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# FLOW OF ENTRAINED LIQUID THROUGH SMALL HOLES IN PIPE WALL AT HIGH GAS VELOCITY

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***Key Words***: Fluid Mechanics, Two Phase Flow, Annular Flow, Discharge Coefficient, High Gas Velocity, Pressure Distribution

In a previous paper,[1] the authors reported experimental and theoretical studies of pressure drop and liquid holdup for a recently developed gas-liquid contacting device with a relatively short verical pipe, which can be used for much higher gas velocities than the flooding velocities of usual gas-liquid contacting equipment. Entrainment of liquid into the pipe, however, is induced mainly by blowing gas into it. Thus the liquid flow rate is an unknown parameter.

In the present study, pressure along the pipe axis was measured to determine the position of the hole through which liquid flows. Further, the relationship for the discharge coefficient of entrained liquid through holes is obtained, using the correlation of liquid holdup proposed previously by the authors.[1]

## 1. Experimental

The experimental apparatus and the procedure used are the same as those described in a previous paper,[1] except for the pressure measurements along the pipe axis as shown in **Fig. 1**. The pressure difference between pipe and column ($\Delta P = P_1 - P_2$) was measured by using a brass tube of 3 mm outer diameter which could be traversed along a pipe axis and which had three 0.5 mm-diameter holes arranged at 120 degrees to each other, and a pressure tap on the side of the column. Details of the pipes and the physical properties of the liquids employed are shown in **Tables 1** and **2**, respectively.

## 2. Results and Discussion

**Figure 2** shows an example of axial distributions of pressure differences between pipe and column without liquid flow. The pressure difference along the pipe axis varies with the distance from the lower end of the pipe and takes a minimum at $Z_D/D$ of about 0.42; this was true of all of other pipes employed in the present experiment. Hence, holes were drilled at the position of $Z_D/D = 0.42$, because the flow rate of liquid through the holes may become maximum, suitable for the treatment of high gas capacity.

**Figure 3** shows a correlation of the pressure difference at $Z_D/D = 0.42$ for various pipe diameters. From the figure, we obtain

$$|\Delta P| = 0.23(\rho_g U_g^2)(Z_p/D)^{-0.14}(D/D_c)^{-0.28} \quad (1)$$

The rate of liquid flow through holes can be expressed as follows by setting up a differential equation describing the flow of liquid over a system of

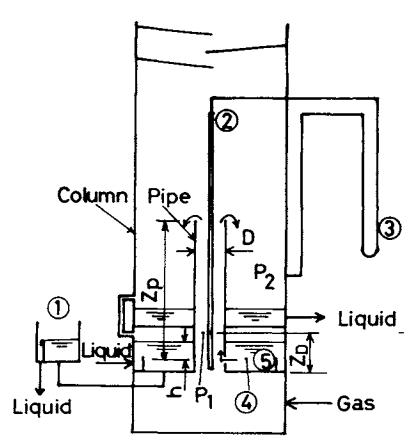



**Fig. 1.** Measuring device for pressure difference and liquid flow rate through holes. 1, head tank; 2, brass tube; 3, manometer; 4, liquid vessel; 5, baffle.

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Table 1. Details of pipes employed

| $D$ [m] | $Z_p$ [m] | $Z_p/D$ [—] | $d_h \times 10^3$ [m] ($n$=1–4) |
|---|---|---|---|
| 0.0292 | 0.062–0.390 | 2.12–13.36 | |
| 0.0294 | 0.353–0.399 | 12.01–13.57 | 1.8, 3.8, 5.8, 7.8, 10.8 |
| 0.0346 | 0.100–0.420 | 2.89–12.14 | |
| 0.0470 | 0.145–0.500 | 3.09–10.64 | |
| 0.0492 | 0.532–0.652 | 10.81–13.25 | 1.8, 3.8, 5.8, 7.8, 10.8 |
| 0.0505 | 0.150–0.583 | 2.97–11.54 | |
| 0.0550 | 0.055–0.550 | 1.00–10.00 | |
| 0.0810 | 0.137–0.649 | 1.69– 8.01 | |

Table 2. Physical properties of liquids

| Liquid | Density $\rho_l$ [kg/m$^3$] | Viscosity $\mu_l$ [Pa·s] | Surface tension $\sigma$ [N/m] |
|---|---|---|---|
| Water | 1000 | 0.001 | 0.0072 |
| Ethanol aq. soln. | 989.0 | 0.0015 | 0.0543 |
| Glycerine aq. soln. I | 1031.0 | 0.0016 | 0.0630 |
| Glycerine aq. soln. II | 1093.0 | 0.0038 | 0.0553 |

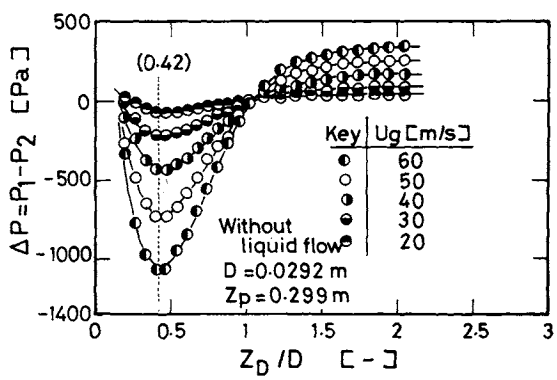



Fig. 2. Axial profile of pressure difference between pipe and column.

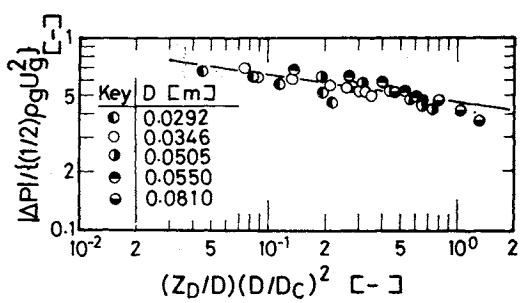



Fig. 3. Correlation of absolute pressure difference.

thickness $dZ$ shown in **Fig. 4** and integrating it over hole area, considering the liquid holdup $\varphi$ in the pipe and using Eq. (1), i.e., the correlation of pressure drop

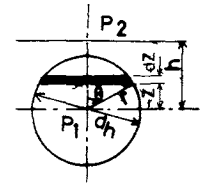



Fig. 4. Schematic drawing of hole section.

without liquid flow:

$$Q = C_d(\pi d_h^2/4)n[2\{|\Delta P|/\rho_l + g(h-\varphi Z_p)\}]^{1/2} \times \int_0^{\pi} \sin^2\theta \left[1 - \frac{\cos\theta}{2\{|\Delta P|/\rho_l + g(h-\varphi Z_p)\}}\right]^{1/2} d\theta \quad (2)$$

Integration of Eq. (2) using the binomial theorem and taking the terms having an exponent less than 4 gives approximately

$$Q = C_d(\pi/4)d_h^2 n\sqrt{2\{|\Delta P|/\rho_l + g(h-\varphi Z_p)\}} \cdot B \quad (3)$$

where

$$B = 1 - \frac{1}{32}\left[\frac{\rho_l g d_h}{2\{|\Delta P| + g(h-\varphi Z_p)\rho_l\}}\right]^2 - \frac{5}{1024} \times \left[\frac{\rho_l g d_h}{2\{|\Delta P| + g(h-\varphi Z_p)\rho_l\}}\right]^4 \quad (4)$$

Under the present conditions, we may assume $B=1$. Data calculated from Eq. (3) together with Eq. (1) are represented in **Fig. 5**, where the liquid holdups are estimated by the correlation proposed in the previous paper.[1] They indicate that discharge coefficients increase with increasing liquid velocity through holes and decreasing gas velocity. It may be anticipated that the discharge coefficient approaches a constant value, indicated by $C_{d\infty}$ in the same figure. The correlation of $C_{d\infty}$ is expressed by the following equation:

$$C_{d\infty} = 1 - 1.7(d_h/D) \quad (5)$$

**Figure 6** illustrates the correlation of discharge coefficients. The data are well correlated by the following equation:

$$C_d/C_{d\infty} = 1 - \exp\{-25(U_l/U_g)(d_h/D)^{-0.4}\} \quad (6)$$

**Nomenclature**

| | | | |
|---|---|---|---|
| $C_d$ | = | discharge coefficient | [—] |
| $C_{d\infty}$ | = | discharge coefficient showing constant value | [—] |
| $D_c$ | = | hydraulic equivalent diameter of column | [m] |
| $d_h$ | = | hole diameter | [m] |
| $h$ | = | liquid depth | [m] |
| $n$ | = | number of holes | [—] |
| $P_1$, $P_2$ | = | pressure in pipe and column without liquid flow | [Pa] |
| $\Delta P$ | = | pressure difference $= P_1 - P_2$ | [Pa] |
| $Q$ | = | volumetric liquid flow rate through holes | [m$^3$/s] |
| $r$ | = | hole radius | [m] |
| $U_g$ | = | superficial gas velocity based on empty pipe | [m/s] |

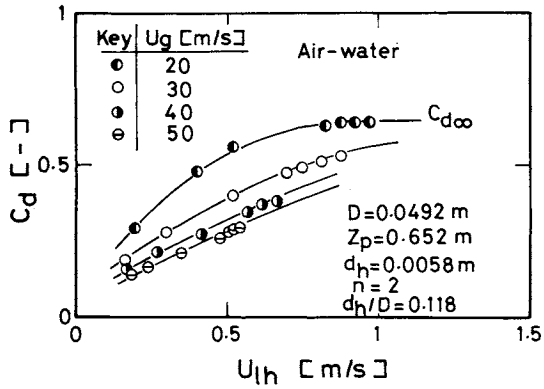



**Fig. 5.** Discharge coefficient.

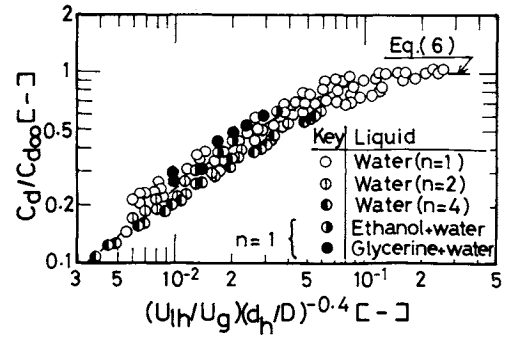



**Fig. 6.** Correlation of discharge coefficient.

| | | | |
|---|---|---|---|
| $U_l$ | = | superficial liquid velocity based on empty pipe | [m/s] |
| $U_{lh}$ | = | liquid velocity through holes | [m/s] |
| $Z$ | = | distance | [m] |
| $Z_D$ | = | measuring position for pressure in pipe | [m] |
| $\theta$ | = | angle | [rad] |
| $\varphi$ | = | liquid holdup | [—] |

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# ON THE PERMEATION MECHANISM OF ULTRAFILTRATION WITH AN ANODIC ALUMINUM OXIDE MEMBRANE

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*Key Words*: Ultrafiltration, Pore Model, Permeation Mechanism, Aluminum Oxide Membrane, Inorganic Membrane

## Introduction

The pore model originally proposed by Ferry[3] for the mechanism of ultrafiltration has been developed by a number of investigators.[8,9,12] However, the validity of the model has not been sufficiently examined since most investigators in past experimental work employed polymer membranes with complex pore structures.

Recently, the authors reported a preparation method for an inorganic membrane, porous anodic aluminum oxide film,[4] which had a well-defined pore structure in terms of the straightness of the pores and the narrow distribution in pore size. The present work is aimed at examining the validity of the pore theory using this membrane.

## 1. Experimental

To improve the poor resistance of the aluminum oxide membrane to water,[11] the surface of the membrane was chemically modified by a condensation reaction* prior to experiments. **Figure 1** shows the efficiency of the surface modification observed in the preliminary experiments of water permeation. The reduction in permeation rate that occurred with the unmodified membrane scarcely appeared with the modified one.

Experiments were conducted in a permeation cell equipped with a stirrer at its center. A modified membrane was located at the bottom of the cell. **Figure 2** presents the dimensions of the cell. In each run, dilute aqueous solutions were used. The solutes used were monodispersed polyethylene glycol (PEG) of three different molecular weights, bovine serum hemoglobin and bovin serum $\gamma$-globulin. The concentration of the aqueous solutions was adjusted to

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* Stearic acid was used as condensation agent, and dicyclohexylcarbodiimide as a condensation catalyst. Stearic acid reacts with hydroxyl groups existing on the surface of aluminum oxide substances in the presence of the catalyst.[7]