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SOME CHARACTERISTICS OF GAS–LIQUID FLOW IN NARROW RECTANGULAR DUCTS

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Abstract—Flow regime, void fraction, slug bubble velocity and pressure loss were measured for rectangular ducts with a narrow gap and a large aspect ratio. The neutron radiography technique was used to visualize the flow and the void fraction was obtained by image processing. The void fraction was well-correlated by the drift flux model with the existing correlation for the distribution parameter, which was about 1.35. Similar results were obtained for the slug bubble velocity, however the distribution parameter was in the range 1.0–1.2. The frictional pressure loss was well-correlated by the Chisholm–Laird correlation. In collaboration with previously obtained data, it was found that the Chisholm's parameter C, however, changed from 21 to 0 as the gap decreased.

Key Words: gas–liquid flow, rectangular duct, narrow gap, flow regime, void fraction, pressure loss, neutron radiography

1. INTRODUCTION

The coolant channel of an MTR-type fuel element has a rectangular cross-sectional shape with a very narrow gap and a large aspect ratio. It is anticipated that the characteristics of two-phase flow in such a narrow slit differ from those in other channel geometries, because of the significant restriction of the bubble shape which, consequently, may affect the heat removal by boiling under abnormal operating conditions. Although much work has been performed on gas–liquid two-phase flows in round tubes, only a limited amount is available for test sections with a narrow gap or a non-circular cross-sectional shape (Martin 1972; Iida & Takahashi 1976; Jones & Zuber 1979; Sadatomi *et al.* 1982; Troniewski & Ulbrich 1984; Mishima *et al.* 1988). In view of this, the flow regime, void fraction, average velocity of slug bubbles and the pressure loss have been investigated for two-phase flow in rectangular ducts with a narrow gap ranging from 1.0 to 5.0 mm.

2. EXPERIMENTAL

2.1. Test Rig

The test loop is shown schematically in figure 1, and is the same as described previously (Mishima *et al.* 1988). Air was supplied by a compressor and was introduced into a mixing chamber through an injection nozzle. The entrance configuration is shown in figure 2. The injection nozzle for the test section with a 1 mm gap consisted of 14 capillary tubes (0.8 mm o.d.) mounted in a line to fit the flow channel (as shown in figure 2), and that for a 2.4 mm gap consisted of 10 capillary tubes (1 mm o.d.). The injection nozzle for the test section with a 5 mm gap had the same slit (2.4 × 30 mm) as described previously (Mishima *et al.* 1988). The air and purified water were mixed in the mixing chamber and the mixture flowed upwards through the test section. After flowing through the test section, the air was released into the atmosphere through a separator, while the water was circulated by a centrifugal pump. The flow rates of the air and water were measured with a float-type flowmeter and a turbine flowmeter, respectively.

The test sections used in the present experiment were rectangular ducts made of transparent acrylic resin. Three test sections were fabricated, with nominal gaps of 1.0, 2.4 and 5.0 mm. The gaps were measured with a clearance gauge to be 1.07, 2.45 and 5.00 mm, respectively. The width and the length of the test sections were 4 and 200 cm, respectively. In the measurements of void fraction, however, the test sections were made of aluminum so that the neutron radiography

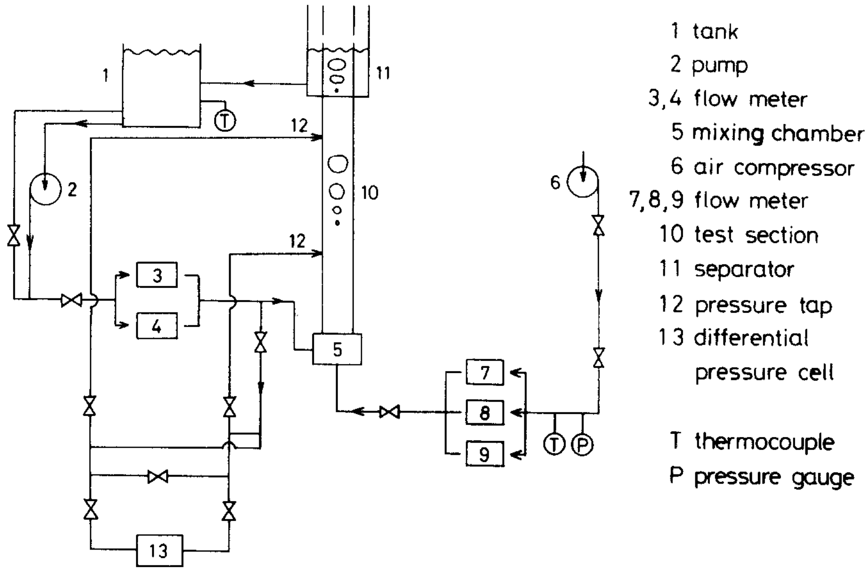

Figure 1. Flow diagram of the test loop.

technique could be applied (Mishima *et al.* 1988). In those experiments, the length of the test section was 140 cm.

2.2. *Measurement*

2.2.1. *Flow regimes*

The bubble behavior and the overall pattern of flow were observed by a high-speed videocamera at a speed of 200 or 1000 frames/s. The images were played back in slow motion for detailed observation.

2.2.2. *Void fraction*

The void fraction was measured with use of the neutron radiography and image processing techniques. The flow in the aluminum test section was visualized by the neutron television system and the images were processed to calculate the channel-average void fraction. These methods have been described previously and it has been shown that no systematic deviations were observed in

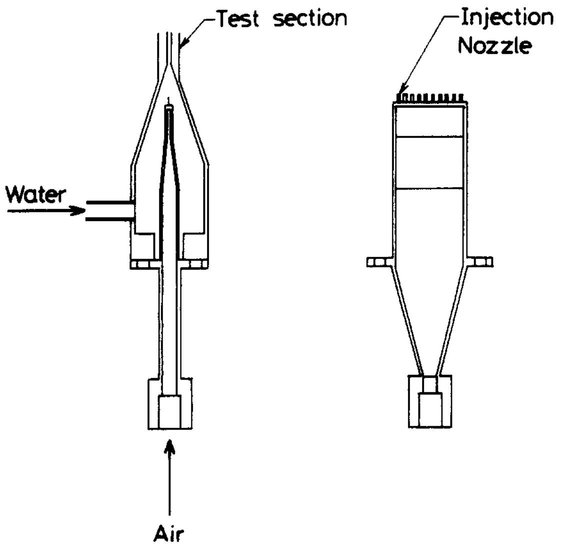

Figure 2. Configuration of the mixing chamber and the injection nozzle.

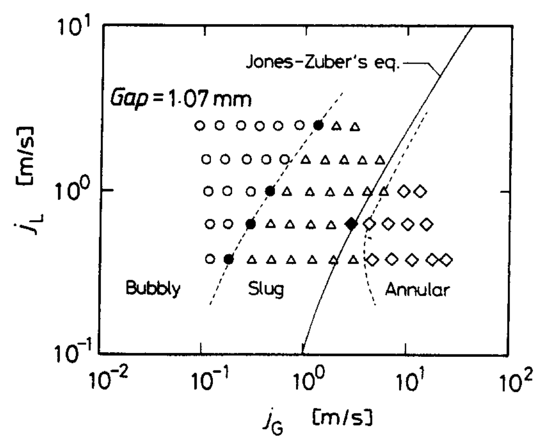

Figure 3. Flow regime map for the test section with a 1.07 mm gap.

void fractions obtained by the image processing methods (combined either with optical or with neutron radiographic methods) and the conductance probe method (Mishima *et al.* 1988). The error in the void fraction measured by the image processing method was estimated to be within 5%, except at very low void fractions.

2.2.3. *Slug bubble velocity*

The average velocity of slug bubbles was measured from the time taken for slug bubbles to rise a given distance in the slow motion picture. The velocity of small and cap bubbles was not taken into account in this measurement. The overall error in the measurement is estimated to be within 20%.

2.2.4. *Pressure loss*

Two pressure taps were located at 50 and 150 cm from the entrance of the test section. The pressure difference between the taps was measured with a differential pressure transducer to within 5% error

3. RESULTS

3.1. *Flow Regimes*

Four flow regimes were specified, i.e. bubbly, slug, churn and annular flows. The aspect ratio of the duct was so large and the gap so narrow that small bubbles, cap bubbles and slug bubbles looked as if they were crushed between the two walls. Thus, the flow regime was determined based upon the shape of the bubbles observed through the wider wall. When bubbles of pancake shape and/or crushed cap bubbles were observed, the flow regime was called bubbly flow. Crushed slug bubbles characterized slug flow. The discrimination between slug and churn flow was rather subjective; however, when the void fraction was increased, the distance between the slug bubbles became so small that the noses of the slug bubble became unstable in the wake of the preceding ones. This means that slug bubbles began to lose their identity at this condition. Therefore, the flow was called churn flow when the round noses of the slug bubbles became unstable and noticeably deformed. The definition of annular flow was similar to the conventional one.

Figures 3, 4 and 5 show flow regime maps for the test sections with a 1.0, 2.4 and 5.0 mm gap, respectively. The solid symbols mean that the flow regime indicated was rather fuzzy. The broken lines denote the approximate locations of the boundaries between the flow regimes and the solid line denotes the boundary between the slug and annular flows predicted by the Jones–Zuber equation (Jones & Zuber 1979). It can be seen that the Jones–Zuber equation reproduces well the boundary for slug and annular flows. It is also noted that churn flow is not observed when the gap is 1.0 mm.

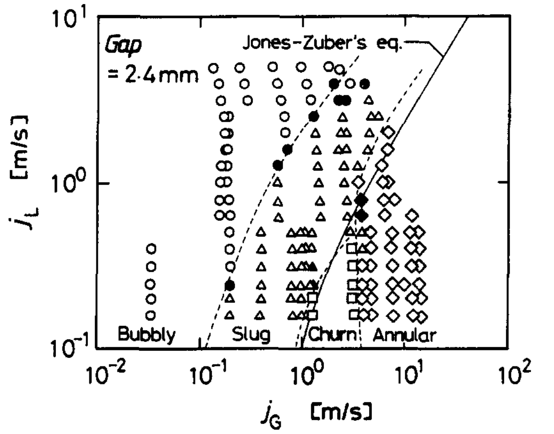

Figure 4. Flow regime map for the test section with a 2.4 mm gap.

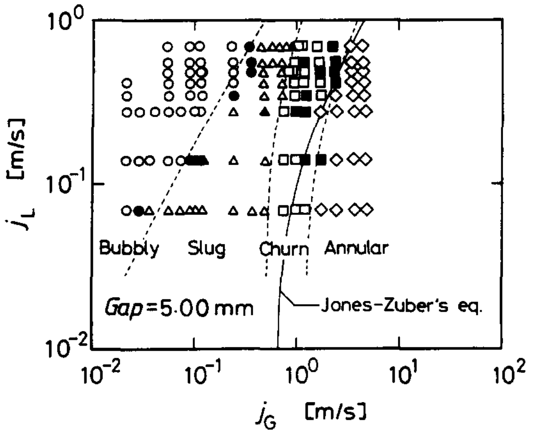

Figure 5. Flow regime map for the test section with a 5.0 mm gap.

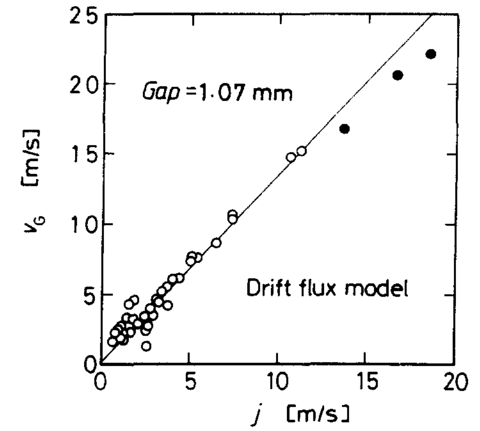

Figure 6. Correlation of the void fraction for the test section with a 1.07 mm gap.

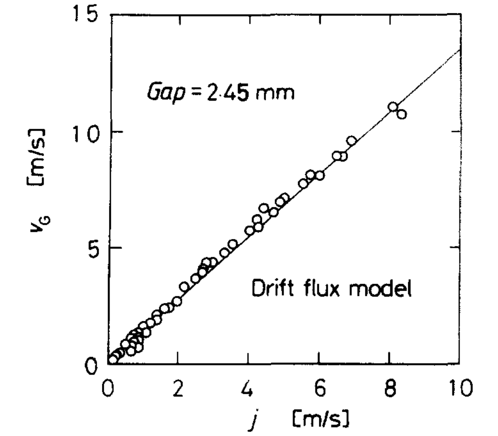

Figure 7. Correlation of the void fraction for the test section with a 2.45 mm gap.

3.2. Void Fraction

The void fraction was correlated in view of the drift flux model (Jones & Zuber 1979):

$$v_G = j_G/\epsilon = C_0 j + (0.23 + 0.13s/w)\sqrt{\Delta\rho g w/\rho_L}, \qquad [1]$$

where v_G is the gas velocity, j_G is the superficial gas velocity, j_L is the superficial liquid velocity, ϵ is the channel-average void fraction, C_0 is the distribution parameter, j is the mixture volumetric flux ($=j_G + j_L$), ρ_L is the liquid density, $\Delta\rho$ is the difference in the densities of the two phases, s is the gap of the flow channel and w is the width of the flow channel. The second term on the r.h.s. of [1] gives the drift velocity for bubbles in a rectangular duct obtained by Griffith (1963). The distribution parameter C_0 is 1.2 according to Jones & Zuber (1979), while Ishii (1977) proposed the following equation for the distribution parameter for rectangular ducts:

$$C_0 = 1.35 - 0.35\sqrt{\rho_G/\rho_L}. \qquad [2]$$

The experimental results are shown in figures 6 and 7 for the 1.0 and 2.4 mm gaps, respectively. It is seen from the figures that the void fraction can be well-correlated by the drift flux model with the distribution parameter given by [2]. It should be noted also that the solid symbols in figure 6 denote that the corresponding flow regime is annular flow, in which C_0 is about 1.0.

On the other hand, Moriyama & Inoue (1991) recently reported larger values of the distribution parameter C_0 for extremely narrow gaps. Figure 8 shows a comparison for the distribution

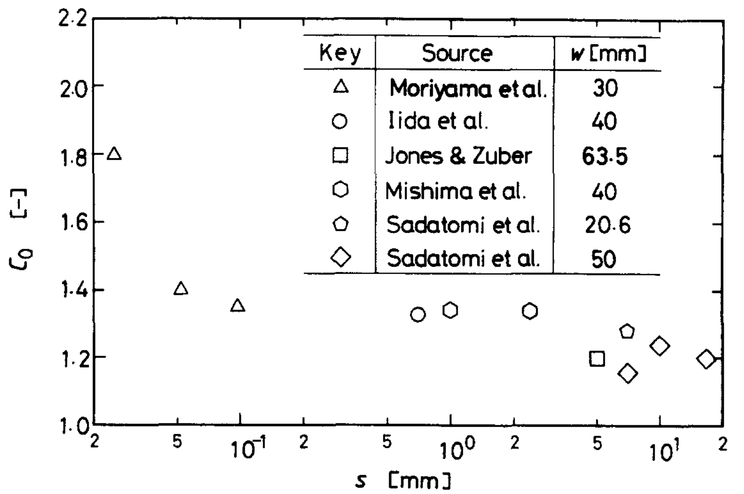

Figure 8. The distribution parameter for a narrow rectangular duct as a function of the gap.

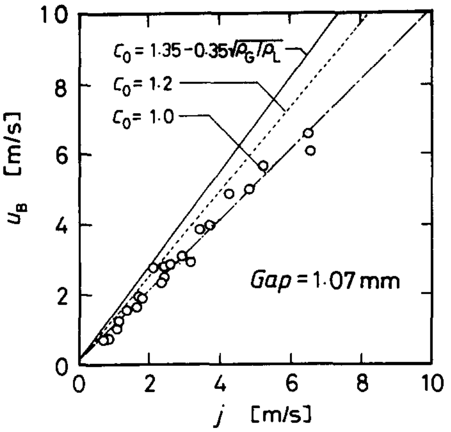

Figure 9. Slug bubble velocity in the test section with a 1.07 mm gap.

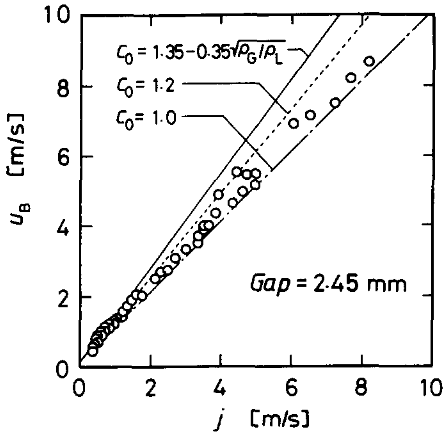

Figure 10. Slug bubble velocity in the test section with a 2.45 mm gap.

parameter between the existing data (Iida & Takahashi 1976; Jones & Zuber 1979; Sadatomi *et al.* 1982; Mishima *et al.* 1988; Moriyama & Inoue 1991). A tendency can be observed for the distribution parameter to become large when the gap is extremely small, otherwise it is predicted by [2]. When the gap is >5.0 mm, the distribution parameter appears to be 1.2. On the contrary, the data base for the Ishii correlation [2] includes data for boiling steam–water flow in ducts with an 11 mm gap. It is known that the distribution parameter is a function of the velocity and void profiles; these profiles may change, depending upon the duct spacing, fluid properties and the existence of phase change, and so distribution parameter changes. More data are needed on this point.

3.3. Bubble Velocity

The average velocity of slug bubbles was correlated by the drift flux model. The results are shown in figures 9, 10 and 11 for the 1.0, 2.4 and 5.0 mm gaps, respectively. The figures indicate that the drift velocity appears to be constant for all the gaps used in the present experiment, a value which agrees with the Griffith (1963) correlation. The distribution parameter C_0, however, is in the range 1.0–1.2, which is smaller than that for the void correlation. This may be explained by the fact that the present measurement of velocity takes only the slug bubbles into account. This means that the contribution of the small bubbles in the liquid continuum is neglected. This situation is similar to idealized slug flow, in which the distribution parameter is $\leqslant 1.21$ (Jones & Zuber 1979).

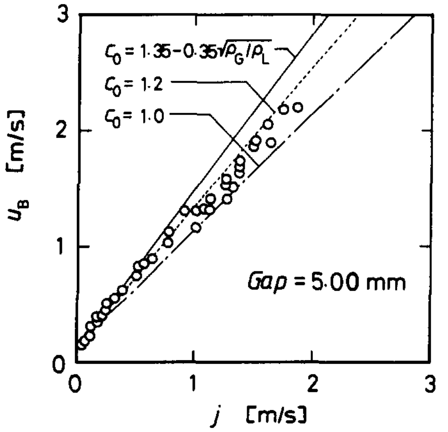

Figure 11. Slug bubble velocity in the test section with a 5.0 mm gap.

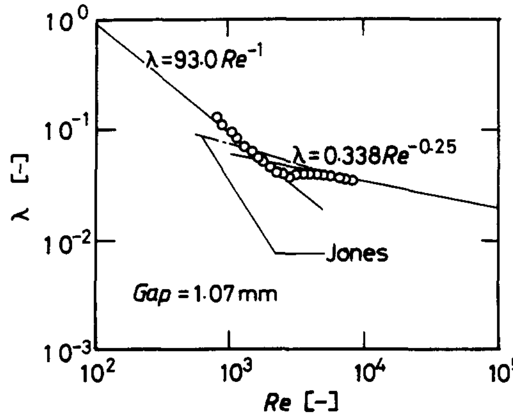

Figure 12. Single-phase friction factor for the test section with a 1.07 mm gap.

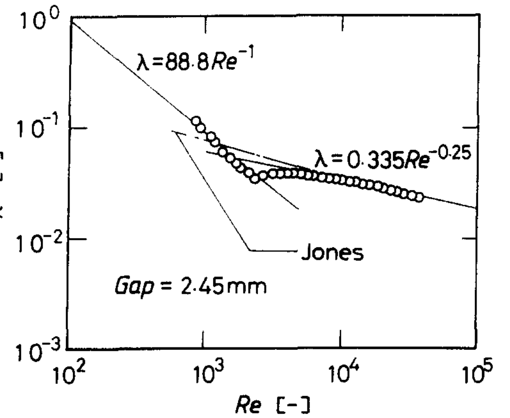

Figure 13. Single-phase friction factor for the test section with a 2.45 mm gap.

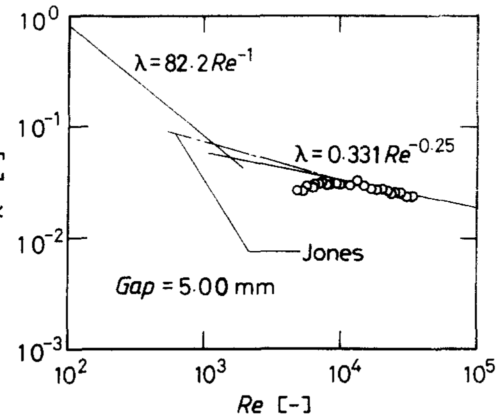

Figure 14. Single-phase friction factor for the test section with a 5.00 mm gap.

3.4. Pressure Loss

3.4.1. Single-phase pressure loss

Since the friction factor for single-phase flow in a narrow rectangular duct is different from that in a round tube, the pressure loss for single-phase flow was measured as a reference and compared with the existing results.

Usually the friction factor for single-phase flow is expressed by the following equations:

$$\lambda = C_V \mathrm{Re}^{-1} \quad \text{for laminar flow} \qquad [3]$$

and

$$\lambda = C_T \mathrm{Re}^{-0.25} \quad \text{for turbulent flow,} \qquad [4]$$

where λ is the friction factor and Re is the Reynolds number.

For the friction factor for single-phase flow in a non-circular channel, Sadatomi *et al.* (1982) took account of the effect of the channel geometry and proposed the following relationship between the coefficients C_V and C_T:

$$C_T = C_{T0}(0.0154C_V/C_{V0} - 0.012)^{1/3} + 0.85, \qquad [5]$$

where $C_{V0} = 64$ and $C_{T0} = 0.3164$—which are taken from the friction factors for a smooth round tube. Since C_V is given by the theoretical solution for laminar flow in a rectangular duct, C_T is calculated from [5]. Jones (1976) also examined turbulent flow data for rectangular ducts and proposed a modified Prandtl–Karman equation for smooth round tubes to take account of the effect of the aspect ratio.

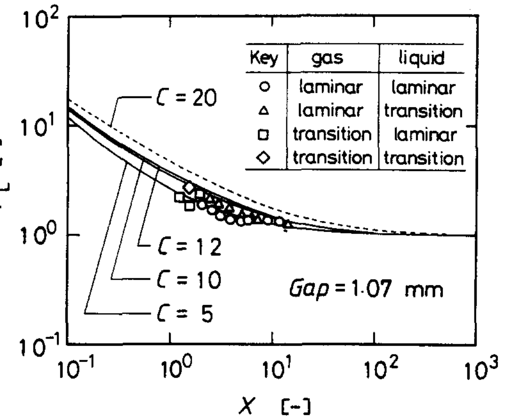

Figure 15. L–M correlation for the test section with a 1.07 mm gap; liquid and gas—laminar and/or transition.

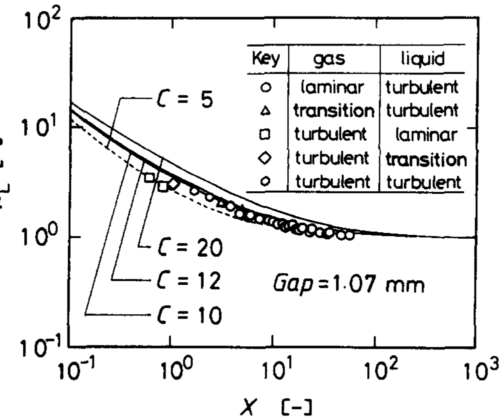

Figure 16. L–M correlation for the test section with a 1.07 mm gap; either liquid or gas—turbulent.

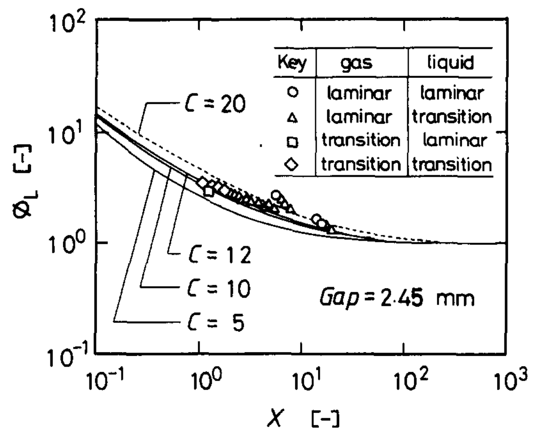

Figure 17. L–M correlation for the test section with a 2.45 mm gap; liquid and gas—laminar and/or transition.

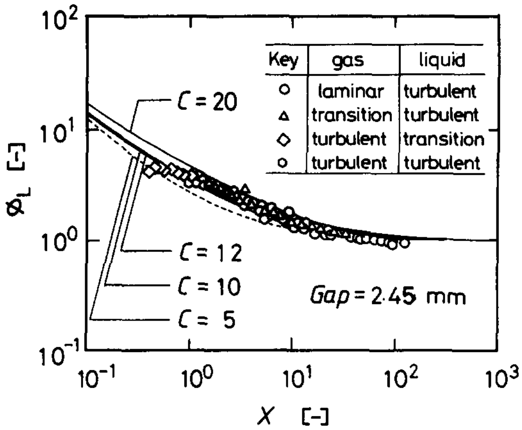

Figure 18. L–M correlation for the test section with a 2.45 mm gap; either liquid or gas—turbulent.

Measured friction factors for single-phase flows were compared with the theoretical solution for laminar flow in a rectangular duct as well as [5] and the modified Prandtl–Karman equation (Jones 1976) for turbulent flow. The results for laminar flow agreed well with the theoretical solution, within 2%, as shown in figures 12, 13 and 14 for the 1.07, 2.45 and 5.00 mm gaps, respectively. These figures also show good agreement for turbulent flow.

3.4.2. Two-phase pressure loss

The two-phase frictional pressure loss was correlated by the Lockhart & Martinelli (1949) method (L–M), i.e. the data were plotted in terms of the two-phase multiplier ϕ_L vs the L–M parameter X. The present experimental data were used for the reference single-phase friction factor.

The results are shown in figures 15 and 16 for the 1.07 mm gap, in figures 17 and 18 for the 2.45 mm gap and in figures 19 for the 5.00 mm gap. The lines in the figures denote the prediction by the Chisholm–Laird (1958) correlation:

$$\phi_L^2 = 1 + C/X + 1/X^2. \qquad [6]$$

The parameter C on the r.h.s. of [6] depends upon the flow regimes of both phases, i.e. the classifications of laminar, transition and turbulent flows, and is shown in table 1 (Chisholm 1967).

A similar equation can be obtained for laminar flow based upon the separated flow model. Assuming the friction factor as

$$\lambda = C_f \mathrm{Re}^{-n}, \qquad [7]$$

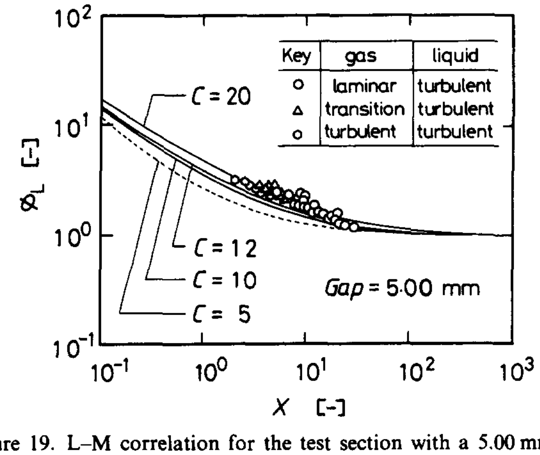

Figure 19. L–M correlation for the test section with a 5.00 mm gap.

Table 1. Parameter C (Chisholm 1967)

Liquid –gas	Flow regime			
	Turbulent –turbulent	Laminar –turbulent	Turbulent –laminar	Laminar –laminar
Re_L	>2000	<1000	>2000	<1000
Re_G	>2000	>2000	<1000	<1000
C	20	12	10	5

one obtains the following equation:

$$\phi_L^2 = [1 + (1/X)^{4/(5-n)}]^{(5-n)/2}. \quad [8]$$

Now that $n = 1$ for laminar flow, one obtains

$$\phi_L^2 = 1 + 2/X + 1/X^2. \quad [9]$$

Expression [9] is the same as [6] if we put $C = 2$.

Sadatomi *et al.* (1982) reported that the frictional pressure loss was correlated by [6] with $C = 21$. On the other hand, Moriyama & Inoue (1991) recently obtained $C = 0$ with some modification for [6] for extremely narrow gaps. Their data for the parameter C are plotted together with the present results as a function of the hydraulic diameter d in figure 20. In the present results, the parameter C depends upon the classification of the flow, therefore the average and the range of the values of C are shown with a triangle and a bar, respectively. From figure 20 it can be seen that the parameter C changes its values from 21 to 0 as the hydraulic diameter decreases in the range from about 10 to 0.1 mm, which can be expressed by the following equation:

$$C = 21 \tanh(0.199d). \quad [10]$$

An approximate form of [10] is

$$C = 21[1 - \exp(-0.27d)]. \quad [11]$$

A similar equation has been proposed by Sugawara *et al.* (1967) for small-diameter round tubes as follows:

$$C = 21[1 - 1.056\exp(-0.331d)], \quad [12]$$

where d is the tube diameter. From the similarity of [11] and [12], it can be said that C is correlated by essentially the same equation for both round tubes and rectangluar ducts, if one uses an

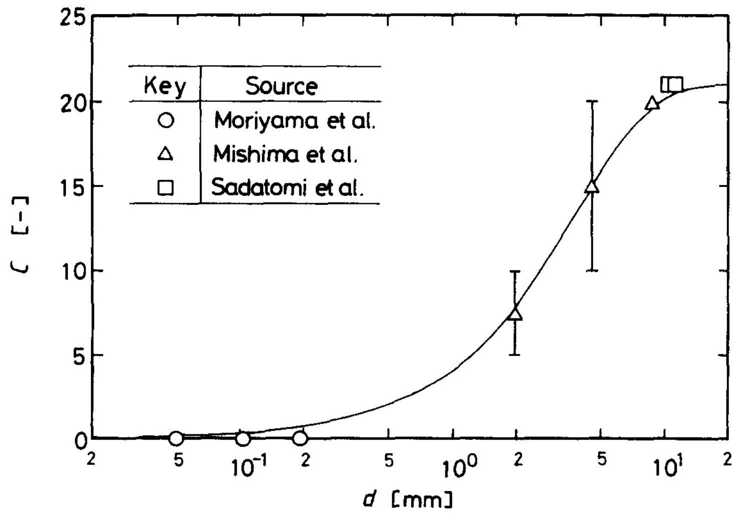

Figure 20. Chisholm's parameter C as a function of the hydraulic diameter for a narrow rectangular duct.

appropriate hydraulic diameter. It is also noted that the value of C is approximated by 2 when the hydraulic diameter is less than about 1 mm, which means that the flow is like a separated laminar flow (see [9]) in this region.

4. SUMMARY

Experimental data on the flow regime, void fraction, slug bubble velocity and the pressure loss were obtained for narrow rectangular ducts, and the results were compared with previous data. The following characteristics have been found for narrow rectangular ducts:

(1) The overall shape and motion of bubbles in a narrow duct are strongly restricted by the proximity of the walls. Churn flow was not observed with the 1.0 mm gap.

(2) The void fraction was well-correlated by the drift flux model. In collaboration with existing data, a tendency was found for the distribution parameter to become large when the gap is <0.1 mm, otherwise it is predicted by [2].

(3) The average velocity of slug bubbles was also well-correlated by the drift flux model. The drift velocity was the same as that for the void correlation. The distribution parameter, however, was found to be smaller than that for the void correlation, being in the range 1.0–1.2.

(4) The frictional pressure loss was found to be well-correlated by the Chisholm–Laird correlation even when the gap is 1.0 mm. The parameter C, however, depends on the hydraulic diameter, decreasing from 21 to 0 as the hydraulic diameter decreases from 10 to 0.1 mm. This tendency can be expressed by essentially the same equation ([10]–[12]) for both round tubes and rectangular ducts if one uses an appropriate hydraulic diameter.

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