Unsteady-State Absorption of CO_2 into w/o Emulsion with Aqueous Alkaline Liquid Droplets

Sang-Wook Park†, Hidehiro Kumazawa* and In-Joe Sohn

Department of Chemical Engineering, Pusan National University, Busan 609-735, Korea
*Department of Material System Engineering and Life Science, Toyama University, Toyama 930-8555, Japan

Abstract—Unsteady-state absorption of CO_2 into w/o emulsion was studied by experimental measurements and prediction from mathematical modeling. Absorption experiments were performed by using a stirred vessel with a flat gas-liquid interface under 0.101 MPa and 25 °C. Continuous phase was benzene that has larger solubility than water. Dispersed phase was an aqueous solution of NaOH and AMP. The effects of reactant concentration, size of emulsified droplets, volume fraction of continuous phase and stirring speed on the absorption rate of CO_2 were investigated. In the mathematical model, the mechanism of CO_2 absorption into the continuous phase through a gas-liquid interface was described on the basis of the penetration model, while the subsequent absorption/reaction in the dispersed aqueous droplets was modeled by the film model.

Key words: Gas Absorption, Carbon Dioxide, Emulsion, Amine

INTRODUCTION

Carbon dioxide is a major component of greenhouse gases, which cause global warming, and many efforts have been made to solve this problem. Recently chemical absorption and membranes based on separation processes are the possible promising processes by which CO_2 can be successfully reduced from industrial waste gases and other gaseous mixtures.

Artificial membranes have been a topic of great interest in recent years because of their potential applications. One of the most intriguing classes of artificial membranes is the liquid membrane. In general, there are two main types of liquid membrane systems that have been considered for practical applications: emulsion-type liquid membranes and supported liquid membranes. Emulsion-type liquid membranes are made by forming emulsions of two immiscible phases and then dispersing them in a third phase (the continuous phase). The emulsion is stabilized by surfactants. The liquid membrane processes have found applications in separation of metal [Chan et al., 1984; Bunge et al., 1984, 1987; Danesi et al., 1986] and hydrocarbons [Bunge et al., 1987; Teramoto et al., 1981; Ho et al., 1982; Kim et al., 1983].

It is known that the dispersed second liquid in w/o emulsion can enhance the mass transfer of a dissolved gas in a gas-liquid system. Various authors have given a qualitative explanation of this phenomenon: small droplets of a liquid immiscible with the continuous liquid phase absorb the gas in the hydrodynamic mass-transfer film, after which desorption of the gas takes place in the gas-poor bulk of the liquid.

Linek and Benes [1976] have studied gas absorption into oil-in-water (o/w) emulsion or water-in-oil (w/o) emulsion. In o/w type emulsions, the mass transfer coefficient is not affected by the content of the oil phase, whereas in the w/o type emulsion, the coeffi-

cient increases in proportion to the volume fraction of oil.

Mehra and Sharma [1985, 1986] have reported on the absorption of isobutylene, butene-1 and propylene in microemulsions of chlorobenzene in aqueous solutions of sulfuric acid, where enhancement factors as high as 25 have been achieved. They have suggested that the specific rate of absorption of a sparingly soluble gas, in a liquid where reaction occurs, may be substantially enhanced by the use of a second liquid phase which is immiscible with the original liquid phase but exhibits a pronounced solubility for the gas. The second liquid phase may be simply dispersed or emulsified. The emulsion may have dispersed liquid droplets in size smaller than the diffusional film thickness. Enhancements of rates are expected due to an additional mode of transport of the solute gas via the second liquid phase.

Bruining et al. [1986] have studied the absorption of oxygen into oil-in-water emulsions. It has been shown that the rate of mass transfer of oxygen into an aqueous sulfite solution can be enhanced by the presence of small amounts of a dispersed organic phase. Mehra [1988] and Mehra et al. [1988] have analyzed the process of absorption of gases into emulsion of an additional liquid phase on the basis of the unsteady-state theory and compared the predicted enhancement factors with the measured ones.

As mentioned above, the dispersed phase plays a role of a carrier which transports the dissolved gas from the gas-liquid interface to the bulk body of the liquid, and the reaction of the dissolved gas with reactant occurs in the continuous phase.

If the system is w/o type emulsion such that the dispersed phase is the aqueous solution containing reactant, and the continuous phase is the organic solvent having larger solubility of gas than water, then the specific rate of absorption may be enhanced because of larger solubility and chemical reaction.

The hindered amine such as 2-amino-2-methyl-1-propanol (AMP) is often used to absorb CO_2, because the desorption of CO_2 from the absorbed AMP solution is easy and the data about solubility of CO_2 with AMP was well established systematically [Baek et al.,

†To whom correspondence should be addressed.
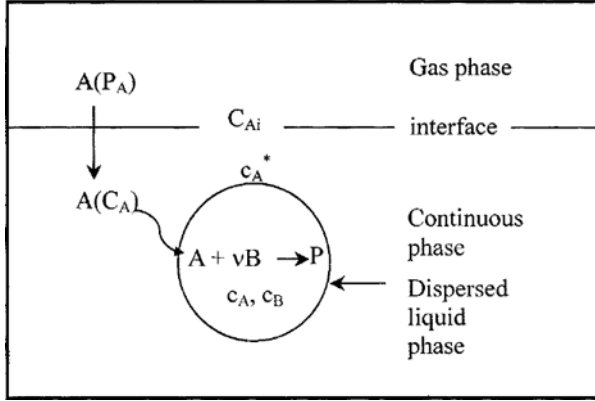E-mail: swpark0@hyowon.pusan.ac.kr

Fig. 1. Chemical absorption path of gas (A) into w/o emulsion.

2000].

In this study, the absorption mechanism of CO_2 into w/o emulsion composed of aqueous (AMP) amine solution and benzene is presented, and the measured absorption rates of CO_2 are compared with those obtained from the model based on penetration theory with chemical reaction.

THEORY

In case of absorption of CO_2 into w/o emulsion with benzene-aqueous amine solution as shown in Fig. 1, a mathematical model is developed to describe the absorption of CO_2 into the continuous benzene phase through the gas-liquid interface under unsteady-state and transfer into the dispersed aqueous droplets through the liquid-liquid interface under steady-state, where the chemical reaction of CO_2 occurs.

The following assumptions are made to set up the conservation equations:

(1) Henry's law holds, (2) the reaction of CO_2 with reactant in the aqueous droplets is of first-order with respect to both CO_2 and reactant, (3) isothermal condition prevails, (4) size and shape of the dispersed aqueous droplets are uniform and spheroid, respectively.

Under these assumptions, the conservation equations of CO_2 absorbed in the dispersed aqueous phase are given as

$$D_{eA}\left(\frac{d^2c_A}{dr^2}+\frac{2}{r}\frac{dc_A}{dr}\right)=k_2c_Ac_B \tag{1}$$

$$D_{eB}\left(\frac{d^2c_B}{dr^2}+\frac{2}{r}\frac{dc_B}{dr}\right)=\nu k_2c_Ac_B \tag{2}$$

Boundary conditions to be imposed are

$$r=R;\ c_A=c_A^*=H_AC_A,\ \frac{dc_B}{dr}=0 \tag{3}$$

$$r=0;\ \frac{dc_A}{dr}=\frac{dc_B}{dr}=0 \tag{4}$$

Eqs. (1), (2) and the boundary conditions are put into dimensionless forms as follows:

$$\frac{d^2\alpha_A}{dy^2}+\frac{2}{y}\frac{d\alpha_A}{dy}=m_A^2\alpha_A\alpha_B \tag{5}$$

$$\frac{d^2\alpha_B}{dy^2}+\frac{2}{y}\frac{d\alpha_B}{dy}=\frac{m_A^2}{r_Ar_B}\alpha_A\alpha_B \tag{6}$$

$$y=1;\ \alpha_A=1,\ \frac{d\alpha_B}{dy}=0 \tag{7}$$

$$y=0;\ \frac{d\alpha_A}{dy}=\frac{d\alpha_B}{dy}=0 \tag{8}$$

where $\alpha_A=\dfrac{c_A}{c_A^*}$, $\alpha_B=\dfrac{c_B}{c_{B0}}$, $y=\dfrac{r}{R}$, $m_A=R\sqrt{k_2c_{B0}/D_{eA}}$, $r_B=D_{eB}/D_{eA}$,

$$q_B=c_{B0}/\nu c_A^*=c_{B0}/(H_AC_A)=c_{B0}/(\nu H_AC_A Y_A)$$
$$=q_{B0}/Y_A\ \text{and}\ Y_A=C_A/C_A^*$$

The effectiveness factor here can be defined as

$$E_f=\frac{4\pi R^2 n_A}{(4/3)\pi R^3 k_2 c_A^* c_{B0}}=\frac{3}{m_A^2}\frac{d\alpha_A}{dy}\bigg|_{y=1} \tag{9}$$

where n_A is the flux of CO_2 defined as $D_{eA}dc_A/dr|_{r=R}$.

The conservation equation for the dissolved gas in the continuous liquid phase at unsteady-state can be written as

$$D_A\frac{\partial^2C_A}{\partial z^2}=\frac{\partial C_A}{\partial t}+(1-\varepsilon)k_2c_{B0}H_AC_AE_f \tag{10}$$

Boundary and initial conditions are given as

$$z=0,\ t>0;\ C_A=C_{Ai} \tag{11}$$

$$z>0,\ t=0;\ C_A=0 \tag{12}$$

$$z=\infty,\ t>0;\ C_A=0 \tag{13}$$

Eqs. (10) through (13) are put into the dimensionless form as follows:

$$\frac{\partial^2Y_A}{\partial x^2}=\frac{\partial Y_A}{\partial\theta}+E_fY_A \tag{14}$$

$$x=0,\ \theta>0;\ Y_A=1 \tag{15}$$

$$x>0,\ \theta=0;\ Y_A=0 \tag{16}$$

$$x=\infty,\ \theta>0;\ Y_A=0 \tag{17}$$

where $\theta=Mk_L^2t/D_A$, $x=\sqrt{M}k_Lz/D_A$ and $M=\dfrac{(1-\varepsilon)k_2c_{B0}H_AD_A}{k_L^2}$

The mass flux with chemical reaction at any contact time θ is defined as

$$N_A=-D_A\frac{\partial C_A}{\partial z}\bigg|_{z=0} \tag{18}$$

The mean mass flux during contact time, t is written as

$$\bar{N}_A=\frac{1}{t}\int_0^t N_Ad\theta \tag{19}$$

The mean mass flux without chemical reaction based on the penetration model has been derived as follows [Higbie, 1935]:

$$\bar{N}_A^0=2C_A\sqrt{\frac{D_A}{\pi t}} \tag{20}$$

The enhancement factor (ϕ) here defined as the ratio of mass flux

with chemical reaction to that without chemical reaction, is described by using Eqs. (19) and (20) as follows:

$$\phi = \frac{\overline{N}_A}{N_A^\circ} \qquad (21)$$

EXPERIMENTAL

All chemicals in this study were reagent grade and used without further purification. Purity of both CO_2 and N_2 gases was more than 99.9%. Sodiumhydroxide (NaOH), and 2-amino-2-methyl-1-propanol (AMP) were used as reagents of CO_2. The w/o type emulsion from benzene and aqueous solution was made by the same procedure as those reported elsewhere [Park et al., 1997] by adding Tween 80 and Arlacel 83 as surfactant, by using a homogenizer (Fisher Scientific Co.) in the range of agitation speed of 1,500 to 10,000 rev/min, and the mean size of aqueous droplets was measured by Image Analyzer (Leitz TAS Plus Co.). The absorption rates of CO_2 with a flat stirred vessel were measured along the procedure identical to those reported elsewhere [Park et al., 1994] at 25 °C and an atmospheric pressure. For the absorption experiments, the range of concentration of reactant was 0.5-2.0 kmol/m³, that of agitation speed, 100-200 rev/min, that of droplet radius, 2-15·10⁻⁶ m and that of volume fraction of continuous phase, 0.6-0.8.

PHYSICOCHEMICAL PROPERTIES

In the reaction of CO_2 with NaOH [Danckwerts et al., 1966] and AMP [Messaoudi et al., 1996] the reaction rate constants were estimated as follows.

For NaOH, $\log k_2 = 13.635 - \frac{2895}{T} + 0.131 I$

For AMP, $\log k_2 = 10.968 - \frac{2551.2}{T}$

The value of diffusivity of CO_2 in benzene estimated from the Wilke-Chang equation [Danckwerts, 1970] was $3.853 \cdot 10^{-9}$ m²/s at 25 °C.

The values of diffusivity of CO_2 in NaOH [Hikida et al., 1979] and AMP [Nijsing et al., 1995] solutions were estimated as follows:

For NaOH, $D_{eA} = D_{eAw}(1 - 0.129 c_{Bo})$
For AMP, $D_{eA} = 2.1625 \cdot 10^{-5} - 6.85 \cdot 10^{-6} c_{Bo} + 7 \cdot 10^{-7} c_{Bo}^2$

The ratio of diffusivity of reactant to that of CO_2 in benzene (r_B) was assumed to be equal to the ratio in water, i.e., $D_{eB}/D_{eA} = D_{eBW}/D_{eAW}$ [Nijsing et al., 1995]. The diffusivities of NaOH [Hikida et al., 1979] and AMP [Nijsing et al., 1995] in water at 25 °C have been reported to be $3.24 \cdot 10^{-5}$ m²/s and $7.24 \cdot 10^{-10}$ m²/s, respectively.

The values of solubility of CO_2 in benzene and water were 0.1107 kmol/m³ [Park et al., 1997] and 0.035 kmol/m³ [Danckwerts, 1970] at 25 °C and 0.101 MPa, respectively. The values of solubility of CO_2 in NaOH [Danckwerts, 1970] and AMP [Saha et al., 1993] solutions were estimated as follows:

For NaOH $\log\left(\frac{c_A^*}{c_{Aw}^*}\right) = -hI$

For AMP, $c_A^* = 3.485 \because 10^{-5} - 3.76 \because 10^{-6} c_{Bo} + 4 \because 10^{-7} c_{Bo}^2$

The distribution coefficient of CO_2 between benzene and aqueous solution, H_A, was obtained from the ratio of the solubility of CO_2 in benzene to that in aqueous solution.

The mass transfer coefficient, k_L, of CO_2 in CO_2/benzene system was measured along the procedure as reported elsewhere [Park et al., 1994] and the values at agitation speeds of 100, 150 and 200 rpm were $4.55 \cdot 10^{-5}$ m/s, $5.13 \cdot 10^{-5}$ m/s, and $10.34 \cdot 10^{-5}$ m/s, respectively.

RESULTS AND DISCUSSION

The chemical absorption of CO_2 into two reactants used in this study lies in a pseudo-first-order fast reaction region [Doraiswamy et al., 1984], where it is assumed that the concentration of reactant, c_B, in the aqueous droplets may be constant as either the feed concentration (c_{Bo}) or the interfacial concentration (c_{Bi}) between benzene and aqueous solution.

If c_B is equal to c_{Bo}, Eqs. (5) through (8) are reduced to

$$\frac{d^2\alpha_A}{dy^2} + \frac{2}{y}\frac{d\alpha_A}{dy} = m_A^2 \alpha_A \qquad (22)$$

$$y = 1; \quad \alpha_A = 1 \qquad (23)$$

$$y = 0; \quad \frac{d\alpha_A}{dy} = 0 \qquad (24)$$

The exact solution to Eq. (22) with the boundary conditions, Eqs. (23) and (24) is given as follows:

$$\alpha_A = \frac{\sinh(m_A y)}{y \sinh(m_A)} \qquad (25)$$

Using Eqs. (9) and (25), the effectiveness factor is written as

$$E_f = \frac{3}{m_A}\left(\frac{1}{\tanh(m_A)} - \frac{1}{m_A}\right) \qquad (26)$$

If c_B is equal to c_{Bi}, α_A and E_f are written as follows:

$$\alpha_A = \frac{\sinh(m_A \eta y)}{y \sinh(m_A y)} \qquad (27)$$

$$E_f = \frac{3}{m_A\sqrt{1 - \frac{1-E_f}{q_B}}}\left[\frac{1}{\tanh\left(m_A\sqrt{1 - \frac{1-E_f}{q_B}}\right)} - \frac{1}{m_A\sqrt{1 - \frac{1-E_f}{q_B}}}\right]$$

or

$$E_f = \frac{3}{m_A\sqrt{1 - \frac{(1-E_f)Y_A}{q_B^0}}}\left[\frac{1}{\tanh\left(m_A\sqrt{1 - \frac{(1-E_f)Y_A}{q_B^0}}\right)}\right.$$
$$\left. - \frac{1}{m_A\sqrt{1 - \frac{(1-E_f)Y_A}{q_B^0}}}\right] \qquad (28)$$

where, $\eta = \sqrt{\dfrac{c_{Bi}}{c_{Bo}}}$ and $\alpha_{Bi} = 1 + \dfrac{1-E_f}{q_B}$

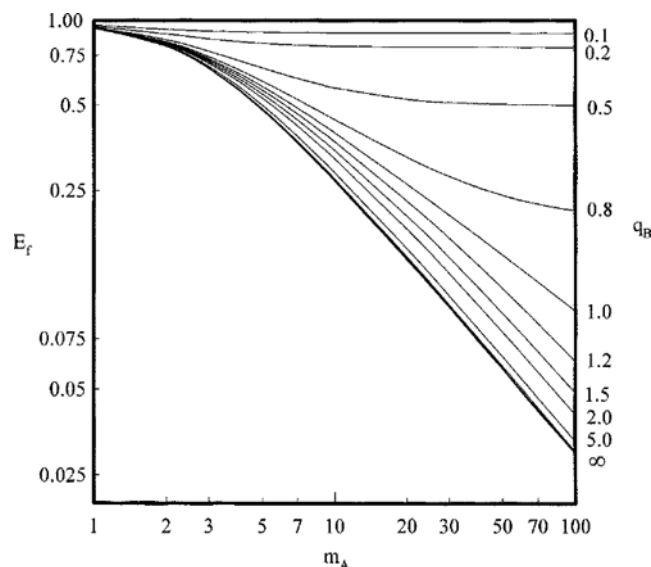The values of E_f calculated from Eq. (28) were plotted for var-

Fig. 2. Effect of m_A on effectiveness factor for various values of q_B.

ious values of m_A with a parameter of q_B in Fig. 2. As shown in Fig. 2, E_f decreased with increasing m_A and q_B, and E_f approached to an asymptote. It can be said that the concentration of CO_2 in the continuous phase decreases with an increase in the depth from the gas-liquid interface, and the reaction can be regarded as a pseudo-first-order one becuause c_{Bi} approaches c_{Bo} for large values of q_B, i.e., $q_B=\infty$.

The concentration of CO_2 in aqueous droplets can be calculated from Eq. (25) or (27) when c_B is equal to c_{Bo} or c_{Bi}. Fig. 3 shows typical concentration profiles of CO_2 when c_B is equal to c_{Bo} with a parameter of m_A in case of M of 40 and q_B^0 of 20. As shown in Fig. 3, α_A increases as y approaches unity, i.e., the surface of droplet, and the concentration gradient at the surface, $d\alpha_A/dy|_{y=1}$ increases with increasing m_A, which is contrary to the results as shown in Fig.
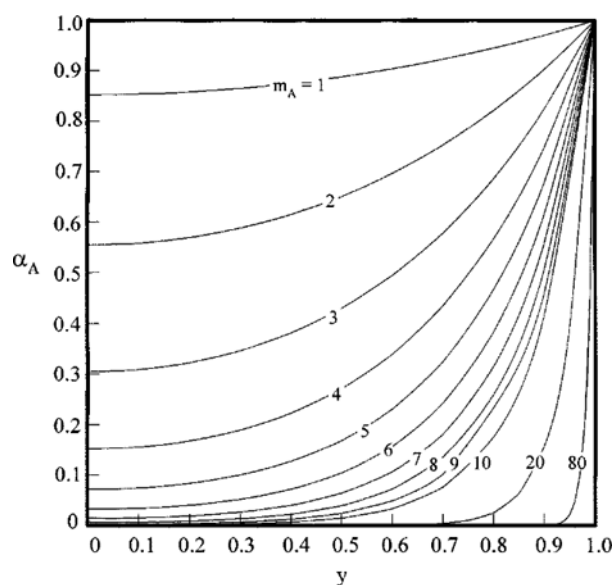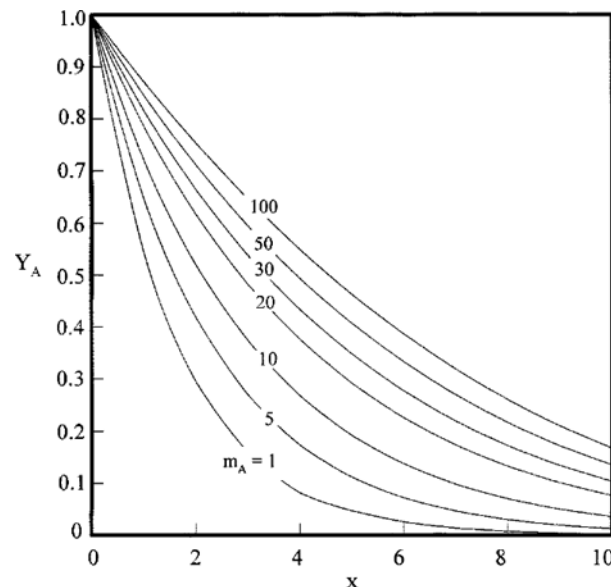

Fig. 4. Concentration profile of CO_2 in the continuous phase at various values of m_A at M=40.

2. Eq. (9) suggests that the degree of decrease in $1/m_A^2$ should be smaller than that of increase in $d\alpha_A/dy|_{y=1}$ with increasing m_A.

In order to observe the effects of m_A and M on the concentration profile of CO_2 in the continuous phase, Y_A was obtained from the numerical solution to Eq. (14) by the finite difference method with centered difference formula for variable x and forward difference formula for variable θ.

Fig. 4 shows typical plots of Y_A against x at various values of m_A at M of 40. As shown in this figure, Y_A decreased as the depth from the gas-liquid interface increased and m_A decreased.

The concentration gradient at the gas-liquid interface, $-dY_A/dx|_{x=0}$, was obtained as the slope of plots of Y_A against x depicted in Fig. 4, and it was plotted against m_A in Fig. 5 with a parameter of M. As
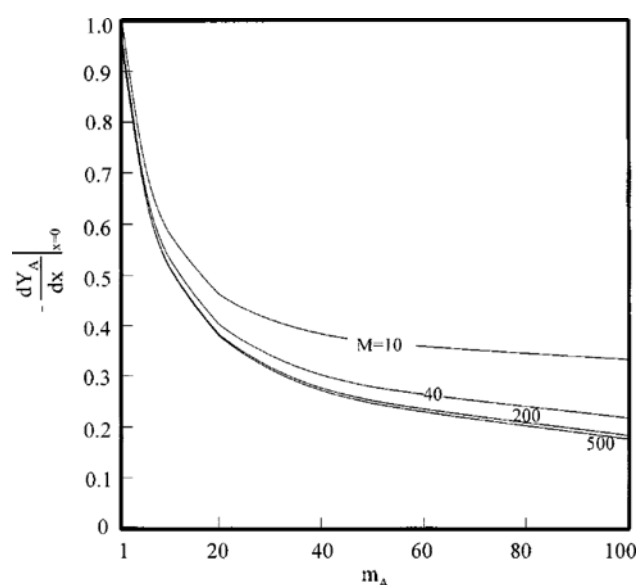

Fig. 3. Dimensionless concentration profiles of CO_2 in the dispersed phase for various values of m_A at M=40 and q_B^0=20.

Fig. 5. Effect of m_A on the slope at the gas-liquid interface for various values of M.

Fig. 6. Concentration profile of CO_2 for various values of M at $m_A =$ 50.

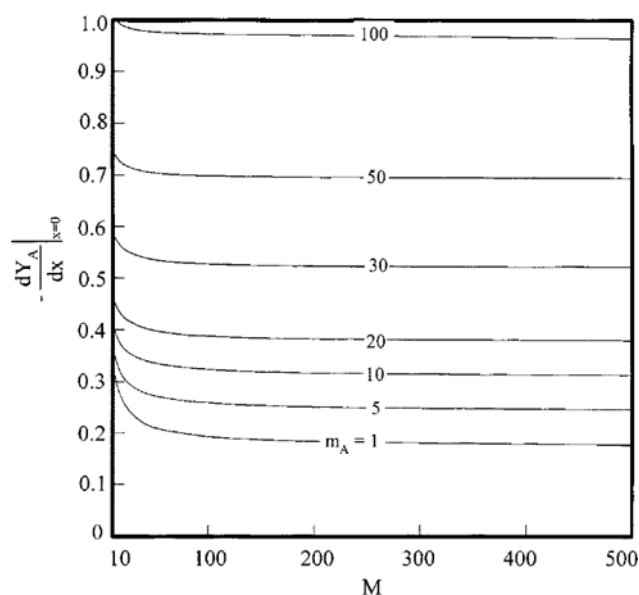**Fig. 8. Effect of M on ϕ for various values of m_A.**

Fig. 7. Effect of M on the slope at the gas-liquid interface for various values of m_A.

shown in Fig. 5, the slope decreased with increasing m_A and M.

Fig. 6 shows typical plots of Y_A against x at various values of M at m_A of 50. As shown in Fig. 6, Y_A decreased with increasing depth and decreasing M. The slope at x=0 in Fig. 6 was plotted against M in Fig. 7 with a parameter of m_A. It is apparent in this figure that the slope decreases with increasing M and decreasing m_A.

In order to observe the effects of m_A and M on the enhancement factor, ϕ, was calculated by using Eq. (21). Fig. 8 shows a plot of ϕ against M with m_A as a parameter. As shown in Fig. 8, ϕ increased with increasing M and decreasing m_A. Because the concentration gradient decreased with increasing M as shown in Fig. 7, ϕ should decrease, but the tendency was the contrary to that shown in Fig. 8. Therefore, it may be explained that the increase of ϕ exerts influ-
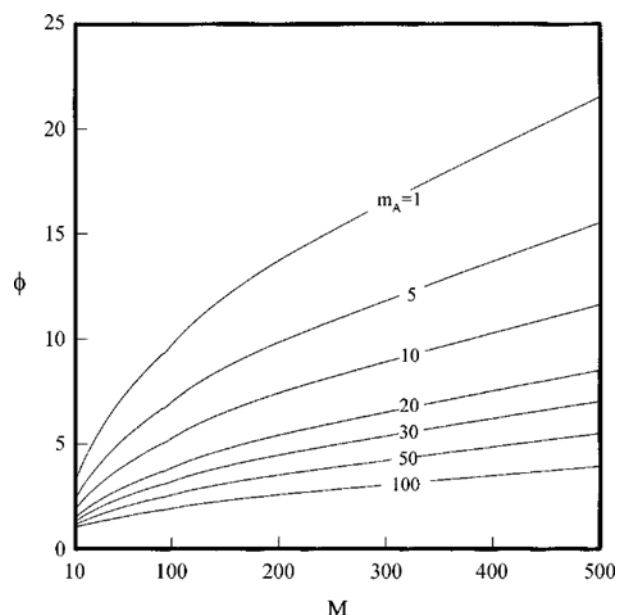
ence more on the increase of M rather than the decrease of the concentration gradient.

The calculated values of enhancement factor based on the penetration model were compared with those determined from the absorption rates by changing the concentration of reactant, the agitation speed, the size of droplets and the volume fraction of continuous phase in w/o type emulsion, in order to check the conformity of the proposed model.

Fig. 9 shows a plot of enhancement factor against the concentration of reactant under the typical experimental conditions such as agitation speed of 200 rev/min, aqueous droplet size of 10 μm in
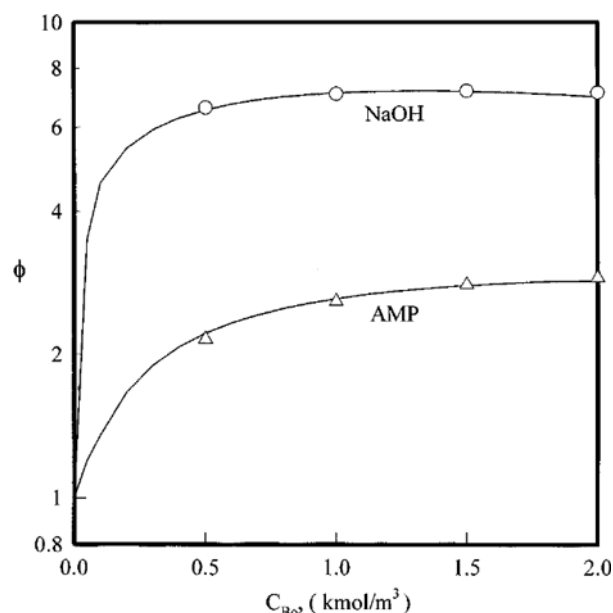

Fig. 9. Effect of amine concentration of enhancement factor for various amines at R=10 μm, k_L=1.034×10^{-4} m/s, and ε= 0.6.

emulsion prepared at 5,000 rev/min and volume fraction of 0.6. The solid curves represent the calculated values from Eq. (21) and the symbols refer to experimental data. As shown in Fig. 9, the calculated values approach reasonably to the experimental points, and ϕ increases with increasing reactant concentration. It is apparent from their definition that the values of m_A and M increase with increasing c_{Bo}. Although E_f decreases with increasing m_A and q_B as shown in Fig. 2, the product term of E_f and M increases with increasing c_{Bo}. Therefore, it can be said that ϕ is influenced more by M than m_A with an increase of c_{Bo}. As shown in Fig. 9, ϕ also depends on

the species of reactant. In other words, it increases in the order of NaOH and AMP. This is caused by the fact that the reaction rate constant for the reactant increases in the order of the reactants mentioned above.

Fig. 10 shows a plot of enhancement factor against mass transfer coefficient, which depends on the agitation speed, under the typical experimental conditions such as reactant concentration of 1.0 kmol/m³, droplet size of 10 μm and volume fraction of 0.6. As shown in Fig. 10, the enhancement factor was decreased with increasing mass transfer coefficient, i.e., increasing of agitation speed. This tendency can be explained by the fact that M decreases with increasing mass transfer coefficient. It may be said that the effect of agitation speed on ϕ, is diminished owing to a more decreased degree of ϕ with an increase of mass transfer coefficient, as shown in Fig. 10.

Fig. 11 shows a typical plot of enhancement factor against droplet size at reactant concentration of 1.0 kmol/m³, agitation speed of 200 rev/min and volume fraction of 0.6. It is proved from this figure that the enhancement factor decreases with increasing droplet size. This is because m_A increases with increasing droplet size, and the ratio of the interfacial area between benzene and aqueous phase to the volume of droplet decreases with increasing droplet size.

Fig. 12 shows a typical plot of enhancement factor against volume fraction of benzene phase at reactant concentration of 1.0 kmol/m³, agitation speed of 200 rev/min and droplet size of 10 μm. As shown in Fig. 12, the enhancement factor decreased with increasing volume fraction. For M decreases with increasing ε, and the zone of chemical reaction becomes narrow with an increase of the volume of benzene phase.

As shown in Figs. 9 through 12, the enhancement factor was influenced by experimental variables such as reaction rate constant, reactant concentration, mass transfer coefficient, droplet size and volume fraction of benzene phase. In order to investigate the effects of such experimental variables on the enhancement factor as
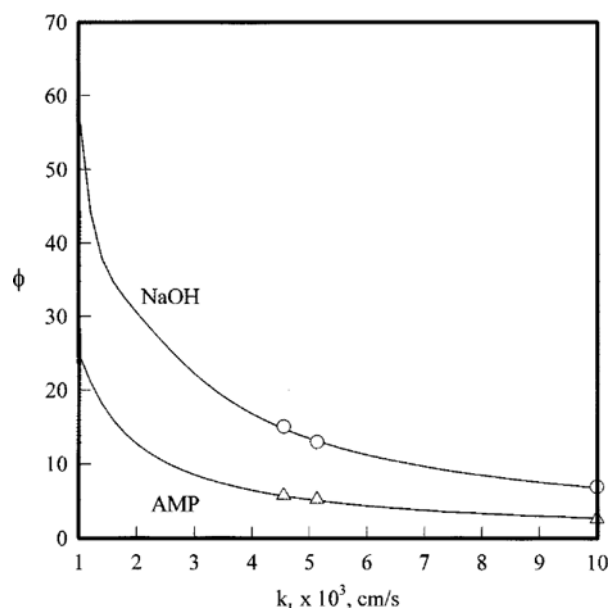

Fig. 10. Effect of mass transfer coefficient on enhancement factor for various amines at c_{Bo}=1.0 kmol/m³, R=10 μm, and ε=0.6.
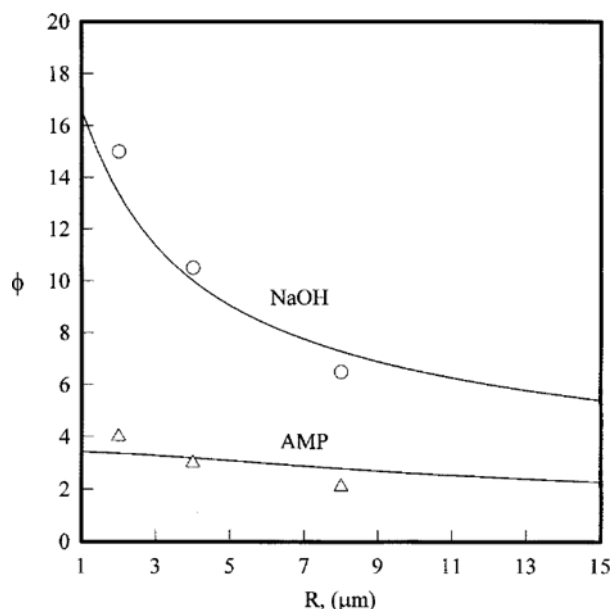

Fig. 11. Effect of liquid droplet size on enhancement factor for various amines at c_{Bo}=1.0 kmol/m³, k_L=1.034×10⁻⁴ m/s, and ε=0.6.

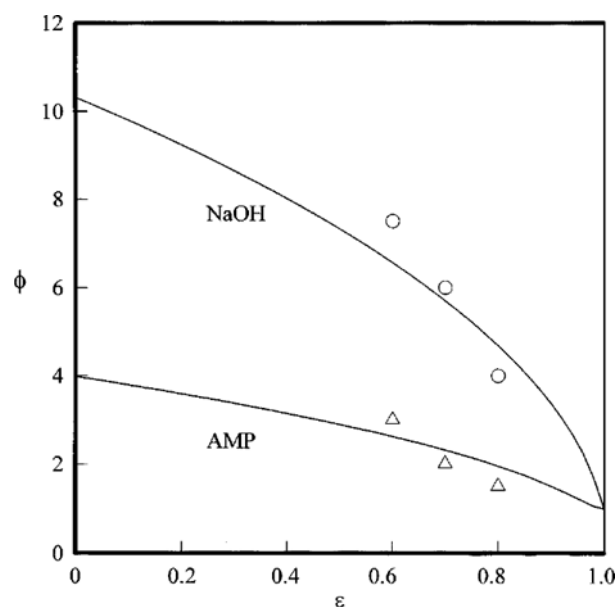

Fig. 12. Effect of volume fraction of continuous phase on enhancement factor for various amines at c_{Bo}=1.0 kmol/m³, R=10 μm, and k_L=1.034×10⁻⁴ m/s.
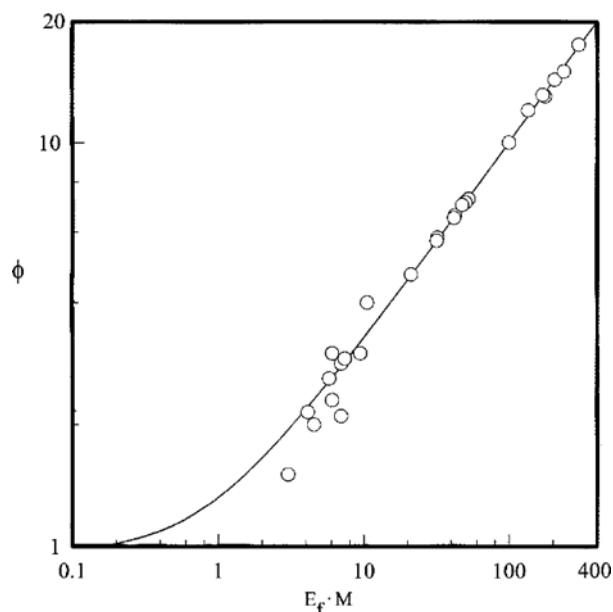
Fig. 13. Effect of the multiplication of E_f and M on enhancement factor.

a whole, the relationship between ϕ and the product of E_f and M, which are calculated for the experimental variables, is shown in Fig. 13. As shown in this figure, the experimental values of ϕ approached reasonably to the calculated ones, and ϕ increased with an increase of the product of E_f and M, from which ϕ could be expressed as a function of the product of E_f and M.

CONCLUSION

Carbon dioxide from CO_2-N_2 gas mixtures was absorbed into w/o emulsion composed of aqueous amine solution and benzene by using a stirred vessel with a flat gas-liquid interface at 25 °C and an atmospheric pressure. The enhancement factor of CO_2 absorption increased with increasing reactant concentration, whereas it decreased with increasing agitation speed, size of aqueous droplet and volume fraction of benzene.

A mathematical model was developed as a combination of physical absorption into the continuous phase through the gas-liquid interface on the basis of the penetration model and chemical absorption into the dispersed phase through the liquid-liquid interface on the basis of film model.

The enhancement factors calculated by the numerical analysis of the proposed model of diffusion with chemical reaction approached reasonably to the experimental values.

ACKNOWLEDGEMENT

NOMENCLATURE

C_A : concentration of CO_2 in benzene [kmol/m^3]

c_A' : solubility of CO_2 in aqueous phase [kmol/m^3]
C_{Ai} : solubility of CO_2 in water [kmol/m^3]
c_{Aw}' : feed concentration of CO_2 in water [kmol/m^3]
c_{Bo} : solubility of CO_2 in benzene [kmol/m^3]
c_i : concentration of component i in aqueous phase [kmol/m^3]
D_A : diffusivity of CO_2 in benzene [m^2/s]
D_{ei} : diffusivity of component i in aqueous phase [m^2/s]
E_f : effectiveness factor defined as by Eq. (9)
H_A : dimensionless solubility defined as c_A'/C_A
I : ionic strength [m^3/kg-ion]
k_2 : 2nd order reaction rate constant [m^3/kmol·s]
k_L : mass transfer coefficient of CO_2 in benzene [m/s]
M : dimensionless modulus defined as $(1-\varepsilon)k_2 c_{Bo} H_A D_A / k_L^2$
m_A : dimensionless modulus defined as $R\sqrt{k_2 c_{Bo}/D_{eA}}$
N_A : mass transfer rate of CO_2 at gas-liquid interface with chemical reaction in benzene [kmol/m^2·s]
N_A^o : mass transfer rate of CO_2 at gas-liquid interface without chemical reaction in benzene [kmol/m^2·s]
n_A : mass transfer rate of CO_2 from benzene phase into aqueous phase [kmol/m^2·s]
R : radius of aqueous droplet in benzene phase
r : radial distance in aqueous phase [m]
r_B : diffusivity ratio defined as D_{eB}/D_{eA}
q_B : dimensionless concentration defined as c_{Bo}/c_A'
q_B^0 : dimensionless concentration defined as $c_{Bo}/H_A C_{Ai}$
t : time [s]
T : temperature [K]
x : dimensionless coordinate in film thickness direction in benzene phase defined as $z\sqrt{(1-\varepsilon)k_2 c_{Bo} H_A/D_A}$
Y_A : dimensionless concentration in benzene phase
y : dimensionless radial coordinate defined as r/R
z : coordinate in film thickness direction in benzene phase [m]

Greek Letters

α_A : dimensionless concentration of CO_2 component in aqueous phase defined as c_A/c_{Ao}
α_B : dimensionless concentration of B component in aqueous phase defined as $m\, c_B/c_{Bo}$
ε : volume fraction of benzene phase in the emulsion
θ : dimensionless time defined as $(1-\varepsilon)k_2 c_{Bo} H_A t$
ϕ : enhancement factor
ν : stoichiometric coefficient in chemical reaction of CO_2 with alkaline reactant

Subscripts

A : CO_2
B : reactant (amine)
E : aqueous
i : gas-liquid interface
o : bulk body
W : pure water phase
$*$: liquid-liquid interface

REFERENCES

Baek, J. I., Yoon, J. H. and Eum, H. M., "Prediction of Equilibrium Solubility of Carbon Dioxide in Aqueous 2-Amino-2-Methyl-1,3-Pro-

panediol Solutions," *Korean J. Chem. Eng.*, **17**, 484 (2000).

Blanc, C. C. and Demarais, G., "The Reaction Rate of CO_2 with Diethanolamine," *Int. Chem. Eng.*, **24**, 43 (1984).

Bruining, W. J., Joosten, G. E. H., Beenackers, A. A. C. M. and Hofman, H., "Enhancement of Gas-Liquid Mass Transfer by a Dispersed Second Liquid Phase," *Chem. Eng. Sci.*, **41**, 1873 (1986).

Bunge, A. L. and Noble, R. D., "A Diffusion Model for Reversible Consumption in Emulsion lquid Membranes," *J. Mem. Sci.*, **21**, 55 (1984).

Bunge, A. L. and Noble, R. D., "Batch Extraction of Amines Using Emulsion Liquid Membranes Importance of Reaction Reversibility," *AIChE J.*, **33**, 43 (1987).

Chan, C. C. and Lee, C. J., "Mechanistic Models of Mass Transfer Across a Liquid Membrane," *J. Mem. Sci.*, **20**, 1 (1984).

Danckwerts, P. V. and Sharma, M. M., "The Absorption of Carbon Dioxide into Solutions of Alkalis and Amines," *Chem. Eng.*, **44**, 244 (1966).

Danckwerts, P. V., "Gas-Liquid Reactions," McGraw-Hill Book Co., New York, 15 (1970).

Doraiswamy, L. K. and Sharma, M. M., "Heterogenous Reaction: Analysis, Example and Reactor Design," John wiley & Sons, New York, **2**, 22 (1984).

Danesi, P. R. and Reichley-Yinger, L., "Origin and Significance of the Deviations from a Pseudo First Order Rate Law in the Coupled Transport of Metal Species through Supported Liquid Membranes," *J. Mem. Sci.*, **29**, 195 (1986).

Higbie, R., "The Rate of Absorption of a Pure Gas into a Still Liquid During Short Periods of Exposure," *Trans. Am. Inst. Chem. Eng.*, **31**, 365 (1935).

Hikita, H., Asai, S., Katsu, Y. and Ikuno, S., "Absorption of Carbon Dioxide into Aqueous Monoethanolamine Solutions," *AIChE J.*, **25**, 793 (1979).

Ho, W. S., Hatton, T. A., Lightfoot, E. N. and Li, N. N., "Batch Extraction with Liquid Surfactant Membranes: A Diffusion Controlled Model," *ibid.*, **28**, 662 (1982).

Kim, K. S., Choi, S. J. and Ihm, S. K., "Simulation of Phenol Removal from Waste Water by Liquid Membrane Emulsion," *Ind. Eng. Chem.*

Fundam., **22**, 167 (1983).

Linek, V. and Benes, P., "A Study of the Mechanism of Gas Absorption into Oil-Water Emulsions," *Chem. Eng. Sci.*, **31**, 1037 (1976).

Littel, R. J., van Swaaij, W. P. M. and Versteeg, G. F., "Kinetics of Carbon Dioxide with Tertiary Amines in Aqueous Solution," *AIChE J.*, **36**, 1633 (1990).

Mehra, A. and Sharma, M. M., "Absorption with Reaction: Effect of Emulsified Second Liquid Phase," *Chem. Eng. Sci.*, **40**, 2382 (1985).

Mehra, A. and Sharma, M. M., "Absorption with Reaction in Micro-emulsions Absorption of Olefins," *ibid.*, **41**, 2455 (1986).

Mehra, A., "Intensification of Multiphase Reactions through the Use of a Microphase-I. Theoritical," *ibid.*, **43**, 899 (1988).

Mehra, A., Pandit, A. and Sharma, M. M., "Intensification of Multiphase Reactions through the Use of a Microphase-II. Experimental," *ibid.*, **43**, 913 (1988).

Messaoudi, B. and Sada, E., "Kinetics of Absorption of Carbon Dioxide into Aqueous Solutions of Sterically Hindered 2-Amino-2-Methyl-1-Propanol," *J. Chem. Eng. Japan*, **29**, 193 (1996).

Nijsing, R. A. T. O., Hendriksz, R. H. and Kramers, H., "Absorption of CO_2 in Jet and Falling Films of Electrolyte Solutions, with and without Chemical Reaction," *Chem. Eng. Sci.*, **4**, 49 (1995).

Park, S. W. and Suh, D. S., "Absorption of O_2 into Aliquat 336-Diphenylmethane Heterogeneous System," *HWAHAK KONGHAK*, **32**, 700 (1994).

Park, S. W., Ryu, J. H., Lee, S. S., Hwang, K. S. and Kumazawa, H., "Gas Absorption of CO_2 into Emulsion with Alkaline Aqueous Solution," *ibid.*, **35**, 476 (1997).

Saha, A. K. and Bandyopadhyah, S. S., "Solubility and Diffusivity of N_2O and CO_2 in Aqueous Solution of 2-Amino-2-Methyl-1-Propanol," *J. Chem. Eng. Data*, **38**, 81 (1993).

Teramoto, M., Takihara, H., Shibutnani, M., Yuasa, T., Miyake, Y. and Teranishi, T., "Extraction of Amine by w/o/w Emulsion System," *J. Chem. Eng. Japan*, **14**, 122 (1981).

Wang, Y. W., Xu, S., Otto, F. D. and Mather, A. E., "Solubility of N_2O in Alkanolamines and in Mixed Solvents," *Chem. Eng. J.*, **48**, 31 (1992).