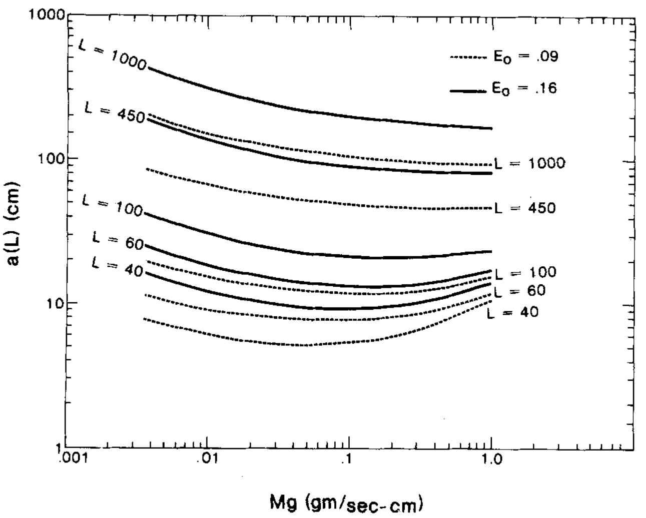

Fig. 3. Half width of jet at liquid surface vs. mass flow rate of air.

jet at the surface for a given value of M_g and L. The minor disagreement between the present results and the limited data available is due to the uncertainty in specifying accurately the value of E_o. More experimental work is needed to determine the correct value of E_o. However, it is felt that the present model is well suited for predicting accurately the liquid pumping capability of the two-phase, two-dimensional jet.

NOTATION

a = half width of jet, cm
K = ratio of wake volume to bubble volume = 1.5, see Hussain and Siegal (1976)
E = entrainment coefficient
E_o = entrainment constant
L = depth of row of orifices below liquid surface, cm
M = mass flow rate per cm of slot length, g/s-cm
P = pressure, g/cm^2
Q = volume flow rate per meter of slot length, cm^3/s-m
R = gas constant, g cm/g °K
T = absolute temperature, °K
U = fluid velocity, cm/s
ρ = fluid density, g/cm^3
σ = surface tension

Subscripts

a = atmosphere
c = jet's central bubbly region
g = gas
i = inside the jet, $y < a$
l = liquid
∞ = terminal
o = outside the jet, $y > a$

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On Desorption of Air from Liquid in Gas Absorption

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In the experiment (Mitsutake, 1973) of the the absorption of carbon dioxide into liquids, even in the case of small content of air in the liquids, air was liberated from the liquids. No experiments have yet been made about the effect of the desorption of air from liquids on the absorption of gas into them. The analogous experiments reported so far follow.

Dwyer and Dodge (1941) reported that the effect of humidity of the inlet gas on the rate of absorption of ammonia from air by water in a packed tower was quite small and within the experimental error. Grenier (1966) studied the effect of the counterdiffusion of water vapor on ammonia-air-hydrogen mixture on the absorption of ammonia into a water jet. Bourne (1969) and Tanaka et al. (1976) studied the effect of heat liberated by the dissolving ammonia and that of the temperature of the interface (by the evaporation of water) on the absorption of ammonia into water.

Again, as for our experiments, when pure carbon dioxide gas is absorbed in a bubble column, air liberated

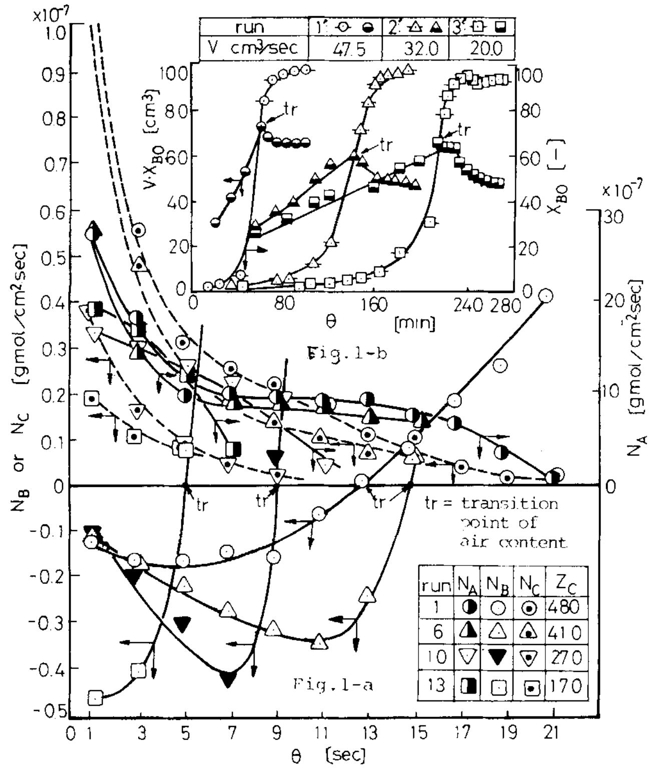

Fig. 1a. Variations of N_A, N_B, and N_C with time (bubble column).

Fig. 1b. Variations of X_{BO} and $V \cdot V_{BO}$ with time at 1 atm. (absorption chamber).

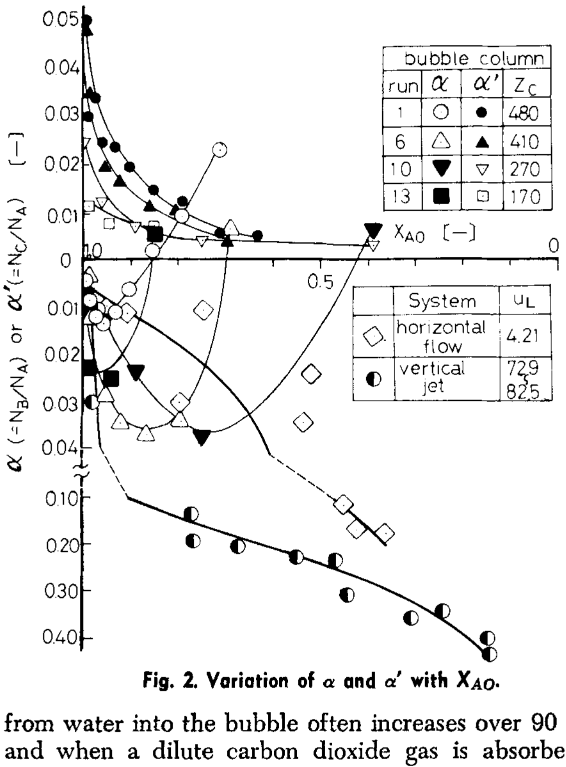

Fig. 2. Variation of α and α' with X_{AO}.

from water into the bubble often increases over 90 vol %, and when a dilute carbon dioxide gas is absorbed in a water jet or in horizontally flowing water, the desorption rate of air from water tends somewhat toward an equimolal counterdiffusion with carbon dioxide. The effect of the desorption rate of air and that of the condensation rate of water vapor on the absorption rate of carbon dioxide were investigated to give a clue to the solution of the mechanism of gas absorption, by means of the calculation of the ratios N_B/N_A and N_C/N_A.

THEORETICAL

The theory to analyze this experiment is based on the assumptions that the temperature is constant and that the ideal gas law is applicable.

1. Bubble column. From the material balance for carbon dioxide, air, and water vapor, the following equations hold:

$$\partial n_A/\partial\theta = -N_A A, \quad \partial n_B/\partial\theta = -N_B A \quad \text{and} \quad \partial n_C/\partial\theta = -N_C A \qquad (1)$$

where

$$n_A = nX_{AO} = (PV/RT)X_{AO}, \quad n_B = (PV/RT)X_{BO},$$
$$n_C = (PV/RT)X_{CO} = p_O V/RT, \quad X_{AO} + X_{BO} + X_{CO} = 1,$$
$$X_{CO} \simeq p_O/P, \quad P = P_O + \rho_L(Z_C - Z)/1033$$

Accordingly, equations in Equation (1) become respectively

$$N_A = -(1/RTA)\partial(PVX_{AO})/\partial\theta \qquad (2)$$

$$N_B = -(1/RTA)\partial(PVX_{BO})/\partial\theta \qquad (3)$$

$$N_C = -(p_O/RTA)\partial V/\partial\theta \qquad (4)$$

Putting $\alpha = N_B/N_A$ and $\alpha' = N_C/N_A$, then we get

$$\alpha = \partial(PVX_{BO})/\partial(PVX_{AO}), \quad \alpha' = p_O \partial V/\partial(PVX_{AO}) \qquad (5)$$

2. Vertical jet and horizontal flow. No change of the volume of gas and no condensation of the water vapor in gas phase are considered in these systems. If Pv^*/RT indicates the rate of carbon dioxide entering into the absorption chamber through a soap-film flowmeter, $-N_A A$ that of the same leaving by absorption, and $\partial n_A/\partial\theta$ that of the same accumulating there, the material balances become

$$\partial n_A/\partial\theta = Pv^*/RT - N_A A, \quad \partial n_B/\partial\theta = -N_B A \qquad (6)$$

where

$$n_A = (PV/RT)X_{AO}, \quad n_B = (PV/RT)X_{BO}, \quad \text{and} \quad X_{AO} + X_{BO} + X_{CO} = 1$$

According, we obtain

$$N_A = (P/RTA)(v^* - V \cdot \partial X_{AO}/\partial\theta) = (Pv^*/RTA)\{1/(1+\alpha)\} \qquad (7)$$

$$N_B = -(PV/RTA)\partial X_{BO}/\partial\theta = (PV/RTA)\partial X_{AO}/\partial\theta \qquad (8)$$

$$\alpha = N_B/N_A = -1 + v^*/\{v^* - V \cdot \partial X_{AO}/\partial\theta\} \qquad (9)$$

EXPERIMENTAL

Carbon dioxide is saturated with water vapor by the water vapor saturator.

1. Bubble column. A single bubble of pure carbon dioxide, of which the equivalent spherical diameter was 0.85 — 1.23 cm at the inlet of the column, was blown regularly at intervals of 1.0 to 3.1 s into the downflowing water in a 12-cm-diameter column. The effective heights of the columns were 170, 270, 410, and 480 cm. The gas bubble was collected by a specially designed bottle at any height in the column and was analyzed with GC by use of active carbon and helium. The state of contraction of rising bubbles by absorption was photographed with 8 or 16 mm cine camera.

In addition, pure carbon dioxide gas, stored in an absorption chamber (10 × 8 × 40 cm), a model of a bubble column kept in the water tank, was absorbed by flowing water and was analyzed with GC at regular intervals (see Figure 1*b*).

2. Vertical jet and horizontal flow. The differences between the rates of absorption of carbon dioxide into water and those of desorption of air from water were measured by the soap-film flowmeter at each inlet of the absorption chamber. The concentration of carbon dioxide in the chamber at the start of each run

was regulated by the injection of air into the absorption chamber in order to make the carbon dioxide concentration in the gas phase similar to the carbon dioxide concentration which would be expected for longtime absorption.

RESULTS AND DISCUSSION

The desorption of air from water and the condensation of water vapor occurring in a bubble in the bubble column and in the absorption chamber of vertical jet or of horizontal water flow were investigated.

1. Bubble column. It was found experimentally that the concentration of air in a bubble increases continuously, and the volume of the bubble progressively decreases with the rise of bubble in falling water in a column. Accordingly, there occurs, in general, a maximum content of air, the transition point in Figure 1, in the course of absorption of a bubble into flowing water. At such a point, neither desorption nor absorption of air but the condensation of water vapor in gas phase is thought to occur in spite of the progressive contraction of the bubble with the absorption of carbon dioxide into water. The maximum content of air varies widely in the range of about 20 to 85% and seems to be correlated with the height of column, the rate of falling water, and the total interfacial area of bubbles in the bubble column. The excessive increase of the percentage of air in the bubble beyond the maximum content of air results in a transition of the direction of diffusion of air from the bubble to the water to keep equilibrium of air between the bubble and the water. Namely, $N_A > 0$ and $N_B > 0$; therefore $\alpha > 0$ (see Figures 1 and 2).

When α becomes small, the absorption of a bubble of carbon dioxide is regarded as unidirectional diffusion, but the partial pressure of air in the bubble cannot be neglected in the final period of absorption because of its high concentration. The rise in temperature of the water by the heat of dissolution of carbon dioxide into water and by that of condensation of water vapor is negligible in this experiment but will not be necessarily the same for the absorption of a great many bubbles into a liquid. The variations of the condensation of water vapor in bubbles with time and with X_{AO} are shown in Figures 1 and 2.

2. Vertical jet and horizontal flow. In water jet and horizontal water flow systems, the volume of the gas phase is constant. Accordingly, no maximum volume of air appears in the gas phase, and the change of humidity in the gas phase may be neglected. As the concentration of air increases with time, namely, as X_{AO} decreases in the absorption chamber, α is found to tend somewhat toward -1, the equimolal counterdiffusion, as shown in Figure 2, which can also be understood theoretically from Equation (9).

NOTATION

A = interfacial area between gas and water, cm^2
n = $n_A + n_B + n_C$, gmole
n_A, n_B, n_C = mole concentrations of carbon dioxide, air, and water vapor, respectively, gmole spectively, gmole
N_A = absorption rate of carbon dioxide, gmole/cm^2 s
N_B = desorption rate of air,gmole/cm^2 s
N_C = condensation rate of water vapor, gmole/cm^2 s
P = total pressure = $[\rho_L(Z_C - Z)/1\,030] + P_O$, atm
P_O = atmospheric pressure, atm
p_O = vapor pressure of water at 1 [atm], atm
R = gas constant = 82.05 cm^3 atm/gmole °K
T = absolute temperature, °K
u_L = velocity of water, cm/s
V = V_A (volume of carbon dioxide) + V_B (volume of air) + V_C (volume of water vapor), cm^3
v^* = rate of gas indicated at soap-film flowmeter, cm^3/s
X_{AO}, X_{BO}, X_{CO} = mole fractions of carbon dioxide, air, vapor, respectively
Z = height of bubble in column, cm
Z_C = effective height of column, cm
α = N_B/N_A
α' = N_C/N_A
θ = time, s
ρ_L = density of water, g/cm^3

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Wall Region Mass Transfer for Large Schmidt Numbers in Turbulent Pipe Flow

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Shaw and Hanratty (1976) have presented experimental mass transfer data for the Schmidt number range of 693 to 37 200 with turbulent flow in a circular pipe. The authors suggest that a greater precision was attained than in previous investigations because of the care given to the execution of these experiments. The fully developed mass transfer coefficients were correlated by

$$k = 0.0889\, u^* N_{Sc}^{-0.704} \qquad (1)$$

Excellent agreement is shown between Equation (1) and the experimental data.

Hughmark (1975) proposed the equation for fully developed mass transfer in a circular pipe:

$$\frac{1}{k^+} = \frac{1}{\dfrac{1}{1.6\, N_{Sc}} + \alpha N_{Sc}{}^{-2/3}} + \frac{1}{\dfrac{1}{33\, N_{Sc}} + 0.0615\, N_{Sc}{}^{-1/2}}$$