

GAS ABSORPTION OF CARBON DIOXIDE IN A HOLLOW FIBER CONTAINED LIQUID MEMBRANE ABSORBER

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Abstract – Experiments on the absorption of CO₂ into a hollow fiber contained liquid membrane absorber were performed. The feed gas was a mixture of CO₂ and N₂, absorbent liquid was 2-amino-2-methyl-1-propanol and the hollow fiber was a microporous hydrophobic polytetrafluoroethylene membrane. Outlet concentration of CO₂ from the absorber decreased as absorbent concentration increased, gas flow rate increased and were held constant for speed of agitation, but had a maximum value in the range of inlet concentration of CO₂ from 5 to 40 mole %. The reaction rate constant obtained for CO₂-amine system was 231 l/mol · s at 25 °C using a flat stirred vessel, and the membrane-side-mass-transfer coefficient was 1.217×10^{-5} mol/cm² · s · atm in CO₂/N₂-amine system. A diffusion model based on mass transfer with fast-reaction was proposed to predict the performance of the absorber.

Key words: Hollow Fiber Contained Liquid Membrane, Absorption, CO₂, 2-Amino-2-Methyl-1-Propanol

INTRODUCTION

In conventional large-scale gas absorption processes, the gas mixture is contacted with a scrubbing liquor in devices like packed towers, spray towers, venturi scrubbers, and bubble columns. These dispersion-based contacting methods have many drawbacks. An approach having much promise and without these shortcomings is membrane-based contacting using microporous hollow fibers. The microporous membrane-based device acts as a gas absorber, with the gas flowing on one side and the absorbent liquid flowing on the other side of the membrane without either phase being dispersed in the other. The gas-liquid interface is at the pore mouth. Unlike that in a true liquid membrane process, the absorbent liquid has to be regenerated in a separate stripper which can be also a membrane-based contactor. These membrane-based gas separation devices offer several advantages [Lonsdale, 1982] over conventional contacting devices: much higher surface area per unit contactor volume; independent control of gas and liquid flow rates without any flooding, loading, weeping, or foaming; known gas-liquid interfacial area; modularity, easy to scale up or down; availability of all of the membrane surface area for contacting regardless of how low the individual phase flow rates are.

The disadvantage [Bhave and Sirkar, 1986] is that the fibers supply a new mass transfer resistance, that of the membrane, which is not present in packed towers. This new resistance may make the mass transfer slower and less selective. The membrane-phase resistance may be eliminated when there is a very fast or instantaneous chemical reaction in the liquid

phase filled in the pores.

Qi and Cussler [1985] studied the absorption of a number of gases using various solvents and aqueous solutions in a hydrophobic microporous hollow fiber device where the membrane pores were gas filled. Yang and Cussler [1986] have noted a 10-fold increase in the gas separation efficiency when using a hollow fiber device over a conventional packed column. Sirkar [1992] has recently reviewed microporous membrane-based gas absorption processes.

The type of tube and shell was, in general, used as a modules of hollow fiber for gas separation [Qi and Cussler, 1985; Yang and Cussler, 1986; Rudisill and Leven, 1990; Karoor and Sirkar, 1993], but these modules need another desorption process of gas from the discharged liquid. A new type of membrane absorber such as a hollow fiber contained liquid membrane absorber (HFCLM) can be used in order to carry out simultaneously two processes of absorption and desorption. This modules consist of two bundles of hollow fibers soaked into the absorbent liquid. The mixture gases flow in the tubes of the first bundle, and the gas transferred to the absorbent liquid through the pores of tubes moves to the tubes of the second bundle, where the inert gas flows.

In this present study, as the first part of gas separation in HFCLM, a diffusion model of gas absorption into aqueous solution of 2-amino-2-methyl-1-propanol (AMP) was proposed, overall reaction rate constant, individual liquid side- and overall gas side-mass transfer coefficient were measured respectively, and the measured values of absorption rate of CO₂ from the modules of HFCLM were compared with the predicted values for the changes of experimental parameters such as concentrations of CO₂ in feed gases and AMP in absorbent liquid, speed of agitation and flow rate of feed gases.

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THEORY

The theoretical model is developed here to describe the absorption of CO₂ from CO₂-N₂ mixture flowing in the tube into liquid through the pore of the porous hollow fiber, where bundles of the hollow fibers are soaked. We call this modules as a hollow fiber contained liquid membrane absorber (HFC-LM). The following assumptions are utilized to set up the governing mass transfer differential equation: 1) the absorbent liquid exists outside the tube and is perfect mixing, 2) the mixture gases flow inside the tube with a plug flow and are ideal gas, 3) the pores of tube are filled with gas mixture, 4) the reaction of CO₂ with a reactant in the absorbent liquid occurs outside the tubes, and is a fast pseudo-first-order reaction, 5) steady-state and isothermal condition, 6) application of Henry's law, 7) no absorption of inert gas. Using these assumptions, the conservation equation for CO₂ flowing inside of the tube is given by

$$\frac{d}{dz} \left(\frac{x_A}{1-x_A} \right) + \frac{\pi D_i \varepsilon N_f k_m R T (x_A - x_{A,i})}{Q_1 (1-x_{A,1})} = 0 \quad (1)$$

The boundary conditions are followings.

$$\text{at } z=0; \quad x_A = x_{A,1} \quad (2)$$

$$\text{at } z=L; \quad x_A = x_{A,2} \quad (3)$$

Also, the conservation equation of CO₂ outside the tube side is given by

$$D_i k_m (x_A - x_{A,i}) = \frac{D_o k_L^\circ \phi}{H_A} (x_{A,i} - x_A^*) \quad (4)$$

where, the relationship between concentration of CO₂ of tube side and that of liquid side is given as following from the assumption of 6)

$$p_{A,i} = H_A C_{A,i} \quad (5)$$

$$p_A^* = H_A C_{A,LO} \quad (6)$$

and ϕ is the enhancement factor defined as $\sqrt{k_{11} D_A C_{AMP,o}} / k_L^\circ$ in the case of fast pseudo first-order reaction.

Using the boundary conditions such as Eq. (2) and (3), integration of differential Eq. (1) is expressed as follows,

$$\int_{x_{A,1}}^{x_{A,2}} \frac{d \left(\frac{x_A}{1-x_A} \right)}{x_A - x_{A,i}} = \alpha_m \quad (7)$$

where,

$$\alpha_m = - \frac{A_i k_m R T}{Q_1 (1-x_{A,1})}$$

Rearrangement of Eq. (4) becomes as follows,

$$(x_A - x_{A,i}) = \beta (x_A - x_A^*) \quad (8)$$

where,

$$\beta = \frac{D_o k_L^\circ \phi / H_A}{D_i k_m + D_o k_L^\circ \phi / H_A} \quad (9)$$

Integrated the combined type of Eq. (7) and (8), the following equation is obtained.

$$a \ln \frac{(x_{A,2} - x_A^*) (1 - x_{A,1})}{(x_{A,1} - x_A^*) (1 - x_{A,2})} + b \frac{x_{A,2} - x_{A,1}}{(1 - x_{A,1}) (1 - x_{A,2})} = \alpha_m \beta \quad (10)$$

where,

$$a = \frac{1}{(1-x_A^*)^2}, \quad b = \frac{1}{1-x_A^*}$$

EXPERIMENTAL

All chemicals in this study were reagent grade and were used without further purification. The hollow fiber used in this study were a microporous hydrophobic polytetrafluoroethylene (PTFE-21, Mitsubishi Co., outside diameter; 2 mm, inside diameter; 1 mm, porosity; 50 %).

The modules of these fibers were made by placing a bundle of 7 fibers with which length of each fiber was 60 cm in a cylindrical glass vessel with 9.5 cm diameter and 10.2 cm depth. The volume of absorbent liquid in the vessel was 700 cm³. These membrane modules were installed in the apparatus shown schematically in Fig. 1. The gas mixture were feeded inside of the tubes with constant flow rate and composition adjusted by using the mass flow controller through the saturator contained water. The absorption temperature was controlled by an air-bath. The compositions of CO₂ at inlet and outlet of the bundle were analyzed by a gas chromatography (Shimadzu GC-8A, TCD, packing material; Porapak Q, detector temperature; 130 °C, the flow rate of carrier gas, He; 20 cm³/min), and flow rates of outlet were measured by a soap-bubbler. The absorbent liquid was mixed by agitator, and the concentration of liquid was measured by HCl titration.

The ranges of flow rate of gas mixture were 20-100 cm³/min, those of composition of CO₂ in feed gases of CO₂-N₂ mixture, 5-40 mole %, those of concentration of AMP as absorbent agent, 0-2 mol/l, and those of agitation speed, 150-500 rev/min, and absorption experiments were carried out at 25 °C and atmospheric pressure.

The mass transfer rates of CO₂ transferred from tube side into the absorbent liquid were obtained from the differences of composition of CO₂ and flow rates between inlet and outlet of tubes at steady-state condition.

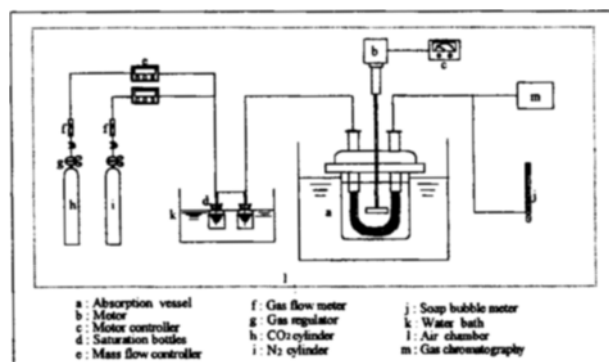


Fig. 1. Experimental setup for gas absorption using hollow fiber contained liquid membrane absorber.

RESULTS AND DISCUSSION

Physical properties such as the liquid-phase diffusivity and solubility of CO₂ in aqueous solutions, reaction rate constant and mass transfer coefficients, which were used for analysis about the transport phenomena in this HFCLM system, were obtained as followings.

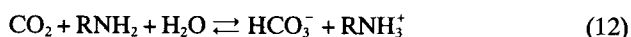
Because the diffusivity and solubility of a gas in aqueous phase were dependent of the ionic strength in the electrolyte aqueous solutions [Danckwert, 1970], these values were obtained from the empirical equation suggested by Messaoudi and Sada [1996], which expressed a relationship between the combined parameter and concentration of AMP.

$$\log \left(\frac{\sqrt{D_{AW}}/H_{AW}}{\sqrt{D_A}/H_A} \right) = c C_{AMP,o}^d \quad (11)$$

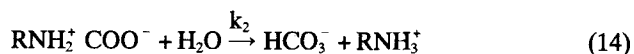
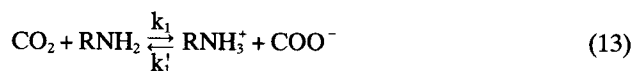
where, subscript w indicates water, $C_{AMP,o}$ initial concentration of AMP, and c and d, empirical constants. D_{AW} and $1/H_{AW}$ were obtained from the reference [Danckwerts, 1970; Hikita, et al., 1976] as 1.97×10^{-5} cm²/s, 3.05×10^{-5} mol/atm · cm³, at 25 °C, respectively.

The constants, c and d in Eq. (11) were obtained as 0.11 and 0.36, respectively from reference [Messaoudi and Sada, 1996].

It has been reported [Chakraborty et al., 1986; Yih and Shen, 1988] that the overall reaction taking place between CO₂ and AMP in aqueous solutions is



This reaction is believed to take place according to the zwitterion path [Sartori and Savage, 1983; Yih and Shen, 1988] as follows,



This zwitterion path is an extension of the zwitterion mechanism for carbamate formation first proposed by Caplow [1968]. By assuming the steady-state for the zwitterion, the reaction rate can be derived as

$$r_A = \frac{k_1 k_2}{k_1 + k_2} [\text{CO}_2(\text{aq})][\text{RNH}_2] \quad (15)$$

In the present work, to confirm the resulting expression and evaluate the reaction rate constant, an (m, n)-th order reaction equation of the type ($r_A = k_m C_A^m C_B^n$) is considered, and both the order of reaction and the rate constant are determined from gas absorption rates in the fast reaction regime, according to the Hikita and Asai [1964] approach.

Yih and Shen [1988], Sada et al. [1985] and Hikita and Asai [1964] reported that the order of reaction with respect to CO₂ and AMP in aqueous solution was 1 and 1, respectively, and the order of overall reaction of CO₂ with AMP was 2. Also, they concluded that these reactions occurred in the range of fast reaction region.

The reaction rate of CO₂ with AMP in the range of fast

reaction region can be expressed [Doraiswamy and Sharma, 1984].

$$N_A = C_A^* \sqrt{k_{11} D_A C_{AMP,o}} \quad (16)$$

The mass transfer rate of CO₂ into AMP aqueous solutions were obtained from the measured absorption rate of CO₂ with the same stirred vessel used in the previous study [Lee, 1997] at speed of agitation, 200 rev/min. The influence of AMP concentration on the absorption rate was examined by plotting $N_A/(\sqrt{D_A}/H_A)$ versus $\sqrt{C_{AMP,o}}$ as shown in Fig. 2. The reaction rate constant (k_{11}) was evaluated to be 231 l/mol · s obtained from the slope of the linear relationship between $N_A/(\sqrt{D_A}/H_A)$ and $\sqrt{C_{AMP,o}}$ as shown in Fig. 2. To confirm to the fast reaction region, the requirement $(\sqrt{k_{11} D_A C_{AMP,o}})/k_L^o < C_{AMP,o}/C_A^*$ [Doraiswamy and Sharma, 1984] must be fulfilled. This is satisfied when AMP concentration are approximately greater than 0.5 mol/l.

The conservation equation of CO₂ for the liquid-side in the CO₂-H₂O system with HFCLM is given [Lee, 1997] by

$$\frac{dn_A}{dt} = A_{to} k_L^o (C_A^* - C_A) \quad (17)$$

The initial rate of absorption [Lee, 1997] can be expressed by

$$\left. \frac{dV}{dt} \right|_{t=0} = \frac{A_{to} R T}{p_T - p_V} k_L^o C_A^* \quad (18)$$

where, p_T is the atmospheric pressure (1.0 atm), p_V , water vapor pressure (0.03126 atm) at 25 °C and C_A equals to zero at initial condition.

The value of k_L^o can be obtained from the initial rate of CO₂ absorption in Eq. (18) at a given speed of agitation in the absorption vessel.

The rates of absorption of pure CO₂ were measured in the HFCLM, where the pure gas flowed in the tube at a given flow rate and water existed outside the bundle of the tubes. The volumes of absorbed gas were plotted according to the time of absorption at the flow rate of gas, 40.2 cm³/min and speed of agitation, 300 rev/min in Fig. 3 typically.

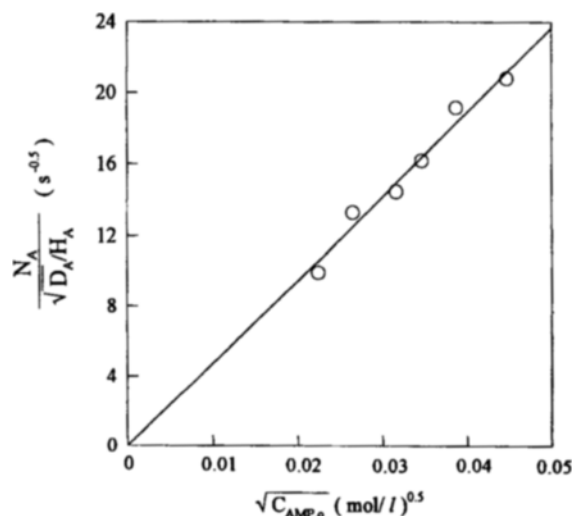


Fig. 2. Effect of AMP concentration on $N_A H_A / \sqrt{D_A}$ at 25 °C.

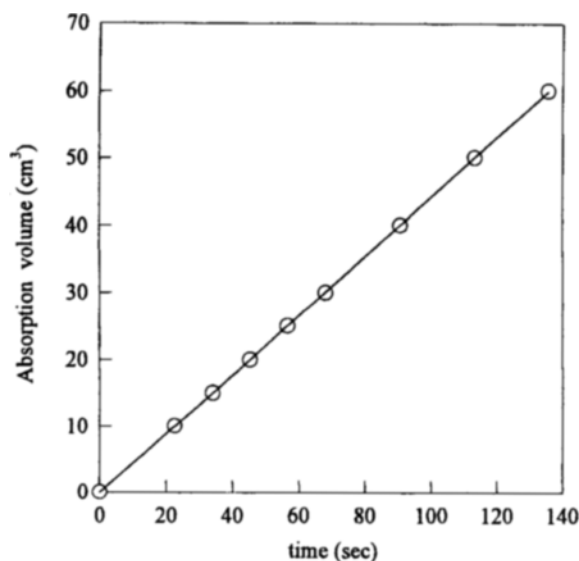


Fig. 3. Absorption volume vs. time at agitation speed, 300 rev/min and flow rate of CO₂, 40.2 cm³/min.

As shown in Fig. 3, the linear relationship between the absorbed volume and absorption time was satisfied. k_L^o obtained from the slope of the plots in Fig. 3 was 4.05×10^{-3} cm/s. The values of k_L^o obtained by changes of the speed of agitation were shown in Table 1, where k_L^o increased from 150 to 300 rev/min, but were held constant from 300 to 500 rev/min.

The conservation equation of CO₂ for the overall mass transfer in the CO₂/N₂-H₂O system with HFCLM is given by

$$\frac{d}{dz} \left(\frac{x_A}{1-x_A} \right) + \frac{\pi D_e \epsilon N_f K_o R T (x_A - x_A^*)}{Q_1 (1-x_{A1})} = 0 \quad (19)$$

Integration of Eq. (19) with boundary condition as shown in Eq. (2) and (3) yields the following equation,

$$a \ln \frac{(x_{A2} - x_A^*)(1 - x_{A1})}{(x_{A1} - x_A^*)(1 - x_{A2})} + b \frac{x_{A2} - x_{A1}}{(1 - x_{A1})(1 - x_{A2})} = \alpha_o \quad (20)$$

where,

$$\alpha_o = - \frac{A_o K_o R T}{Q_1 (1 - x_{A1})}$$

The value of K_o in Eq. (20) can be obtained from the measured values of x_{A2} at the outlet of the tubes. The outlet

concentrations of CO₂ were measured in the CO₂/N₂-H₂O system at the given values of x_{A1} , Q_1 and speed of agitation, and the value of K_o were calculated from the Eq. (20). These values were shown in Table 1.

In the case of mass transfer without chemical reaction, ϕ equals to 1. Therefore, combined Eq. (10) with Eq. (20), the relationship for modules of hollow fiber between overall mass transfer coefficient and individual mass transfers can be expressed as followings.

$$\alpha_m \beta = \alpha_o \quad (21)$$

$$\frac{1}{D_e K_o} = \frac{1}{D_i k_m} + \frac{H_A}{D_o k_L} \quad (22)$$

The values of k_m were calculated by using K_o , k_L^o and Eq. (22), and shown in Table 1. Because the k_m is the mass transfer coefficient in the pore of the membrane, k_m may be independent of experimental variables such as the speed of agitation, the gas flow rate and inlet concentration of absorbed gas. The average value of k_m from each value of k_m as shown in Table 1 was 1.217×10^{-5} mol/cm² · s · atm, and this value would be used for prediction of outlet concentration of CO₂ in Eq. (10).

The performance of absorber in the absorption of CO₂ with HFCLM of CO₂/N₂-AMP aqueous solution system was analyzed by comparison of the measured outlet concentrations of CO₂ with the calculated values from Eq. (10) for the changes of experimental variables such as inlet concentration of CO₂, concentration of AMP, flow rate of mixed gases and speed of agitation.

The concentration of CO₂ in bulk body of AMP solution becomes to be zero on the assumption that reaction of CO₂ with AMP should be fast pseudo first-order reaction, that is, x_A^* equals to zero.

Fig. 4 shows the relationship between the measured outlet concentration of CO₂ and initial concentration of AMP, where in initial concentration of AMP was varied from 0 to 2 mol/l, inlet concentration of CO₂, flow rate of gas mixture, and speed of agitation were held constant at 10 mole %, 40 cm³/min, 300 rev/min, respectively. The solid line represents the outlet concentration of CO₂ calculated from Eq. (10). As shown in Fig. 4, the measured values decreased as the concentrations of AMP increased, and approached reasonably to the calculated values. This is caused by increase of enhancement factor due to increase of the reaction rate. The theoretical prediction had a maximum deviation of 0.43 % from the

Table 1. Mass transfer coefficient for change of agitation speed in CO₂/N₂-H₂O system

Agitation speed [rev/min]	$k_L^o \times 10^3$ [cm/s]	Q_1 [cm ³ /min]	x_{A1} [mole %]	x_{A2} [mole %]	$K_o \times 10^8$ mol/cm ² · s · atm]	$K_m \times 10^5$ [mol/cm ² · s · atm]
150	2.94	41.2	10.1	9.72	1.254	1.336
200	3.49	41.7	9.8	9.38	1.444	1.431
250	4.04	38.8	9.7	9.19	1.653	1.057
300	4.35	40.3	10.1	9.53	1.854	1.281
400	4.65	39.5	10.1	9.48	1.980	1.056
500	4.44	41.8	9.6	9.09	1.798	1.138

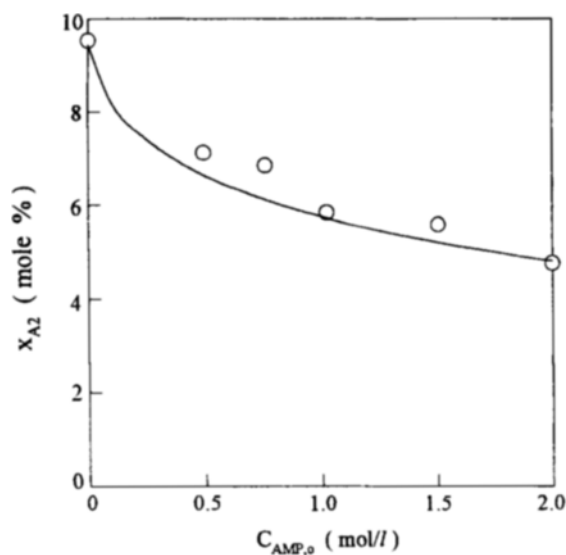


Fig. 4. Effect of concentration of AMP on outlet concentration of CO₂ at 300 rev/min, x_{A1} , 10 mole %, Q_1 , 40 cm³/min, and agitation speed, 300 rev/min.

experimental results.

The outlet concentrations of CO₂ were measured according to the change of flow rates of mixture gases at the given values of x_{A1} , $C_{AMP,o}$ and speed of agitation.

Fig. 5 shows a plot of the measured outlet concentration of CO₂ versus flow rate of gas mixture varied from 20 to 120 cm³/min at constant value of inlet concentration of CO₂, initial concentration of AMP and speed of agitation, 10 mole %, 1.5 mol/l, 300 rev/min, respectively. As shown Fig. 5, the measured outlet concentration of CO₂ increased as flow rate of gas mixture increased.

Decrease of absorption rate due to decrease of residence time of gas in the tubes may make the outlet concentration

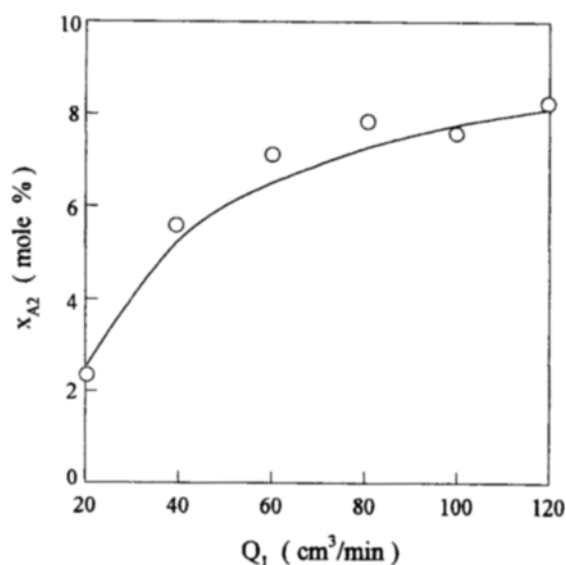


Fig. 5. Effect of flow rate of gas on outlet concentration of CO₂ at $C_{AMP,o}$, 1.5 mol/l, x_{A1} , 10 mole %, and agitation speed, 300 rev/min.

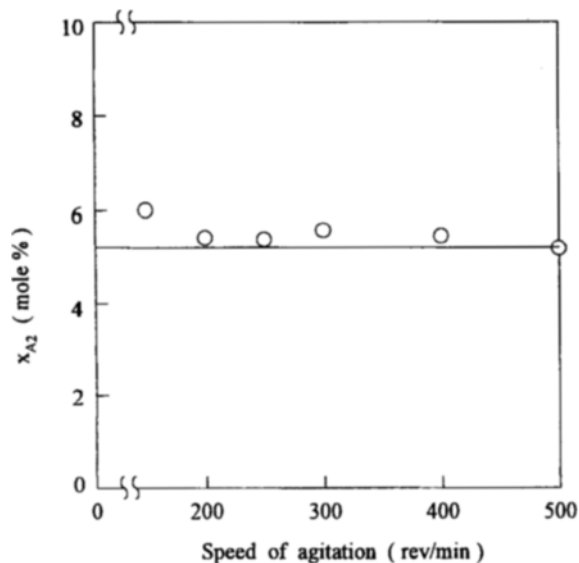


Fig. 6. Effect of speed of agitation on outlet concentration of CO₂ at $C_{AMP,o}$, 1.5 mol/l, x_{A1} , 10 mol%, and Q_1 , 40 cm³/min.

of CO₂ increased as gas flow rate increased.

The outlet concentrations of CO₂ were measured according to the change of speed of agitation at the given values of x_{A1} , $C_{AMP,o}$ and Q_1 . Fig. 6 shows the plot of the outlet concentrations of CO₂ versus the speed of agitation in the range 150-500 rev/min at x_{A1} , 10 mole %, $C_{AMP,o}$, 1.5 mol/l and Q_1 , 40 cm³/min. As shown in Fig. 6, the outlet concentrations of CO₂ were held constant for the change of the speed of agitation.

Although k_L^o and k_m affect outlet concentration of CO₂ for physical absorption, x_{A2} should be effected by k_m rather than k_L^o because the combined term of k_L^o and ϕ becomes to be $\sqrt{k_{11} D_A C_{AMP,o}}$ in the case of absorption with fast-pseudo first-order reaction.

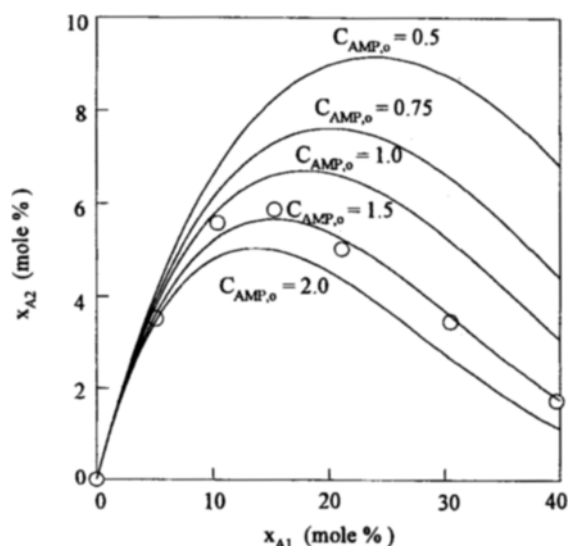


Fig. 7. Effect of inlet concentration of CO₂ on outlet concentration of CO₂ at Q_1 , 40 cm³/min, and agitation speed, 300 rev/min.

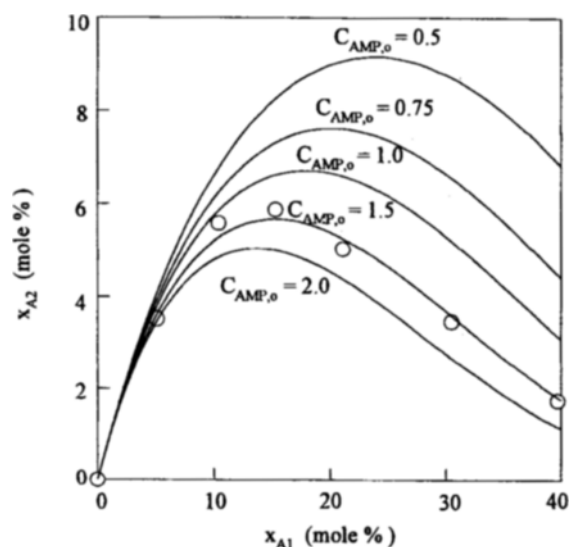


Fig. 8. Effect of inlet concentration of CO₂ on outlet concentration of CO₂ at $C_{AMP,o}$ 1.5 mol/l, and agitation speed, 300 rev/min.

The influence of inlet concentration of CO₂ on outlet concentration of CO₂ was examined by plotting x_{A2} versus x_{A1} . Fig. 7 and 8 show typically the plots of the measured outlet concentration of CO₂ against the inlet concentration of CO₂ at concentration of AMP, 1.5 mol/l, Q_1 , 40 cm³/min and agitator speed, 300 rev/min.

As shown in Fig. 7 and 8, the measured outlet concentration of CO₂ increased and decreased as inlet concentration of CO₂ increased from 5 to 40 mole %. The solid lines in Fig. 7 and 8 represent the calculated value from Eq. (10) for various values of AMP concentration and flow rate, respectively. It is interesting to note that there are maximum ranges in such plots which shift from right and upper side to left and lower side as AMP concentration increases and flow rate decreases in Fig. 7 and 8, respectively.

CONCLUSION

The outlet concentrations of CO₂ were measured using a hollow fiber contained liquid membrane absorber with various experimental variables such as AMP concentration, inlet concentration of CO₂, gas flow rate and speed of agitation in CO₂/N₂-AMP system in order to analysis the performance of HFCLM. Liquid side mass transfer coefficients were obtained in the range 150-500 rev/min of agitation speed in CO₂-H₂O system.

The data of absorption rate for CO₂-AMP system under the fast reaction regime were analyzed by chemical absorption theory to evaluate reaction rate constant as 231 l/mol · s using a stirred vessel with a flat gas-liquid interface at 25 °C.

The analysis of the CO₂/N₂-H₂O system using the film theory allows the calculation of the membrane-side-mass-transfer coefficient as 1.217×10^{-5} mol/cm² · s · atm, which is used for prediction of outlet concentration of CO₂ in CO₂/N₂-AMP system.

The outlet concentration of CO₂ decreased as AMP con-

centration increased, gas flow rates decreased and were held constant for speed of agitation, but had a maximum value in the range of inlet concentration of CO₂, 0-40 mole %.

A diffusion model based on mass transfer with fast-reaction in a modules of hollow fiber consisted of plug flow inside tube and perfect mixing outside tube could predict the performance of the absorber by comparison theoretical values with measured ones.

ACKNOWLEDGEMENTS

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NOMENCLATURE

- A_{ii} : surface area of tube inside [cm²]
- A_{to} : surface area of tube outside [cm²]
- A_{te} : surface area of equivalent diameter of tube [cm²]
- C_A : concentration of CO₂ in bulk body of liquid in a stirred vessel [mol/l]
- C_A^* : solubility of CO₂ in liquid [mol/l]
- C_{ALO} : concentration of CO₂ in bulk body of liquid in HFCLM [mol/l]
- C_{ALt} : concentration of CO₂ in liquid at tube outside in HFCLM [mol/l]
- $C_{AMP,o}$: initial concentration of AMP [mol/l]
- C_B : concentration of reactant [mol/l]
- $[CO_2(aq)]$: concentration of CO₂ dissolved in amine solution [mol/l]
- D_A : diffusivity of CO₂ in AMP aqueous solution [cm²/s]
- D_{AW} : diffusivity of CO₂ in water [cm²/s]
- D_i : inside diameter of tube [cm]
- D_o : outside diameter of tube [cm]
- D_e : equivalent diameter of tube [cm]
- H_A : Henry constant of CO₂ in liquid [atm · cm³/mol]
- H_{AW} : Henry constant of CO₂ in water [atm · cm³/mol]
- K_o : gas-side overall mass transfer coefficient [mol/cm² · s · atm]
- k_m : membrane mass transfer coefficient [mol/cm² · s · atm]
- k_L^o : liquid-side mass transfer coefficient [cm/s]
- k_1 : forward reaction rate constant in Eq. (13) [cm³/mol · s]
- k_{-1} : backward reaction rate constant in Eq. (13) [cm³/mol · s]
- k_2 : forward reaction rate constant in Eq. (14) [s⁻¹]
- k_{11} : second order reaction rate constant in Eq. (16) [cm³/mol · s]
- k_{mn} : (m+n) order reaction rate constant [cm^{3(m+n-1)}/mol^(m+n-1) · s]
- L : length of tube [cm]
- n_A : moles of CO₂ absorbed into water [mol]
- N_A : mass transfer rate of CO₂ [mol/cm² · s]
- N_f : number of tube [-]
- P_{Ar} : partial pressure of CO₂ at tube inside [atm]
- P_A^* : equilibrium partial pressure of CO₂ equivalent of C_{ALO} [atm]
- P_T : atmospheric pressure [atm]
- P_v : water vapor pressure [atm]
- Q_1 : inlet flow rate of gas [cm³/min]
- R : gas constant [atm · cm³/mol · K]
- $[RNH_2]$: concentration of amine [mol/l]
- r_A : reaction rate of CO₂ with amine [mol/cm³ · s]

- t : absorption time of CO_2 into water [s]
 T : temperature [K]
 t : absorption time of CO_2 into water [s]
 T : temperature [K]
 V : absorption volume of CO_2 into water [cm^3]
 x_A : concentration of CO_2 in tube [mol %]
 x_{A1} : inlet concentration of CO_2 of tube [mol %]
 x_{A2} : outlet concentration of CO_2 of tube [mol %]
 x_{Ai} : concentration of CO_2 at tube inside [mol %]
 x_A^* : equilibrium concentration of CO_2 equivalent to C_{ALo} [mol %]
 z : position of tube [cm]

Greek Letters

- α_m : dimensionless constant defined by Eq. (7)
 α_o : dimensionless constant defined by Eq. (20)
 β : dimensionless constant defined by Eq. (9)
 ε : porosity of membrane
 ϕ : enhancement factor defined by $\sqrt{k_{11}D_A C_{AMP,o}}/k_L^o$

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