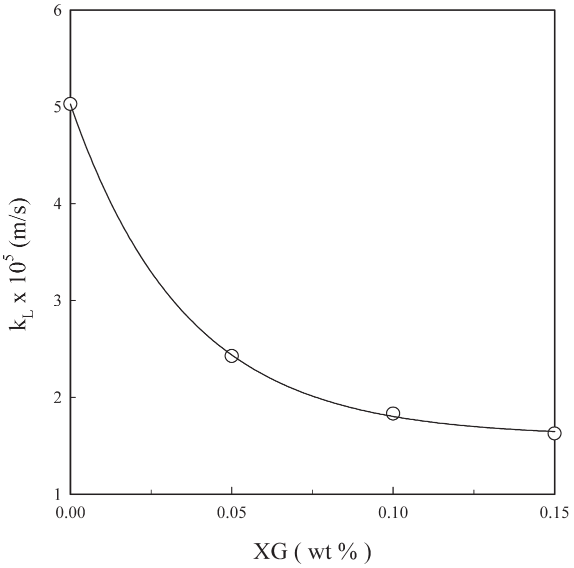

Figure 5. Effect of XG concentration on k_L.

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 aqueous XG solution with elasticity. As shown in Fig. 3, the k_La_L 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_La_L in water is larger that in the aqueous XG solution. If the aqueous XG solution in this study would have only viscous behavior, the k_La_L should be the k_La_L represented as the line 3. But, the actual k_La_L of line 4 is larger than that of line 3. The increase of k_La_L from line 3 to 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 a role as an increasing agent of k_La_L based on the same viscosity of the XG concentration.

Effect of Rheological Properties on the Chemical Absorption of CO_2

To observe the effect of visco-elasticity on the chemical absorption rate of CO_2, R_A were measured against XG concentration in the range 0–0.15 wt.% at various concentrations of MEA. As shown in Fig. 6, R_A decreases with increasing XG concentration and increases with increasing MEA concentration. Increase of R_A with increasing MEA concentration is due to the reactant of MEA in reaction of CO_2. The solid lines in Fig. 6 present the R_A obtained from Eq. (12).

The concentration profile of CO_2 was obtained by the numerical solution of Eqs. (7) and (8) with the known parameters containing k_L using the finite element method at given concentrations of XG and MEA, and then, the calculated β was obtained from Eq. (11). The measured and calculated values of β were plotted against the XG concentration in Fig. 7 as symbol and solid line, respectively. As shown in Fig. 7, the values of β hold to be constant almost with increasing XG concentration and increase with increasing MEA concentration.

As shown in Fig. 3, k_La_L decreased with increasing XG concentration, and, C_{Ai} in the aqueous XG solution did not vary significantly from that in water, as shown in Table 2. Therefore, decrease of R_A was affected mainly by decrease of k_La_L rather than β and C_{Ai}, i.e., reduction of k_La_L by the elastic properties of the aqueous XG solution causes decrease of chemical absorption rate of CO_2.

To apply Eq. (24) broadly, the absorption data for various shapes, sizes, and agitation speeds of the impeller are needed. Also, the quantitative explanation about the phenomena of the reduction of k_La_L by the elastic properties of the aqueous XG solution is needed using hydrodynamic analysis for non-Newtonian liquid.

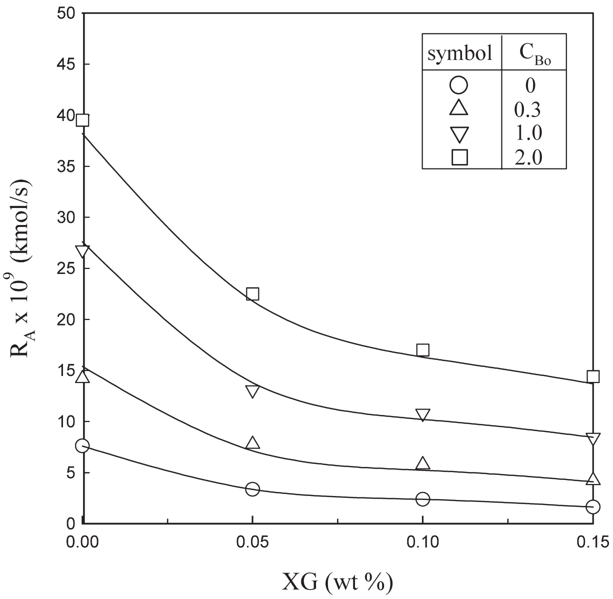

Figure 6. Effect of XG concentration on R_A for various MEA concentrations.

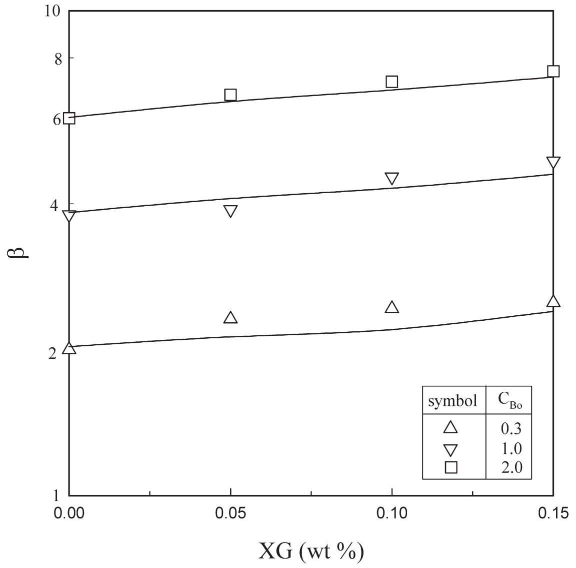

Figure 7. Effect of XG concentration on enhancement factor for various MEA concentrations.

CONCLUSIONS

The k_La_L of CO_2 was obtained from the absorption rate of carbon dioxide, which was measured into the aqueous XG solution of 0–0.15 wt.% with MEA of 0–2 kmol/m^3 in a flat-stirred vessel with 0.05 m size and 50 rpm of agitation speeds of impeller at 25°C and 0.101 MPa.

The aqueous XG solution was an elastic non-Newtonian liquid, and k_La_L was correlated with an empirical formula having the rheological behavior of XG solution such as Deborah number as follow:

$$k_La_L = k_{LW}a_L\left(\frac{\mu_W}{\mu}\right)^{0.33}(1 + 0.541De^{0.828})$$

The chemical absorption rate was estimated from the mass balance accompanied by the chemical reaction based on the film theory using the value of k_La_L, and reduction of k_La_L by the elastic properties of the aqueous XG solution causes a decrease of the chemical absorption rate of CO_2 at a given MEA concentration.

NOMENCLATURE

a_L	Specific gas-liquid area (m^2/m^3)
C_i	Concentration of species, i (kmol/m^3)
d	Diameter of impeller (m)
D_i	Diffusivity of species, i (m^2/s)
k_2	Reaction rate constant in reaction (1) (m^3/kmol·s)
k_L	Liquid-side mass transfer coefficient of CO_2 in absorbent (m/s)
N_1	Primary normal stress difference (kg/m · s^2)
V_L	Volume of the liquid phase (m^3)
r^2	Correlation coefficient
r_A	Reaction rate in Equation (2) (kmol/m^3 · s)
R_A	Chemical absorption rate of CO_2 (kmol/s)
R_{Ao}	Physical absorption rate of CO_2 (kmol/s)
T	Temperature (°K)
XG	Xanthan gum
z	Diffusion coordinate of CO_2 (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/m^2)
μ_w	Viscosity of water (N · s/m^2)

ρ	Density of liquid (kg/m^3)
τ	Shear stress (N/m^2)

Subscripts

A	CO_2
B	MEA
i	Gas-liquid interface
o	Bulk body of the liquid phase

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