Two-Phase Flow Regimes for Counter-Current Air-Water Flows in Narrow Rectangular Channels

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A study of counter-current two-phase flow in narrow rectangular channels has been performed. Two-phase flow regimes were experimentally investigated in a 760 mm long and 100 mm wide test section with 2.0 and 5.0 mm gap widths. The resulting flow regime maps were compared with the existing transition criteria. The experimental data and the transition criteria of the models showed relatively good agreement. However, the discrepancies between the experimental data and the model predictions of the flow regime transition became pronounced as the gap width increased. As the gap width increased the transition gas superficial velocities increased. The critical void fraction for the bubbly-to-slug transition was observed to be about 0.25. The two-phase distribution parameter for the slug flow was larger for the narrower channel. The uncertainties in the distribution parameter could lead to a disagreement in slug-to-churn transition between the experimental findings and the transition criteria. For the transition from churn to annular flow the effect of liquid superficial velocity was found to be insignificant.

Key Words : Counter-Current Two-Phase Flow, Narrow Rectangular Channel, Void Fraction, Flow Regime Transition, Flow Regime Map

Nomenclature

B : Constant in Eq. (17)
C : Constant in Eq. (15)
C_o : Distribution parameter
D : Diameter [m]
D_H : Hydraulic diameter [m]
g : Gravitational acceleration [m/s^2]
j : Superficial velocity [m/s]
K : Constant in Eq. (9)
m : Constant in Eq. (15)
n : Exponent in Eq. (9)
p : Constant in Eq. (17)
q : Constant in Eq. (17)
Q : Volumetric flow rate [m^3/s]
u : Velocity [m/s]
u_{gj} : Drift velocity [m/s]
X : Parameter defined in Eq. (10)
Y : Parameter defined in Eq. (11)

Greek Symbols

α : Void fraction
α_o : Void fraction at zero liquid flow rate
δ : Film thickness [m]
μ : Dynamic viscosity [Ns/m^2]
ν : Kinematic viscosity [m^2/s]

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ρ : Density [kg/m³]
σ : Surface tension [N/m]

Subscripts
b : Bubble
f : Liquid
g : Gas

1. Introduction

In ammonia/water absorption cooling/heating systems, the vapor generated in the desorber contains a certain amount of water. One way to reduce the content of water from an ammonia/water vapor mixture is to use a counter-flow phase-change process. The boiling solution is flowing from top to bottom, while the vapor generated, in contact with solution, flows in the opposite direction bottom to top. As a result of heat and mass exchange between phases in counter-current flow, the concentration of the ammonia/water vapor mixture could be substantially increased at the exit. Thus, careful desorber design that limits the carryover of water and brings the leaving vapor in close contact with the entering rich solution is important to improve the system efficiency. The use of compact heat exchangers in ammonia/water absorption systems requires fundamental studies on the hydrodynamic characteristics of counter-current two-phase flows in narrow rectangular channels.

The behavior of a gas-liquid mixture confined in narrow channels differs from that in a tube due to the increased surface forces and frictional pressure drop. Studies of co-current two-phase flow patterns in rectangular channels cover a period of more than 30 years. Recently published studies include Jones and Zuber (1979), Mishima et al. (1993), Wilmarth and Ishii (1994), and Lee and Lee (1999). The effects of channel gap width and inclination angle were also investigated.

A counter-current two-phase flow is a common occurrence in hypothetical nuclear reactor accidents, and is encountered in chemical and petrochemical systems (e. g. the operation of bubble columns with liquid through-flow). However, little research addressing the hydrodynamic and transport phenomena in counter-current channel flows has been reported. Yamaguchi and Yamazaki (1982) presented flow pattern maps for each operation mode (upflow, counter-current flow, and downflow) in tubes. Taitel and Barnea (1983) modeled the counter-current flow pattern transition and pressure drop in vertical tubes. Ghiaasiaan et al. (1995A) studied counter-current flow patterns, and measured the channel average gas hold-ups in round channels. However, literature on counter-current two-phase flow in narrow rectangular channels were rare.

In the present work, two-phase flow regimes in counter-current flow of air-water mixture in narrow rectangular channels were investigated experimentally. The objective was to understand the hydrodynamic aspects of counter-current two-phase flow in narrow rectangular channels.

2. Experimental Apparatus

The flow apparatus was designed to allow adiabatic flow experiments with air-water mixtures in a channel of small cross-sectional area as shown in Fig. 1. The narrow channel consisted of two acrylic resin plates whose gap was formed by sealing metal strips of a given thickness along the plate's outer boundaries. The width and the length of the test section were 100 mm and 760 mm, respectively. The gap widths were 2.0 and 5.0 mm. Two 10 mm-diameter holes were drilled 15 mm from the top and bottom edges to serve as water inlet and outlet. A 20 mm-diameter hole, 25 mm from the top edge, was used as the air outlet connected to an air-water separator.

The air-water separator was a rectangular box with a 50 x 100 mm base and 60 mm in height. It had a 20 mm-diameter hole located 250 mm from the bottom edge, through which water overflowed to a water tank during experiments. To inject air into the channel 25 capillary tubes, with 0.25 mm inside diameter and 0.3 mm of outside diameter, were planted in the lower part of each plate. Two pressure taps, one 210 mm from the top and the other 350 mm from the bottom of the plate, were located at the center of the plate. The pressure taps were connected to a differential pressure

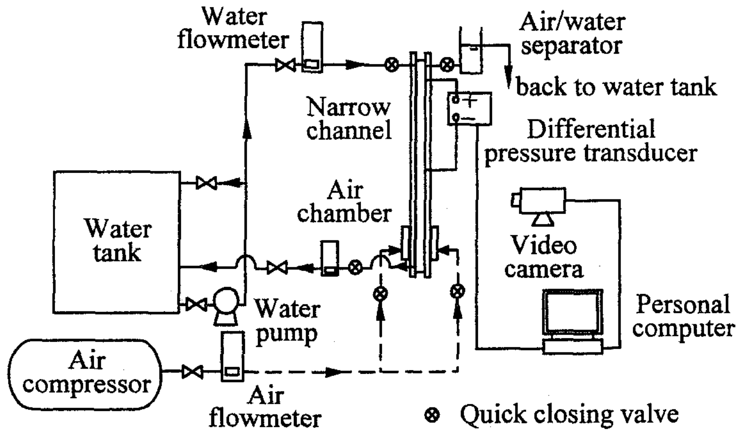


Fig. 1 Schematic of the experimental apparatus.

transducer to measure the pressure drop. The air/water inlets and outlets were equipped with quick-closing valves. These valves were simultaneously activated electrically.

Purified water was supplied by a pump and was regulated by float-type flow meters. The water flow entered the test section through the top water inlet. However a portion of the water was carried over to the air-water separator by the air flow in the test section. Air was supplied by a compressor through a pressure regulator and was controlled by float-type flow meters. Air was first introduced into the air chambers adjacent to the channel and then injected into the channel through capillary tubes. These tubes produced uniform bubbles which mixed with the downward water flow as they rose. The air-water mixture flowed out of the rectangular channel and entered the air-water separator, where the air escaped to the atmosphere while the water flowed back to the water tank. The water flow rate in the test section was measured by a flowmeter. This measurement was reconfirmed by diverting the water to a graduated cylinder at the exit of the test section and measuring the amount collected over a period of time.

Before each experiment the channel and the air-water separator were initially filled with water supplied at a constant flow rate. Water continuously flowed through the system with the flow rate controlled by a needle valve at the water exit. Air was then injected, and the desired air flow rate was set with float-type meters in the air line. When the steady state was reached for each flow rate, the pressure drop was measured. Also, the channel-average void fraction was obtained by the collapsed height of water level in the channel using the quick-closing valves.

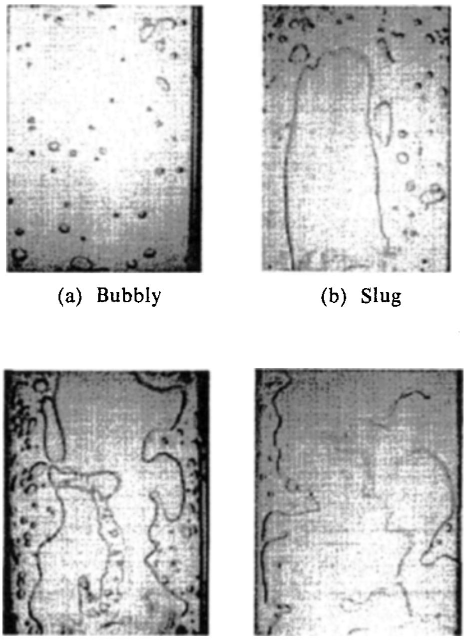
The probability density function of the pressure drop in two-phase flows was analyzed in terms of the flatness and skewness factors to classify flow regimes. However, for all flow segimes, the factors were similar. Therefore, the flow regimes were classified purely according to visual observations. A shutter speed of 1/1000, which enabled easy identification of the air-water interface, was used.

3. Results and Discussion

3.1 Flow regimes

Considerable differences exist in the definitions of two-phase flow regimes. In many instance, the definitions are neither clear not comprehensive. In a narrow and large aspect ratio vertical channel, used in this study, four flow regimes were recognized, bubbly, slug, churn-turbulent, and annular flows. The aspect ratio was so large and the gap was 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 on the shape of the bubbles observed in the video images. Some examples are shown in Fig. 2.

In narrow channels, the entrance length for



(a) Bubbly (b) Slug

(c) Churn (d) Annular

Fig. 2 Sample images of two-phase flow regimes in narrow rectangular channels.

flow regime development was about 50 mm from the air injection nozzle for the bubbly flow regimes. The entrance length seemed to be almost the same for the slug and churn-turbulent flow regimes. Therefore most of the test section showed identical flow patterns except in the vicinity of air inlet. In the annular flow very close to the counter-current flow limitations, frothy bubbles were observed near the air injection port, while a falling sheet of film formed in the rest of test section.

The two-phase flow regimes were classified as follows.

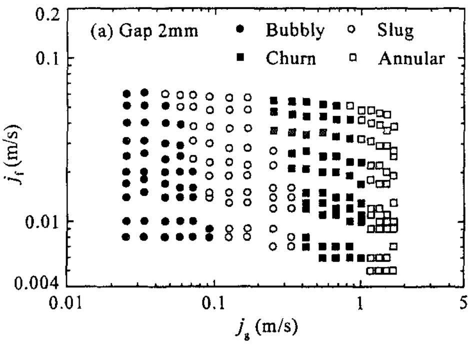
Bubbly flow-Liquid was flowing as a continuous phase while gas was distributed as discrete small bubbles, which were reasonably uniform in a continuous liquid phase. At a lower gas flow rate, spherical bubbles, whose diameter were less than the gap width of the channel, were formed and flowed upward vigorously without coalescence. At a higher gas flow rate, the confinement of the walls caused the growing bubbles to be flattened and distorted. The coalescence of bubbles often formed larger cap bubbles with widths up to 50% of the channel width.

Slug flow-This flow had large two-dimensional 'Taylor bubbles' which contained an ellipsoidal nose and a flat rectangular body. Liquid slug bridged the test section and separated successive Taylor bubbles. Since the channel was too wide, Taylor bubbles were unable to fill up the channel cross-section. The width of Taylor bubble spanned up to 65% of the test section width depending on the size of channel gap width. Individual slug bubble had no interaction with one another and the smooth interface of slug was somewhat well maintained.

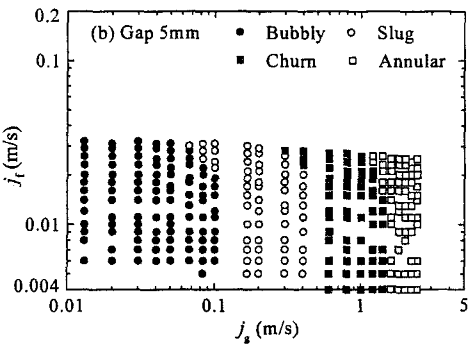
Churn-turbulent flow-This flow was formed by the distortion and breakdown of large gas bubbles in the slug flow. The bubbles were slug-like but were much more chaotic, frothy and disordered. The bullet-shaped slug bubbles were lengthened and distorted until they were no longer discernible. Liquid bridges reaching the width of the test section were repeatedly destroyed due to the high local gas concentration. The churn flow was also marked by oscillatory liquird motion.

Annular flow-This flow was comprised of a solid gaseous core, continuous in the axial direction, with a liquid film surrounding the core. Large amplitude cohefent waves were usually present on the falling film surface. The continuous breakup of these waves formed small droplets in the central gas core, and resulted in the carry-over of droplets. Intermittent flooding type waves forming at the bottom of the test section and moving upwards resulted a lump of liquid entrained in the middle of the gas flow.

These experimental data on the flow regime were represented in Fig. 3 which showed the superficial liquid velocity, $j_f = Q_f/A$, plotted versus the superficial gas velocity, $j_g = Q_g/A$. Q is the volumetric flow rate, A is the flow area and the subscripts f and g denote liquid and gas, respectively. The liquid superficial velocity range was limited by the counter-current flow limitation, which decreased as the gap width increased. As the superficial gas velocities increased the flow regime changed consecutively from bubbly to slug, churn, and annular flow. At higher liquid



(a) Gap width 2mm



(b) Gap width 5mm

Fig. 3 Counter-current flow regimes for narrow rectangular channels.

superficial velocities, the transition gas superficial velocities decreased. As the gap width increased the transition gas superficial velocities seemed to increase. However, the qualitative characteristics of flow regimes were similar for all gap widths.

3.2 Flow regime transition

Since the existing data on air-water counter-current flows in similar geometrical conditions were rare, the flow regime maps obtained from this experiment could not be compared with the existing data. Instead, a comparison was made between the experimental data and model predictions from the traditional two-phase flow regime transition criteria based on the gas and liquid superficial velocities. However, the model and correlations applicable to flow regime transitions in counter-current flow were insufficient.

Several models were examined, and the models of Taitel and Barnea (1983) and Mishima and Ishii (1984) were found to be relevant and selected for comparison with the present study.

Bubbly-slug transition: Taitel and Barnea (1983) proposed a mechanistic set of models for flow regime transitions in counter-current gas-liquid vertical flows by dividing the entire flow map into bubbly, slug, and annular flow patterns. According to their model, a bubbly flow can exist when the following conditions are met.

$$j_f \leq j_g + u_b - (4 j_g u_b)^{1/2} \quad (1)$$

$$0.3 j_f + 0.7 j_g < 0.21 u_b \quad (2)$$

where u_b is the relative rise velocity of the bubble. The rise velocity is a complex function of the bubble diameter, channel geometry, and void fraction. However, it can be considered almost constant for large bubbles and low void fraction and is given by Harmathy (1960) as:

$$u_b = 1.53 \left[\frac{g \Delta\rho \sigma}{\rho_f^2} \right]^{1/4} \quad (3)$$

where g is the gravitational acceleration, σ is the surface tension and ρ is the density. Even though Eq. (2) was based on the criteria that bubbles tend to collapse and form Taylor bubbles at void fractions greater than 0.3, experimental observations in the present study showed that the critical void fraction for the transition from bubbly to slug flow was 0.25.

Slug-churn transition: As the gas flow rate is increased still more, a transition to churn flow occurs. There is considerable difficulty in accurately identifying the slug-churn transition because there is confusion as to the description of the churn flow itself. Some identify churn flows on the basis of the froth that appears within the gas region, and these investigators describe the pattern as frothy. Others associate churn flows with the instability of the liquid film adjacent to the Taylor bubble. A model proposed by Mishima and Ishii (1984) used the criterion that the mean void fraction be greater than the slug-bubble section mean void fraction. Thus,

$$\alpha \geq 1 - 0.813 \left\{ \frac{(C_o - 1) j + 0.35 \left(\frac{g \Delta\rho D}{\rho_f} \right)^{1/2}}{j + 0.75 \left(\frac{g \Delta\rho D}{\rho_f} \right)^{1/2} \left(\frac{g \Delta\rho D^3}{\rho_f \nu_f^2} \right)^{1/18}} \right\}^{0.75} \quad (4)$$

where ν_f represents the liquid kinematic viscosity, and j is the two-phase mixture volumetric flux defined as :

$$j=j_g-j_f \tag{5}$$

Equation (4) is equiralent to the relationship for the channel mean void fraction based on the drift flux model (Ishii, 1977) as

$$\alpha=\frac{j_g}{C_o j+\bar{u}_{gj}} \tag{6}$$

C_o is the two-phase distribution parameter and is given by

$$C_o=1.35-0.35\sqrt{\rho_g/\rho_f} \tag{7}$$

for rectangular channels regardless of the flow regimes. The gas drift velocity, u_{gj}, is found from the rise velocity of the Taylor bubbles relative to the mean velocity of the liquid as given by Nicklin et al. (1962) :

$$\bar{u}_{gj}=0.35(g\Delta\rho D/\rho_f)^{1/2} \tag{8}$$

For co-current downward flow, and for the case of slug flow with $j<0$ (downward mixture volumetric flux) and ascending Taylor bubble, $C_o\leq 1$ may be appropriate, as noted by Martin (1976) in his experiments with air and water. For co-current downward flow Martin obtained $C_o=$ 0.93, 0.90 and 0.86 for channel diameters of 2.6, 10.16 and 14 cm, respectively.

As can be seen in Eqs. (4) and (6), the two-phase distribution parameter has significant effects on the prediction of flow regime transition. To investigate the effects of channel gap width on the distribution parameter in rectangular channels, the void fractions were measured within the range of experimental study.

Channel-average void fraction data with gero liquid throughput, α_o, are depicted in Fig. 4 and are compared with the empirical correlation given by Sudo (1980).

$$\alpha_o=\frac{Y}{KX^n} \tag{9}$$

where

$$Y=\left(\frac{\sigma}{g\rho_f D^2}\right)^{0.064}\left(\frac{\mu_g}{\mu_f}\right)^{0.125} \tag{10}$$

$$X=\left[\left(\frac{\mu_f}{\mu_g}\right)^{0.82}\left(\frac{\rho_g}{\rho_f}\right)^{0.2}\right]\left(\frac{\mu_g j_g}{\sigma}\right) \tag{11}$$

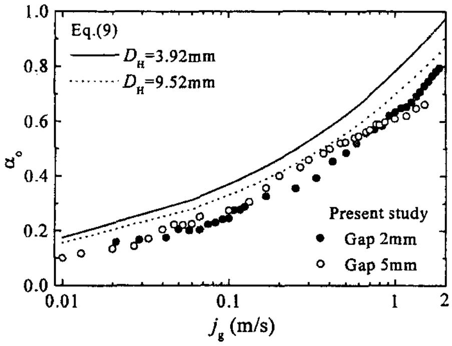


Fig. 4 Average void fraction in narrow rectangular channels with zero liquid flow.

$$K=0.00523,\ n=-0.704 \text{ when } X<0.0005 \tag{12.1}$$

$$K=0.093,\ n=-0.325 \text{ when } 0.0005\leq X\leq 0.004 \tag{12.2}$$

$$K=0.54,\ n=0 \text{ when } X>0.004 \tag{12.3}$$

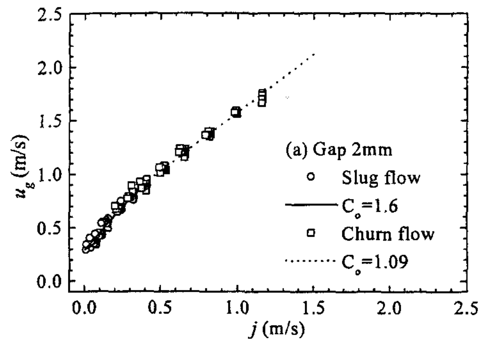
Hydraulic diameters were used in Eq. (10) for comparison. Basically, channel-average void fraction increased with the superficial velocity of air. The experimental data and the correlation showed good agreement except those at high void fractions in an annular flow. Experimental data suggested that the effects of channel gap width on the void fraction were not as significant as the correlation predicted.

According to the drift-flux model, the relationship between the gas velocity and the mixture volumetric flux can be expressed by Eq. (13) :

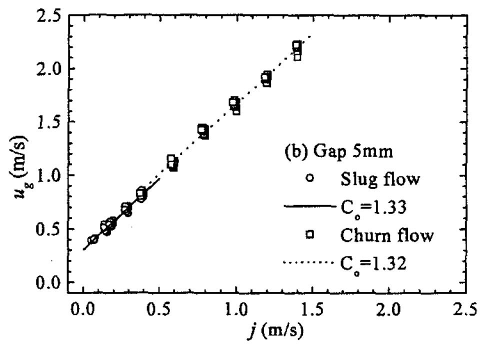
$$u_g=\frac{j_g}{\alpha}=C_o j+\bar{u}_{gj} \tag{13}$$

The experimental results are shown in Fig. 5 for the slug and churn flows. The void fraction can be well-correlated by the drift flux model. At a smaller gap width the distribution parameter for the slug flow were found to be unexpectedly bigger than the prediction of Ishii (1977). However, for the churn flow, the distribution parameter was as small as 1.0 for the gap width of 2.0 mm. As the gap width increased to 5 mm, the difference of the distribution parameter between the flow regimes was hardly noticeable. The distribution parameters became very close to the prediction of Eq. (7).

There exists some confusion on the two-phase



(a) Gap width 2 mm



(b) Gap width 5 mm

Fig. 5 Drift-flux correlation of the void fraction.

distribution parameter in rectangular channels. For smaller gap widths, Mishima et al. (1993) has observed that the distribution parameter becomes smaller, $C_0 \approx 1.0-1.11$. On the other hand, Iida and Takahashi (1976) reported that values larger than 1.3 exist for small test sections. Moriyama and Inoue (1991) also recently reported larger values for extremely narrow gaps. The distribution parameter tended to become large when the gap was extremely small. Otherwise, it could be predicted by Eq. (7) for rectangular channels. For gap widths greater than 5.0 mm, the distribution parameter was proposed to be 1.2.

Churn-annular transition : For high gas flow rates the flow becomes annular. The liquid film flows adjacent to the wall, and gas flows in the center carrying entrained liquid droplets. Taitel and Barnea (1983) modeled the slug-to-annular transition in counter-current flow in vertical tubes. Transition was assumed to occur when the relative velocity between the Taylor bubble and the liquid film adjacent to it reached the condition of flooding.

$$j_g - j_f \le -0.292\sqrt{gD} + \frac{\left\{C[gD(\rho_f-\rho_g)]^{1/4} - m\left[4\frac{\delta}{D}u_f\rho_f^{1/2}\right]^{1/2}\right\}^2}{1.2\left(1-4\frac{\delta}{D}\right)\rho_f^{1/2}} \quad (14)$$

where m and C are constants in Wallis, flooding correlation (Wallis, 1969)

$$j_g^{*1/2} + m j_f^{*1/2} = C \quad (15)$$

$$j_g^* = \frac{j_g \rho_g^{1/2}}{(gD\Delta\rho)^{1/2}} \quad (16.1)$$

$$j_f^* = \frac{j_f \rho_f^{1/2}}{(gD\Delta\rho)^{1/2}} \quad (16.2)$$

For simple vertical channels $m=0.8-1.0$, and $C=0.7-1.0$ have been reported, with C mainly depending on the channel end conditions. Values for m and C significantly differ from the aforementioned ranges for more complex channel configurations as proposed by Osakabe and Kawasaki (1989) and Ghiaasiaan et al. (1995B)

The liquid film thickness δ is estimated using the steady-state falling film momentum conservation equation:

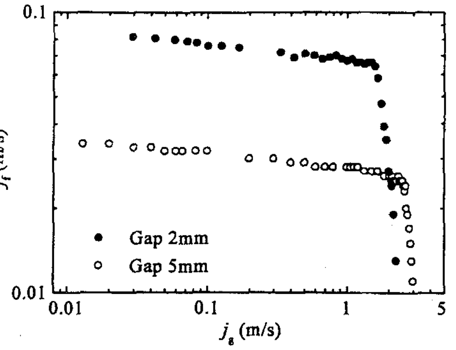
$$\frac{\delta}{D} = B\left[\frac{\mu_f^2}{D^3 g(\rho_f-\rho_g)\rho_f}\right]^p \left[\frac{\rho_f j_f D}{\mu_f}\right]^q \quad (17)$$

where the constants B, p and q equal to 0.909, 0.33 and 0.33 for laminar film flow, respectively.

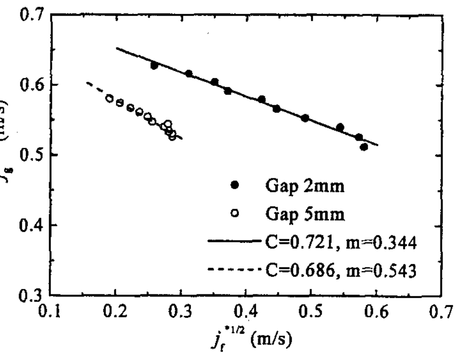
Since it is essential to understand the characteristics of counter-current flow limitation in the given geometry for accurate prediction of churn-to-annular flow transition, additional experiments were performed to estimate the constants C and m. Figure 6 shows that the maximum liquid superficial velocities decrease as the gap width increases. However the maximum gas superficial velocity under CCFL seemed to be slightly higher for wider channels. CCFL data were well-correlated by the flooding curve as shown in Fig. 6 (b). As the gap width increased C decreased but m increased, however m was still smaller than those predicted for simple vertical channels.

3.3 Flow regime map

The actual transition regions for the counter-current flow in vertical rectangular channels were wide bands between each of the flow regimes:

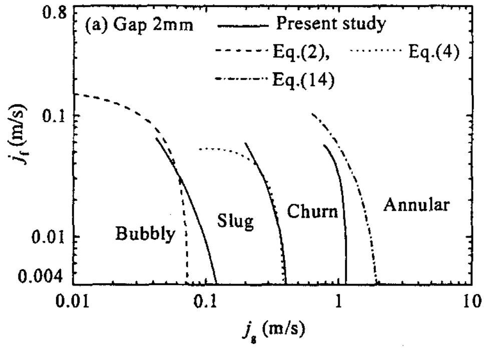


(a) Two-phase flow limitations

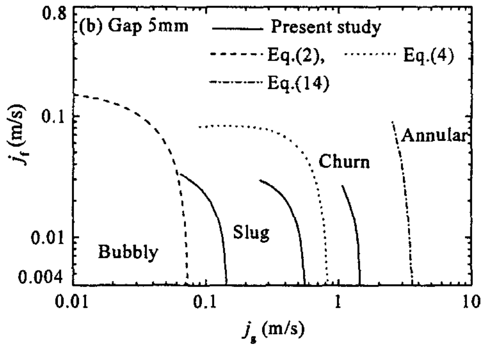


(b) Flooding curves

Fig. 6 Counter-current flow limitations in narrow rectangular channels.



(a) Gap width 2mm



(b) Gap width 5mm

Fig. 7 Comparisons of flow regime map with transition models.

however, they were represented by a single line for simplicity in Fig. 7. Therefore, the location of the transition line only represents general trends and may not be determined precisely. The experimental data and the transition criteria of the models showed relatively good agreements. Also, the discrepancies between the experimental data and the prediction of the models increased with the gap width. The transition criteria seemed to overpredict the effect of the channel gap width compared to the experimental observations, which suggested the need for a new geometrical scale in narrow rectangular channels.

For the transition from bubbly to slug flow, Eq. (2) encompassed the condition of Eq. (1) and was compared with experimental data. As mentioned previously, the critical void fraction used in Eq. (2) is 0.3 wheras it was found to be 0.25 from experimental observations. However, when the critical void fraction of 0.25 was applied to Eq. (2), the discrepancies between the model and the experimental data increased regardless of the channel gap width. Therefore, the rise velocity of the bubble in counter-current two-phase flow in narrow rectangular channels, which should be far different from the case of round tubes due to the increased surface forces and frictional pressure drop, had to be modeled with a proper geometrical scale.

For slug-to-churn flow transition, the agreement between the experimental data and the model happened to be very good for the channel of 2 mm gap width. However, the agreement was no more than a numerical coincidence as seen in the case of 5 mm gap width. Reason for the discrepancies could be attributed to the distribution parameter and the rise velocity of the Taylor bubbles relative to the mean velocity of the liquid. As the distribution parameter decreases, the theoretical transition lines shift slightly to the left, showing better agreement with experimental data.

Wilmarth and Ishii (1994) found that the discrepancies for the flow pattern transition due to the channel gap could be accounted for by the value used for C_o. 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. Thus, the distribution parameter would change. Above all, the rise velocity of the Taylor bubbles, given in Eq. (8), should be well-correlated with a proper characteristic length (Sadatomi et al. , 1982).

For high gas flow rates, the flow becomes annular. The liquid film flows adjacent to the wall, and gas flows in the center carrying entrained liquid droplets. Experimental data showed the effect of liquid flow rate were insignificant in churn-to annular flow transition. For the transition from churn to annular flow, the prediction of the model became far bigger than the experimental data as the gap width increased. If smaller m and C were used, the agreements would become better. To accurately predict churn-to-annular transition by the flooding phenomena, it is necessary to accurately model the ratio of falling film thickness to the characteristic length of a narrow rectangular channel. Also, the characteristic length of narrow rectangular channels should be better defined.

4. Conclusions

A study of counter-current two-phase flows in narrow rectangular channels has been performed. Two-phase flow regimes were experimentally investigated in a 760 mm long and 100 mm wide test section with 2.0 and 5.0 mm gap widths. The resulting flow regime maps were compared with the existing transition criteria.

The experimental data and the transition criteria of the models showed relatively good agreements. However the discrepancies between the experimental data and the prediction of the models on the flow regime transition became serious as the gap width increased. As the gap width increased, the transition gas superficial velocities increased. The critical void fraction for the bubbly-to-slug transition was observed to be about 0.25. The two-phase distribution parameter for the slug flow was larger for the channel of narrower gap width, whose uncertainties could lead to the disagreement in the slug-to-churn transition between the experimental findings and the transition criteria. In transition from churn to annular flows, the effect of liquid superficial velocity was found to be insignificant. Generally the transition criteria overestimated the effect of the channel gap width.

More systematic experiments aimed at better understanding of the effects of aspects ratio of vertical channel on flow regimes are required. For the existing transition criteria to be applied accurately to narrow rectangular channels, the characteristic length and the associated bubble flow behavior should be modeled more precisely.

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