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Mass Transfer by Rotating Jets

Part I. CO_2 Gas Absorption by Cylindrical Liquid Jets

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In this report, gas absorption by a rotating cylindrical liquid jet, whose water traveling length is short, is considered experimentally. Experiments of absorption are proceeded in pure CO_2 gas and water at 20° C: CO_2 gas is cross-currently contacted with a liquid jet. From experimental results, absorption rate was observed to be large immediately after liquid was spouted from small hole drilled through rotating cylinder.

§ 1. Introduction

Recently centrifugal contactors in which mass transfer operations are carried out have been developed, and the author has designed one of the centrifugal contactor whose main part consists of multistage concentric cylinders made of perforated plates.

As a fundamental study on mass transfer in this centrifugal gas-liquid contactor in which liquid is spouted from the small hole drilled through a rotating cylinder wall, and where gas is sent cross-currently to the water jet in an annular space between the rotating cylinder and a stationary concentric outside cylinder, pure CO_2 gas absorption by a rotating cylindrical liquid jet was studied.

Many experiments on pure CO_2 gas absorption by water jets spouting from rotating small holes were carried out at 20°C and the effects of the following variables on the liquid phase mass transfer rate were studied; diameter of the rotor, diameter of the small hole, number of the small holes, width of the annular space, gas flow rate, liquid flow rate, revolution speed of the rotor, contact time of gas and liquid, etc.

In these experiments, the diameter of the small hole was 0.5—2.0 mm, the average velocity of water, 55—950 cm/sec, and the traveling length of water (the distance between two cylinders), 1—5 cm.

From the results of these experimental studies, the gas absorption rate by water was observed to be large immediately after the liquid was spouted from the hole.

§ 2. Flow pattern of liquid jet

Many studies on the flow pattern of liquid jet spouted from small hole in the gravitational field have been done. That is, the studies of jets fuel in internal combustion engines, the atomizing theory of fuel spray, the measurement of droplet size of spray, the photograph and observation of atomizing pattern, and others have been reported by many investigators. However, the quantitative and systematic studies are few, because the problems as mentioned above are complicated. Therefore, there is nothing more than the studies by Tanazawa and Toyoda et al.,[1,2] on the flow pattern of liquid jets spouted from small hole, and for the systematic studies on the atomizing pattern. Besides, as regards these studies in the centrifugal field, it is no more than the studies of the discharge from the rotating pipe[3] and of the atomizing pattern of liquids spouted from the cylindrical nozzle[4].

The flow pattern of the liquid jet spouted from a rotating small hole is very complex, but the water jet spouted from a rotating small hole travels in the air linearly with the resultant velocity due to the composition of the circumferential velocity and that of the direction of radius. Therefore, it is clear that the resultant velocity as mentioned above indicates the relative velocity against the air. As the discharge velocity of liquid is increased, it assumes the form of drops, drop to laminar flow, laminar flow, laminar to turbulent flow, turbulent flow, turbulent to spray, and spray. **Figure 1** shows the most typical forms of liquid jets spouted from rotating small hole. In this figure, (a) is dripping flow, (c) and (d) are laminar flow, (e) is turbulent flow and (g) is spray. From the above results, it is clear that these flow types in centrifugal field are like those spouted from small hole in gravitational field.

Fig. 1. Flow pattern

According to the experimental results of Tanazawa et al[2)], the flow pattern of liquid jet is divided by following equation.

$J_e < 0.1$ dripping
$J_e \cong 0.1 \sim 10$ laminar
$J_e \cong 10 \sim 500$ turbulent
$J_e > 500$ spray

where Jet number of liquid stream is defined by

$$J_e = \left(\frac{dw^2\rho_g}{\sigma}\right)\left(\frac{\rho_l}{\rho_g}\right)^{0.45} \qquad (1)$$

However, the thickness of liquid jet is gradually becoming thinner owing to the increase of rotation speed. Hereafter, the smoothed length of liquid jet become short although the flow of jet is laminar, as shown in Figure 1 (c) and (d). The phenomenon of this kind can not be found in the liquid jet spouted from small hole in gravitational field. Therefore, from the results of the observations and of the experimental studies as mentioned above, it is clear that the liquid jet spouted from small hole in centrifugal field produce effects on the flow pattern because of the turbulence within the liquid jet and because of the friction of surrounding air. For this reason, the flow pattern of liquid jet in centrifugal field must be defined by Jet number based on the resultant velocity of liquid jet spouted from small hole.

§ 3. Traveling length and contact time of a liquid jet

As shown in **Figure 2,** a liquid jet spouted from a small hole of A_1 in any given moment goes straight on an annular space between double cylinders of radius R and mR, by the resultant velocity w_y due to the composition of the circumferencial velocity w_z and that of the direction of radius w_x. In after θ_1 seconds, the liquid as mentioned above arrives to B_1, and simultaneously a small hole of A_1 travels to A_2. Therefore, the line $A_1B_1(=y_1)$ represents the traveling length of a liquid, and time θ_1 represents the contact time of gas and liquid. However, as mentioned in § 2, the flow pattern of liquid jet must be observed along to the curved line A_2B_1, and also the thickness, the shape and the smooth length of liquid jet must be considered along to the line A_2B_1.

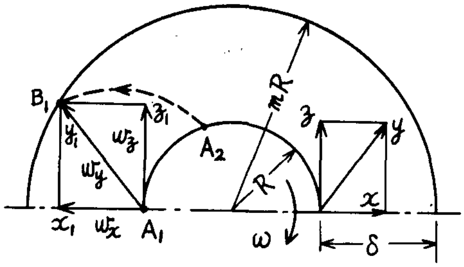

Fig. 2. Mechanism of flying liquid jet in annular space

In the centrifugal gas-liquid contactor, the discharge velocity of the liquid which is spouted from the small holes drilled through the rotating cylinder wall is 1−10 meter per second, and the traveling length of liquid jets in an annular space between the rotating concentric cylinders are several centimeters. Actually the surface velocity of liquid jet immediately after spouted from small hole is slower than that of the center of stream, and the diameter of liquid jet becomes smaller at the downstream. Therefore the author found the traveling length of liquid in accordance with the assumption that the average velocity of discharge liquid is equal to the initial discharge velocity.

As shown in Figure 2, if x, y and z represent the traveling length of liquid in the direction of radius, resultant and tangent, so that the velocity of x-direction, w_x represents the velocity of liquid spouted from small hole, and that of z-direction, w_z is given by the rotation of cylinder.

Therefore, the velocity of liquid spouted from small hole, w_x is given by the following equation.

$$w_x = q/f_c \qquad (2)$$

Where f_c is sectional area of jet stream. The tangential velocity of liquid is given by

$$w_z = 2\pi NR/60 = R\omega \qquad (3)$$

Hereby, from Figure 2, z is given by following equation.

$$z=\frac{2\pi NR}{60}\cdot\frac{f_c}{q}x=\frac{R\omega}{w_x}x \qquad (4)$$

Further, y is calculated by making use of $x^2+z^2=y^2$. That is,

$$y=\sqrt{x^2+z^2}=x\sqrt{\left(\frac{R\omega}{w_x}\right)^2+1} \qquad (5)$$

The boundary conditions are

$$z_1^2+(R+x_1)^2=(mR)^2 \qquad (6a)$$

$$z_1^2+x_1^2=y_1^2 \qquad (6b)$$

Therefore, from Equations (6a) and (6b),

$$y_1^2=(mR)^2-R^2-2Rx_1 \qquad (7)$$

According to Equations (5) and (7),

$$x_1=\frac{R\sqrt{(m^2-1)\left(\frac{R\omega}{w_x}\right)^2+m^2}-R}{\left(\frac{R\omega}{w_x}\right)^2+1} \qquad (8)$$

Therefore, the traveling length of liquid jet, y_l is given by following equation,

$$y_1=\frac{R\sqrt{(m^2-1)\left(\frac{R\omega}{w_x}\right)^2+m^2}-R}{\sqrt{\left(\frac{R\omega}{w_x}\right)^2+1}} \qquad (9)$$

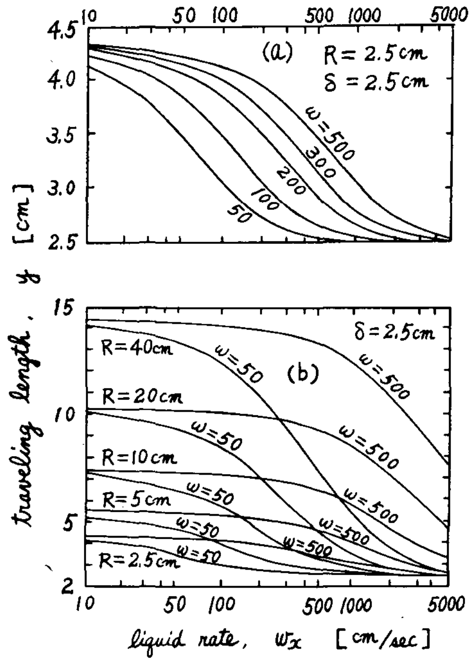

Fig. 3. Flying distance of discharge liquid

Figure 3 shows the relation between the traveling length of liquid jet, y_l, the discharge velocity of liquid spouted from small hole, w and the angular velocity of cylinder, ω, at the radius of cylinder $R=2.5$ cm and the clearance of double cylinders $\delta=2.5$ cm in Figure 3 (a) and at $\delta=2.5$ cm in Figure 3 (b). From these results it is clear that y_l is considerably greater than δ when the discharge velocity of liquid is slow, and the number of rotations is fast. Furthermore, as shown by Figure 3 (b), y_l is greater when the radius of inner cylinder, R is larger. Moreover, the resultant velocity, w_y is given by following equation,

$$w_y=\frac{dy}{d\theta}=w_x\sqrt{\left(\frac{R\omega}{w_x}\right)^2+1} \qquad (10)$$

The contact time of gas and liquid, θ_l is evaluated by using Equations (9) and (10).

$$\theta_1=\frac{y_1}{w_y}=\frac{R\sqrt{(m^2-1)\left(\frac{R\omega}{w_x}\right)^2+m^2}-R}{w_x\left\{\left(\frac{R\omega}{w_x}\right)^2+1\right\}} \qquad (11)$$

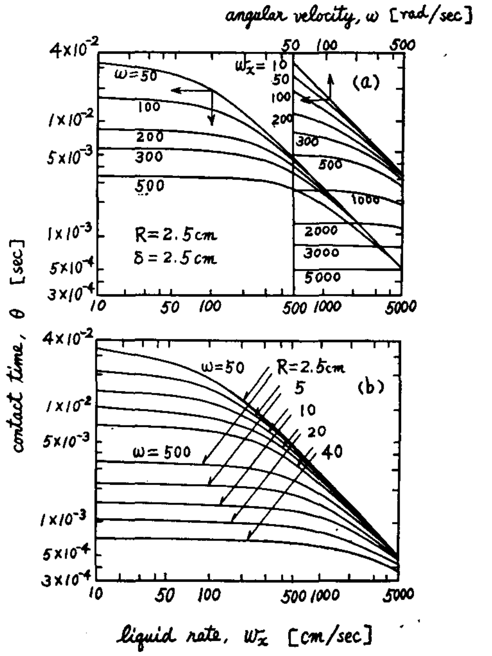

Fig. 4. Contact time between gas and liquid

Figure 4 shows the relation between the contact time, the discharge velocity of liquid and the angular velocity of cylinder. Furthermore, Figure 4 (b) shows the effects of the radius of cylinder.

§ 4. Application of the absorption theory of the past

According to many investigators[5,6,7] it is favourable to think that the process of pure CO_2 gas absorption by a water stream issuing from rotating jet-nozzles conforms rather to the unsteady-state diffusion theory, than to the two film theory, because contact time of gas and liquid is very short in this process. As the flow mechanism of a liquid jet is laminar flow, and the discharge velocity of liquid is large, the diffusion in the direction of flow is negligible. Besides, the penetration length of absorbed gas is very short, and so the absorption process can be treated as one-dimensional diffusion.

In pure CO_2 gas absorption by water, the resistance of gas film is negligible, and liquid film resistance is controlling. Therefore, the average absorption velocity, N_m, during contact time varies from 0 to θ sec., can be expressed by the equation.

$$N_m = 2\sqrt{\frac{D_L}{\pi\theta}}(C^* - C_0) \tag{12}$$

Accordingly, the mass transfer coefficient of the liquid film, k_L, based on the unsteady-state diffusion theory is given as follows:

$$k_L = 2\sqrt{\frac{D_L}{\pi\theta}} \tag{13}$$

Also, the average liquid concentration, C_1, at the point after liquid has traveled during θ sec., can be calculated from the following equation;

$$C_1 - C_0 = N_m a\theta = 2a\sqrt{\frac{D_L\theta}{\pi}}\,(C^* - C_0) \tag{14}$$

where, a is the gas-liquid contact area per unit volume of water jet issuing from rotating small hole. Furthermore, the Murphree efficiency of absorption, E_{ML} is difined by

$$E_{ML} = \frac{C_1 - C_0}{C^* - C_0} \tag{15a}$$

In the case of CO_2-free water, the concentration of CO_2 in liquid, $C_0 = 0$, then, E_{ML} is expressed by Equation (15b),

$$E_{ML} = C_1 / C^* \tag{15b}$$

thus, from Equations (14) and (15),

$$E_{ML} = 2a\sqrt{\frac{D_L\theta}{\pi}} \tag{16}$$

Furthermore, in the case of drop formation, the contact area, a is defined by

$$a = 6/D_p \tag{17a}$$

and in the case of rod-like flow, the contact area, a is given by

$$a = 4/D_c \tag{17b}$$

where D_p and D_c represent diameter of liquid drop and liquid column respectively. Therefore, in these case, E_{ML} can be calculated from Equations (17a)and (17b) easily. However, it is difficult to predict the gas-liquid contact area in various flow pattern of liquid jet.

The factors which influence on the contact area per unit volume of liquid jet are diameter of hole, d, tangential velocity of rotor, Rn, dischage velocity of liquid, w, density of liquid, ρ_l, density of gas, ρ_g, interfacial tension, σ, viscosity of liquid, μ, etc.

Here, considering only d, R, n and w as variables. So, next approximate expression is obtained.

$$a = C\,(d)^{\alpha}(Rn)^{\beta}(w)^{\gamma} \tag{18}$$

§ 5. Experimental apparatus and procedure

The flow sheet of the experimental apparatus and a brief sketch of the rotating components are shown in **Figures 5 and 6.** Water at 20°C, issuing from a constant-head water tank, *1*, flows into a rotating cylinder, *10*, via a hollow shaft, and then into an annular space by passing through several small holes drilled through the wall of the inner cylinder. *10*. It then absorbs CO_2 gas during its flight between the annular space formed by the inner and outer cylinders, and small part of it is sampled through the

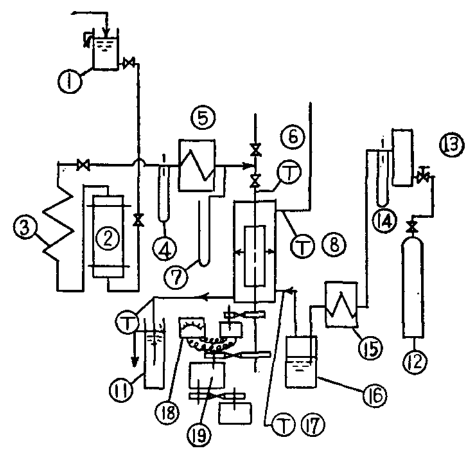

Fig. 5. Flow sheet

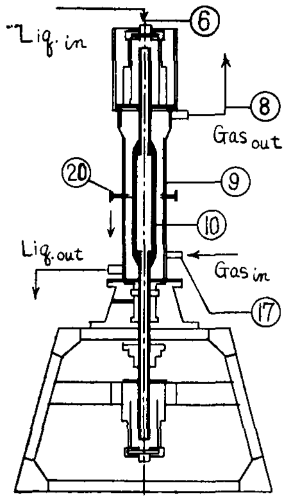

Fig. 6. Experimental apparatus

sampling pipe, *20*, further, large part of it flows down along the wall of the outer cylinder, *9*.

Meanwhile, CO_2 gas from a bomb, *12*, flows into the rotating apparatus after passing through a vapor saturating tank, *16*, and the gas inlet pipe, *17*, at 20°C. It then flows through the annular space formed by the inner and outer cylinders, cross-currently to the water jet. The gas is absorbed during its contact with spouting water and purged off from the outlet pipe, *8*.

In this experiment, the head of the sampling pipe, *20* is covered by thin cloth and water absorbing CO_2 gas is sampled through this cloth. Thereby, CO_2 gas did not enter into the sampling pipe in the appropriate sampling speed. The sample was analyzed by first making $BaCO_3$ precipitate by the reaction of a saturated water solution of $Ba(OH)_2$ with carbon dioxide. The amount of CO_2 absorbed was then determined by back titration with hydrochloric acid.

Furthermore, the variables changed in this experiment are shown in **Table 1.**

Table 1

Rotor O. D. D_1 [cm]	Stator I. D. D_2 [cm]	Hole dia. d [mm]	Hole number n_h	Hole total area A [cm²]	Clearance δ [cm]	Liquid velocity w [cm/sec]	Gas velocity v [cm/sec]	Revolution speed N [r p. m]
5.1	16.2	0.502	8	0.0158	1.0—3.0	190— 950	5.0	300—3000
5.1	16.2	0.714	8	0.3200	1.0—4.0	94— 625	5.0	
5.1	16.2	0.901	8	0.0510	1.0—5.0	98— 590	1.0—10	
5.1	16.2	0.915	16	0.1052	2.0	95— 500	5.0	
5.1	16.2	1.113	8	0.0778	2.0	77— 463	5.0	
5.1	16.2	2.006	8	0.2528	2.0	55— 240	5.0	
5.1	16.2	2.006	4	0.1264	2.0	79— 240	5.0	
5.1	10.1	0.839	8	0.0442	1.0—2.0	300—1100	5.0—40	
5.1	10.9	0.839	8	0.0442	2.5	600—1200	10—40	
7.65	16.2	0.752	8	0.0352	2.0	88— 290	5.0	

§ 6. Experimental results

The experimental results were expressed in terms of the absorption efficiency, E_{ML} defined by Equation (15a). Further, considering the vapor pressure of water at 20°C, saturated concentration of CO_2 in liquid, C^* is 3.81×10^{-2} mole/litter.

a) Effect of gas flow rate.

Within the experimental range of the average mass velocity of gas, $G=0.002-0.8 g/cm^2 sec.$, no effect of the velocity of the gas flow moving axially through the annular space on the efficiency was observed. This is probably due to the fact that the absorption of pure CO_2 gas by water is a liquid-film controlling process, and to the fact that the liquid would not be disturbed by the small rate of gas flow.

Therefore the experiments hereafter were carried out at $G\doteqdot0.01 g/cm^2 sec.$

b) Effect of revolution speed of rotor.

The effect of revolution speed on absorption efficiency, E_{ML} is studied experimentally at various conditions of diameter of holes, number of holes, clearance between rotor and stator. An example of the experimental results is shown in **Figure 7.** It is found from Figure 7 that E_{ML} increases generally as the revolution speed of

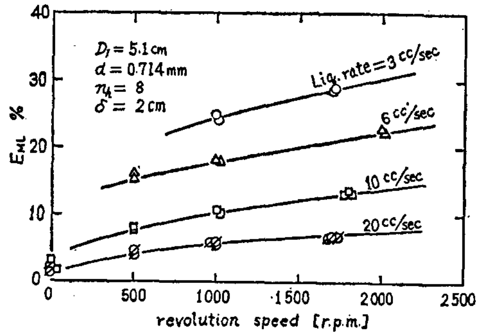

Fig. 7. Effect of revolution speed on absorption efficiency E_{ML}

rotor becomes greater, and also E_{ML} increases as the liquid velocity decreases.

Considering these experimental results, as shown by Figures 3 and 4, traveling length of liquid, y, increases, and gas-liquid contact time, θ, decreases as the revolution speed becomes greater. From these results, it is clear that the contact area per unit volume of water jet becomes greater as the revolution speed becomes greater.

c) Effect of traveling length and clearance.

Figure 8 shows the effect of the traveling length of liquid, y, and of the clearance between rotor and stator, δ. In the figure, E_{ML} is plotted against y and δ, using the velocity of liquid as a parameter. The solid lines in the figure represent the experimental values of the effect of traveling length, y, calculated by Equation (9) on E_{ML}.

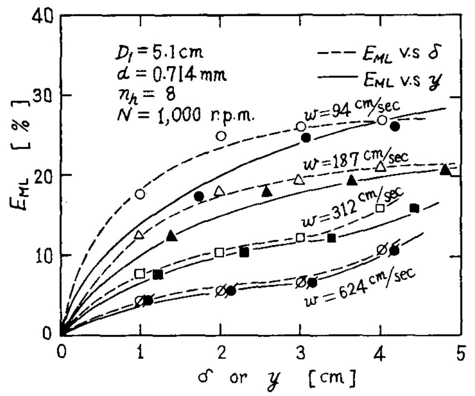

Fig. 8. Effect of clearance or flying distance on E_{ML}

It is clear that Murphree absorption efficiency, E_{ML}, increases as the traveling length of liquid becomes greater. From the results of these experiments, the gas absorption rate by water observed to be large immediately after the liquid was spouted from the hole. However the points plotted in the figure deviate in the direction of increasing E_{ML} when the traveling length and the discharge velocity of liquid are large. This is probably due to the fact that the stream of liquid is disturbed by the large discharge velocity and the traveling length.

d) Effect of velocity of liquid.

Figure 9 shows the effect of liquid velocity, w, on E_{ML}. From the figure, it is clear that the liquid velocity has large effect on absorption efficiency and the smaller liquid velocity is the better absorption efficiency at constant speed of revolution. Considering these experimental results, this is obvious from the Figures 3 and 4 that the contact time and the traveling length of liquid increases as discharge velocity of liquid becomes smaller when the revolution speed of rotor and the clearance between two cylinders are constant. Therefore discharge velocity may have effects on E_{ML}.

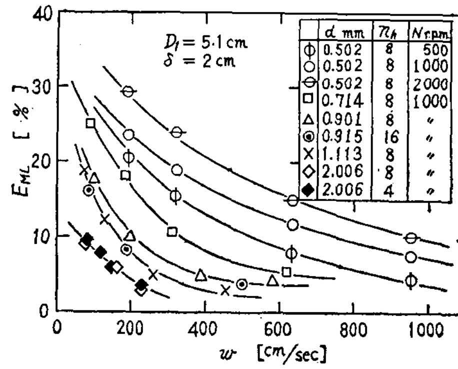

Fig. 9. Effect of liquid velocity, hole diameter and hole number on E_{ML}

e) Effect of diameter of hole.

From Figure 9, it is evident that the diameter of hole has large effect on E_{ML} and smaller diameter of hole is the better absorption efficiency. This is probably due to the fact that the contact area per unit volume of liquid increases as the diameter of hole becomes smaller, when the velocity of liquid spouted from hole is constant.

f) Effect of number of holes.

As shown in Figure 9, the experimental results agree fairly well when the number of holes, n_h was four and eight with the diameter of holes at *2.0 mm*. From the above results, it is clear that the effect of number of holes is not recognized.

g) Effect of diameter of rotor.

The effect of diameter of rotor on E_{ML} is shown in **Figure 10.** In the figure, E_{ML} is plotted against the tangential velocity of liquid, $2\pi nR$, using the discharge velocity, w, as a parameter. From the results of these experiments, it is clear that the effect of diameter of rotor is not recognized, when both $2\pi nR$ and w are constant at the case of the different diameter of rotor.

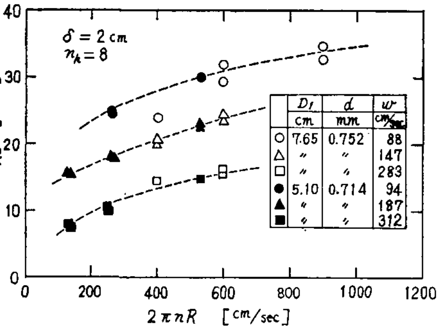

Fig. 10. Effect of rotor diameter on E_{ML}

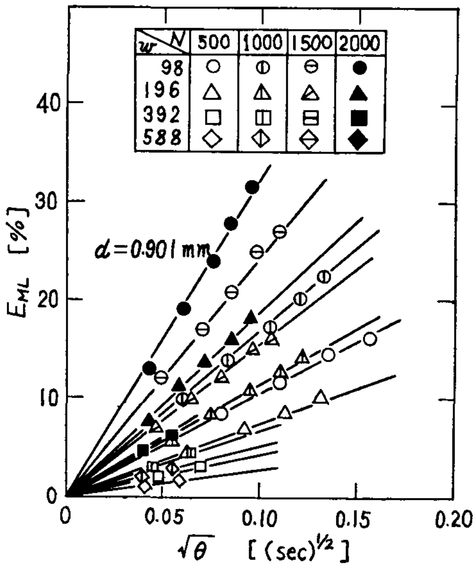

Fig. 11. Relation between contact time $\sqrt{\theta}$ and E_{ML}

h) Effect of contact time.

As an example of the experimental results, **Figure 11** shows the relation between the gas-liquid contact time, θ, and the absorption efficiency, E_{ML}, when the diameter of hole is *0.9 mm.* In this case, θ were evaluated from Equation (11). From this figure it is clear that the plot of E_{ML} versus $\sqrt{\theta}$ leads to a straight line through an origin. However, according to Equation (16), the theoretical absorption efficiency, E_{ML} should change proportional to $\sqrt{\theta}$, and the data in this work coincide with the relation obtained from this theoretical equation within experimental accuracy. Therefore, it is obvious that this diffusion equation is valid for such short contact time as shown in the figure, and also that the process of pure CO_2 gas absorption by a water stream issuing from rotating jet-nozzles conforms to the unsteady-state diffusion theory.

§ 7. Conclusions

As a fundamental study on mass transfer in the centrifugal gas-liquid contactor, pure CO_2 gas absorption by a rotating cylindrical jet were studied.

The results are as follows:

1) It is confirmed theoretically that the traveling length of liquid jet is represented by Equation (9), and the contact time of gas and liquid, by Equation (11). Furthermore, the Murphree efficiency of absorpsion, E_{ML} is defined by Equation (16).

2) It is favourable to think that the process of pure CO_2 gas absorption by a water stream issuing from the small holes drilled through a rotating cylinder wall conforms rather to the unsteady-state diffusion theory, than to the double film theory which is generally widely recognized.

3) The gas absorption rate by water jet spouting from rotating small hole was observed to be large immediately after the liquid was spouted from the hole. Therefore, for the practical designing of this kind of contactor, it would be prepare a multi-rotor-type contactor in order to make many jets of liquid as possible.

Nomenclature

a : contact area per unit volume of liquid [cm^2/cm^3]
C_0 : concentration of CO_2 in liquid [g-mole/cm^3]
C^* : saturated concentration [g-mole/cm^3]
D_1, D_2: diameter of cylinder [cm]
D_C : diameter of liquid column [cm]
D_P : diameter of liquid drop [cm]
D_L : diffusion coefficient in liquid phase [cm^2/sec]
d : diameter of hole [cm]
E_{ML}: Murphree absorption efficiency [——]
f_c : sectional area of stream [cm^2]
J_e : $=(dw^2\rho_g/\sigma)(\rho_l/\rho_g)^{0.45}$, Jet number [——]
k_L : liquid film mass transfer coefficient [cm/sec]
n : revolution speed [r·p·s·]

N_m : mean rate of absorption [g-mole/cm^2 sec]
R, mR: radius of inner and outer cylinder [cm]
w : discharge velocity of liquid [cm/sec]
x, y, z, : flying distance of discharge liquid [cm] (refer to Figure 2)
α, β, γ: exponent in Equation (18) [——]
δ : clearance between two cylinders [cm]
θ : contact time [sec]
ρ : density [g/cm^3]
ω : angular velocity [1/sec]

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