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Experimental study on gas–liquid two-phase flow regimes in rectangular channels with mini gaps

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Abstract

Experimental investigations were conducted for adiabatic air/water two-phase flow in vertical rectangular channels. Three test sections with the narrow gaps of 0.3, 0.6 and 1.0 mm respectively were studied. The flow regimes were observed by using a high-speed video-camera and were identified by examining the video images. The flow regimes in channels with the gaps of 1.0 and 0.6 mm are similar to those found by previous studies, and can be classified into bubbly, slug, churn and annular flow. With decreasing the channel gaps, the transition lines for bubbly-slug, slug-churn and churn-annular flow shift to left in the flow regime maps with the superficial gas velocity as the horizontal coordinate and the superficial liquid velocity as the vertical coordinate. However, the flow regimes in the channel with the gap of 0.3 mm are dramatically different from the previous studies. Bubbly flow was never observed even at very low gas flow velocity. Cap-bubbly flow can exist in the channels stably. Due to the increased influences of the surface tension and friction shear stress in the mini channels, the liquid droplets adhere on the wall surface and are pushed by the flowing gas. The flow regimes can be classified into cap-bubbly, slug-droplet, churn and annular-droplet flow.

Keywords: Micro channel; Two-phase flow; Flow pattern; Cap-bubbly flow; Slug-droplet flow; Annular-droplet flow

1. Introduction

In order to meet the needs of dissipating high heat fluxes from electric, power, and laser devices, attention has been paid to the flow and heat transfer with or without phase change in micro channels. Peng and Wang (1993), Peng et al. (1995) and Peng and Peterson (1996) investigated the flow and heat transfer in micro rectangular channels using water as the working fluid. They measured the single-phase friction pressure drops, heat transfer coefficients, and indicated that the heat transfer is quite different from the classical correlation. They also studied the sub-cooled boiling heat transfer in micro channels. Yao and Chang (1983) investigated pool boiling heat transfer in vertical narrow annular with closed bottoms. The boiling heat transfer phenomena was observed through the transparent quartz shroud. With the addition of wall heat flux, the boiling phenomena evolved the following stages: isolated deformed bubbles, coalesced deformed bubbles, near dryout and post dryout conditions, and nucleation under slightly bubbles. Bowers and Mudawar (1994) investigated the high heat flux boiling in low flow rate, low pressure drop in mini channel and micro channel sinks. They found that the boiling mixture could dissipate heat flux up to 2.0 MW/m^2. Even though there exist a number of studies on convection and boiling of a single component flow in micro channels, little knowledge has been acquired on multi component flow and heat transfer in micro/mini channels. Because the heat transfer with phase change is related to the flow structure, research on two-phase flow pattern in micro/mini channels is necessary to understand such heat transfer process. It is this primary need for further analysis of two phase flow in narrow mini channels that warrants more investigation concerning flow pattern identification, transition criteria, void fraction and interfacial area concentration.

Early study of two-phase flow pattern predominantly consisted of flow in medium size circular tubes with the diameter larger than 10 mm. Sadatomi and Saruwatari (1982) presented the flow regime map in large vertical rectangular channels. They classified flow regimes as bubbly, slug, and annular flow. They also indicated that channel geometry has little influence in the noncircular channels when the channel hydraulic diameter is larger than 10 mm. Troniewski and Ulbrich (1984) studied 10 different rectangular channels. The aspect ratios covered the range from 12 to 0.1 for the vertical channels, and from 0.1 to 10 for the horizontal channels. The air/water mixture was used as the working fluids in most of the tests. However, the sugar/air mixtures were also selected to study the effect of the viscosity on the flow pattern. Mishima et al. (1993) used the neutron radiography technique to study the flow in narrow rectangular channels. They measured flow regimes, void fractions, bubble velocity and two-phase pressure drop. They did not find churn flow with the gap of 1.0 mm. Wilmarth and Ishii (1994) studied the adiabatic co-current and horizontal two-phase flow of air and water in the narrow rectangular channels with the gaps of 1 and 2 mm. They compared their data with predictions by models Mishima and

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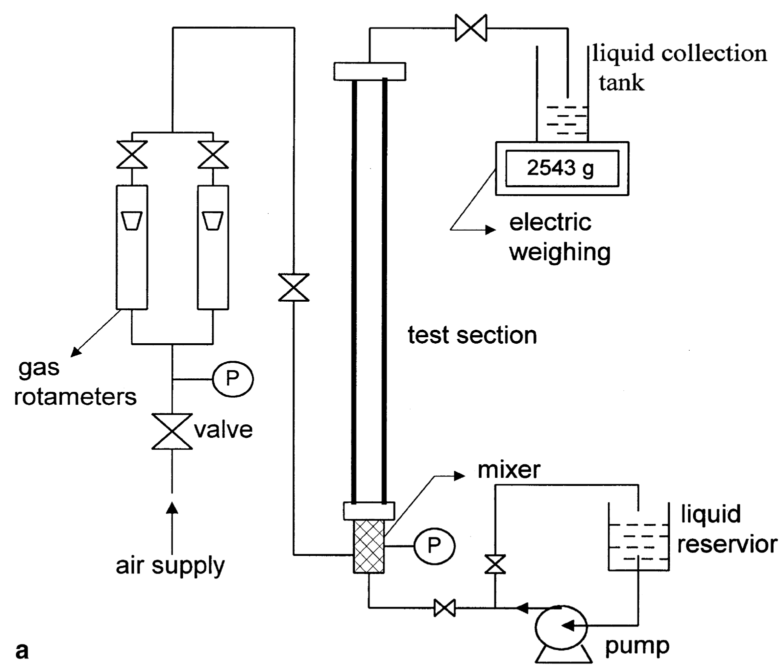
Ishii (1984) and Taitel et al. (1980), and concluded that a new distribution parameter was needed for the transition from bubbly to slug flow. Results were also less satisfactory for the transition from slug to churn flow.

Detailed literature review of flow regimes in small systems can be found in Wilmarth and Ishii (1994). Even though some work has been carried out in this area, some conclusions are inconsistent and even confusing. Some of them may come from the flow regime definition and the complicated flow structures themselves. To author's knowledge, no detailed investigations have been made on the flow structures in very small systems. The present paper is mainly concerned with the flow regime in rectangular channels with mini gaps. With water and air as the working fluids, the flow regimes for the gaps of 1.0 mm and 0.6 mm are similar to those found by previous studies, and can be classified into bubbly, slug, churn, and annular flow. But, in the channels with the gap of 0.3 mm or less, the flow regimes are significantly different from previous studies, indicating the dependence on the channel geometry.

2. Experimental details

A schematic diagram of the test loop is shown in Fig. 1(a). The water was provided by a pump and was regulated by the bypass line and the valves. The liquid entered the bottom plenum of the test section and was mixed with the air before it entered the test section. The air/water mixture left the test section and then was led to the liquid collection tank where the mixture was separated. The air was released into the atmosphere and the liquid was drained into the liquid collection tank. By weighing the collection tank over a given period of time, the liquid flow rate could be accurately determined. The air was provided by the laboratory air system and was controlled by the gas rotameters.

The three test sections were made of Pyrex glass, so that the flow structure visualization could be fulfilled. All test sections had the same width of 12 mm and length of 260 mm, but they possessed different channel gaps of 1.0, 0.6 and 0.3 mm respectively. They had the same overall structures except



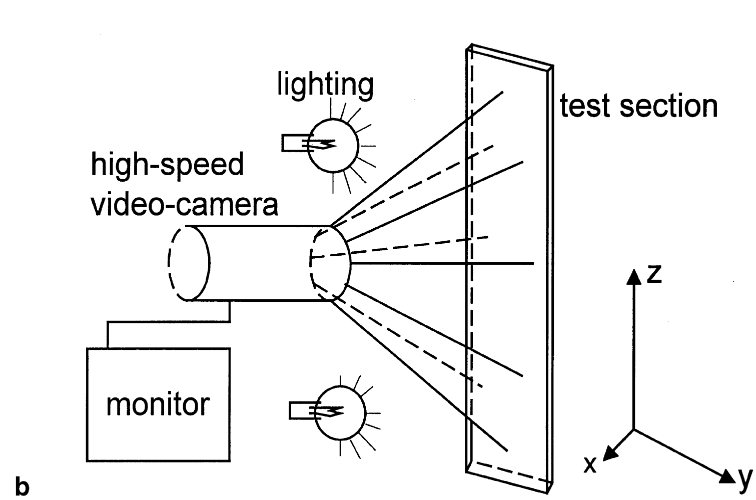


Fig. 1. (a) Schematic diagram of the test loop of air/water system for flow regimes. (b) Schematic diagram of the visualization system.

for the channel gaps. Because the flow pattern might be sensitive to the geometric precision, the test sections were fabricated and measured carefully. The test sections were made using the digital-milling machine. The dimensions were controlled within the range of 0.02 mm. After the fabrication process was finished, each surface of the test sections (including the inside surfaces) was polished by water-sand paper. Thus the flow pattern visualization could be fulfilled clearly. Finally, the channel gaps were measured using the optical method with their accurate values of 1.01, 0.59, and 0.30 mm respectively.

Two pressure gauges were installed at a distance of 220 mm along the test section. One of them was located 20 mm after the entrance and another 20 mm before the exit of the test sections. Measurements included the pressure before the fluids entered the test section and the average flow rates of both the liquid and the gas. The measurement accuracy was estimated to be 2.5% for the gas flow rate and 1% for the liquid flow rate. The pressure was measured with the accuracy of 0.5%. Future study will illustrate the pressure drops across the test section. The pressure drop might explain the differences in the flow maps of different situations. The superficial gas velocity J_g and liquid velocity J_l were applied to plot the flow regime map with the definition of

$$J_g = \frac{Q_g}{A}, \quad J_l = \frac{Q_l}{A}, \tag{1}$$

where Q_g and Q_l are the volume flow rates of the gas and the liquid, A the cross section area of the rectangular channels.

For convenience, we define the coordinate system where the x-axis crosses the gap, the y-axis extends horizontally in the channel width direction, and the z-axis is in the vertical direction. In narrow gaps having large width-spacing ratios like those tested here, the flow is likely to develop large variations in the y-z plane. For example, large coalesced vapor masses may extend over certain areas in the y-z plane with liquid streaks interspersed among them. Such flow patterns can be characterized by observation over the y-z plane. In fact all flow pattern data obtained in the present paper were from the observation of the flow structures in the y-z plane. The author also tried to observe the flow structures in the x-z plane through the channel gap. Because the channel gap was very small, the image was a fine "line" which was covered either by the gas or the liquid discontinuously. So the most useful information in the mini channels was the flow pattern obtained in the y-z plane.

The visualization system included a high-speed camera, two lighting bulbs, and a monitor. When the visualization was in process, the light of the laboratory was turned off and the environment became "black". Two light bulbs, with a total power of 300 W, were adjusted to a suitable brightness to give the clear pictures on the monitor. The distance between the camera and the test section was also adjusted to cover a certain area of the flow on the monitor. The observation was made in the y-z plane, as mentioned above. The shutter speed was also adjustable with the maximum value of 1/4000 s. Generally higher flow velocity in the channel requires higher shutter speed and stronger brightness. The flow pictures with slow moving speed can be seen clearly on the monitor. The flow pattern information was also stored in a videotape for later analyzing. With an electric converter, the information stored in the videotape was transferred to the digital signal, which could be accepted by the computer. A picture-processing software was applied to treat the digital signal. The detailed flow pattern could be identified in the computer and printed out on a color printer. Fig. 1(b) simply illustrates the visualization system.

3. Results and discussion

3.1. Flow regime observations in the vertical rectangular channels with the gaps of 1.0 and 0.6 mm

Even though considerable differences exist in the definitions of two-phase flow patterns in medium size channels, general flow regimes consist of bubbly, slug, churn, and annular flow. Such typical flow regimes are schematically shown in Fig. 2 including two transition flows: cap-bubbly transition flow (Fig. 2(b)) and slug-churn transition flow (Fig. 2(d)). The description of classical flow regimes in vertical medium size channels is mainly due to Collier (1981). Photograph observations of flow structures in the present vertical rectangular channels with the gaps of 1.0 and 0.6 mm confirm such characteristics, except that the gas bubbles in thin rectangular channels are two-dimensional in shape. The detailed characterization of these flow structures is given as follows.

Bubbly flow. In bubbly flow, liquids are flowing in the channels as the continuous phases, gas is distributed in the continuous liquid phase as discrete small bubbles. In thin rectangular channels, the small bubbles are in the shape of a two-dimension circle, while in medium size circular channels, bubbles are spherical in shape.

Slug flow. Slug flow has larger two-dimensional "Taylor bubble" which contains a half circle cap head and a flat rectangular body. The diameters of such Taylor bubbles approach the channel width. The gas is separated from the side walls by slowly descending liquid films. The liquid flow is contained in liquid slugs which separate the successive gas bubbles. Generally the liquid bridges may contain small isolated gas bubbles.

Churn flow. Churn flow is formed by the breakdown of the large gas bubbles in slug flow. The gas flows in a more chaotic manner through the liquid which is mainly displaced to the channel wall. The flow has an oscillatory or time dependent character.

Annular flow. In annular flow, a liquid film forms at the channel side wall with a continuous central gas. Large amplitude coherent waves are usually present on the surface of the film and the continuous breakup of these waves forms a source for small droplet entrainment which occurs in varying amounts in the central gas core.

Fig. 2(b) and (d) show two transition flow: cap-bubbly transition flow and slug-churn transition flow. Usually they do not contain particular regions in the flow regime map. Their characteristics are described by Wilmarth and Ishii (1994).

Fig. 3 and Fig. 4 are the flow regime maps of the 12×1 mm and 12×0.6 mm vertical rectangular channels. Generally flow regimes consist of bubbly, slug, churn, and annular flow. The flow characteristics are not much different from those found in medium size channels except that the gas bubbles are two-dimensional in shape.

Fig. 5 shows the comparisons of the flow pattern transition lines among the rectangular channels with the gaps of 1.0 and 0.6 mm, and the circular tube with the diameter of 25.4 mm. The flow pattern transition boundaries for the circular tube is from the predictions by Mishima and Ishii model (1994) with air/water as the working fluids at 0.1 MPa and 25°C. From Fig. 5 it is clear that the flow pattern transition lines from bubbly to slug, slug to churn, and churn to annular flow shift to the left with decreasing the channel dimensions. The bubbly flow regions for the rectangular channels with the gaps of 1.0 and 0.6 mm are much smaller than that of the circular tube with the diameter of 25.4 mm.

Comparing the flow pattern transition lines between the two present rectangular channels with the gaps of 1.0 and 0.6

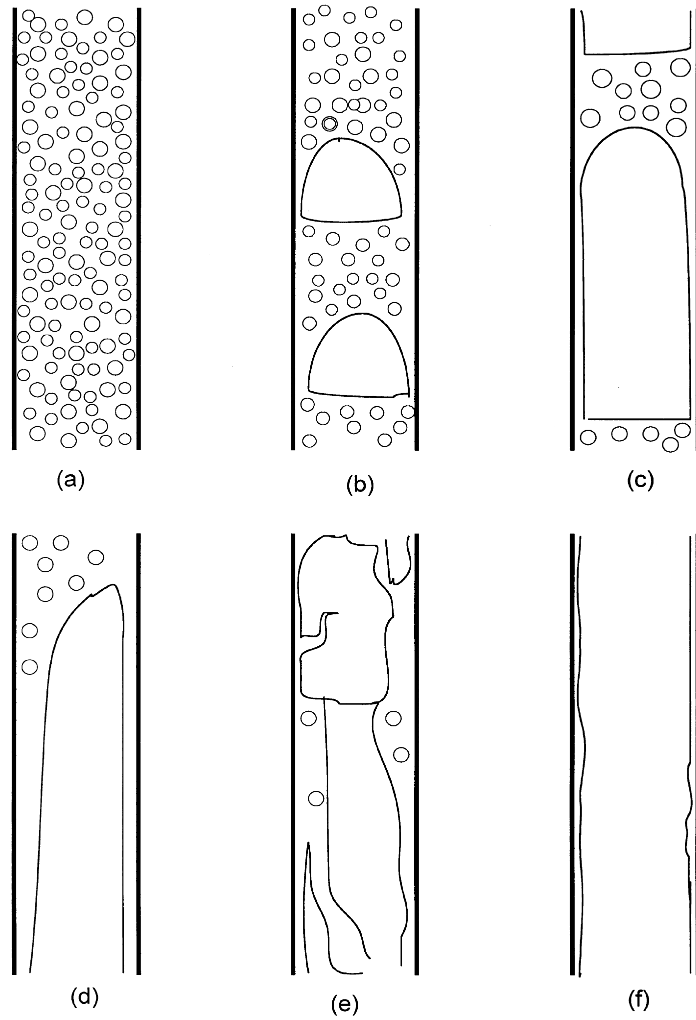


Fig. 2. Flow regimes in vertical channels with medium sizes: (a) bubbly flow; (b) cap-bubbly flow; (c) slug flow; (d) slug-churn flow; (e) churn-turbulent flow; (f) annular flow.

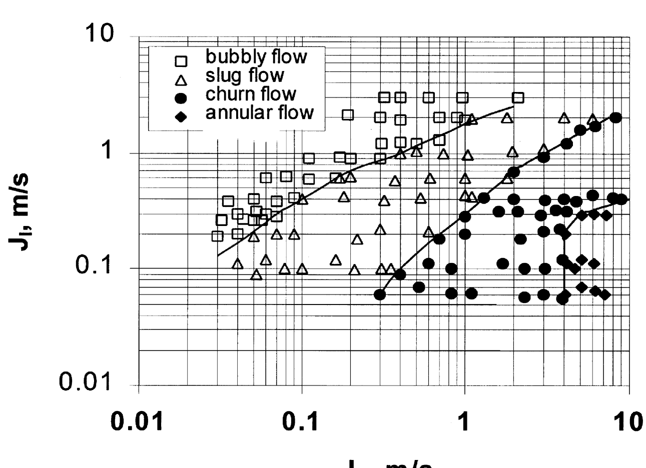


Fig. 3. Flow regime map in vertical rectangular channel with $w = 12$ mm, $s = 1.0$ mm.

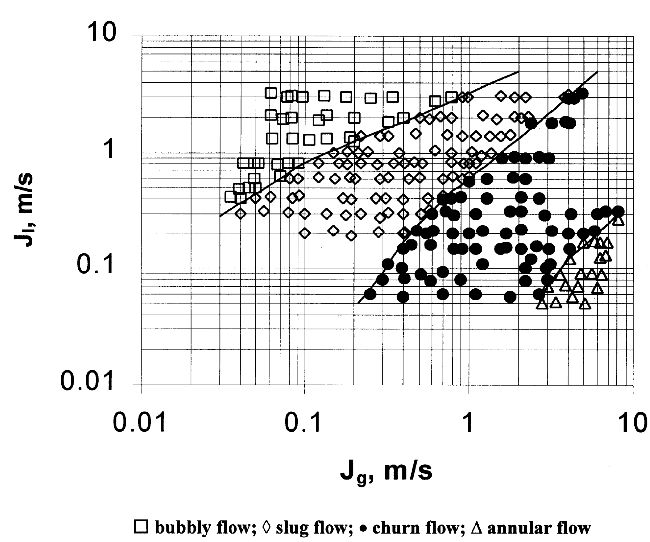


Fig. 4. Flow regime map in vertical rectangular channel with $w = 12$ mm, $s = 0.6$ mm, □ bubbly flow; ◇ slug flow; ● churn flow; Δ annular flow.

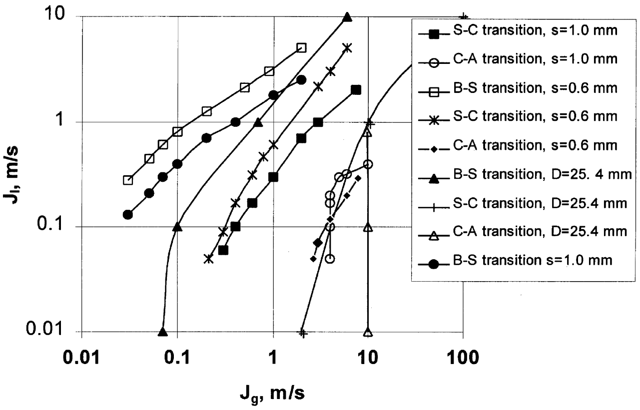


Fig. 5. Comparison of flow patterns among the rectangular channels with the gaps of 1.0, 0.6 mm and the circular tube of 25.4 mm. B-S: bubbly to slug flow transition; S-C: slug to churn flow transition; C-A: churn to annular flow transition.

mm in Fig. 5 can identify how the gaps affect the flow. The bubbly to slug flow transition appears at lower superficial gas velocity in the channel with the gap of 0.6 mm than that with the gap of 1.0 mm. With decreasing the channel gaps, the gas bubbles can only be expanded in the *y-z* plane. The bubbles are squeezed so that the distances between the neighboring bubbles are decreased to induce the small bubbles merging. It is also found that the transition lines from the slug flow to churn flow shift to the left with the mini channel gaps. The reason may come from the increased wall shear stress in the rectangular channels with the mini gaps.

The present flow regime map for the 12×1 mm vertical rectangular channel is similar to that given by Wilmarth and Ishii (1994) for a 20×1 mm vertical rectangular channel. Mishima et al. (1993) developed a flow regime map for a 40×1.07 mm vertical rectangular channel. For such a test section, no churn flow was observed. This may be due to the confusions between the slug and the churn flow, or the churn and the annular flow.

For the 12×1 mm channel, the present study shows that the churn to annular flow transition occurs at about the superficial gas velocity of 4.0 m/s. The flow regime map given by Wilmarth and Ishii (1994) for a 20×1 mm channel showed that such a transition occurs at about 5.0 m/s. However, early study for medium size rectangular channels by Sadatomi and Saruwatari (1982), showed that the transition occurs at the superficial gas velocity larger than 10.0 m/s. This means that the churn to annular flow transition, or the slug to annular flow transition occurs at lower superficial gas velocity in small size channels.

3.2. Flow regimes in the rectangular channel with the gap of 0.3 mm

The flow regimes in the present rectangular channel with the gap of 0.3 mm are quite different from the classical flow regimes found in medium size channels. The author found two important phenomena: (1) Bubbly flow, which exists in medium size channels shown in Fig. 2(a), was never observed in the rectangular channel with the gap of 0.3 mm. However, the cap-bubbly flow can exist stably. (2) At small liquid flow rates, liquid droplets are always observed to be attached on the wall surface and are pushed by the gas phase. Therefore, we identify three new flow regimes beside the normal churn flow: cap-bubbly, slug-droplet, and annular-droplet flow. Typical photographs of the four different flow structures are shown in Fig. 6 and the flow regimes are shown in Fig. 7. The four flow regimes are described as follows.

Cap-bubbly flow. Even at very low gas flow rate, bubbly flow, which was shown in Fig. 2(a) in channels with medium sizes, or in the vertical rectangular channels with the gaps of 1.0 and 0.6 mm, was never observed in the rectangular channel with the gap of 0.3 mm. Bubbly flow is suppressed in such a channel with the thin gap. The small isolated bubbles are squeezed to be merged with each other. Such an effect causes the coalescence of small bubbles forming the cap-bubbly flow. Cap-bubbly flow can occur stably in the channel at high liquid flow rate and at low gas flow rate (represented in the top-left region in Fig. 7). The shape of the cap-bubbles is the two-dimensional half circle at the top with a nearly flat bottom. The cap-bubbles may cover the whole width of the channel. The distances of the two neighboring cap-bubbles are nearly the same. At the cap-bubbly flow, continuous increasing the gas flow rate can lead to the churn flow. With continuous decreasing the liquid flow rate can cause the slug-droplet flow.

Slug-droplet flow. At low gas flow rates and low liquid flow rates, there exists slug-droplet flow in the rectangular channel with the gap of 0.3 mm. Compared with the classical slug flow in channels with a medium size, the slug-droplet flow has the following special characteristics: (1) in the elongated slug, liquid droplets are always detected. Due to the small confined gap of the channel, the isolated liquid droplets adhere on the wall surface and are pushed by the flowing slug. The droplets on the wall surface are dominated by the surface tension, gravity, and drag force created by the flowing gas. (2) The liquid bridges, which separate the successive slugs, do not contain any small gas bubbles.

In this channel, the slug-droplet flow occurs only at low gas flow rates and low liquid flow rates. Early studies showed that the classical slug flow can cover a vide range of liquid flow rates at medium gas flow rates.

The transition from the slug-droplet to the churn flow in this channel is found to occur at the superficial gas velocity of 0.46 m/s.

Churn flow. Churn flow in the rectangular channel with the gap of 0.3 mm is similar to that found in medium size channel. The characteristics are described in the above section. The churn flow covers a wide range of liquid flow rates at medium superficial gas velocities.

At churn flow, continued increasing gas flow rate can cause annular-droplet flow. Such a transition occurs at the superficial gas velocity of 3.3 m/s. But annular-droplet flow exists only at the superficial liquid velocities below 0.34 m/s.

Annular-droplet flow. Annular-droplet flow consists of a continuous gas core and a surrounding liquid film which separates the gas core and the side walls of the channel. Compared with the classical annular flow in medium size channels, annular-droplet flow contains isolated liquid droplets in the gas core. The liquid droplets are attached on the wall surface and are pushed by the gas core. Such a characteristic is similar to that of the slug-droplet flow in the channel with the gap of 0.3 mm.

4. Conclusions

From the present investigations, the conclusions can be summarized as follows:

1. A study of two-phase flow regimes in rectangular channels with mini gaps has been performed. The three test sections are 260 mm in lengths, 12 mm in widths with different gaps of 1.0, 0.6 and 0.3 mm. The flow regimes are observed by a high-speed video-camera and are identified by examining the video images.

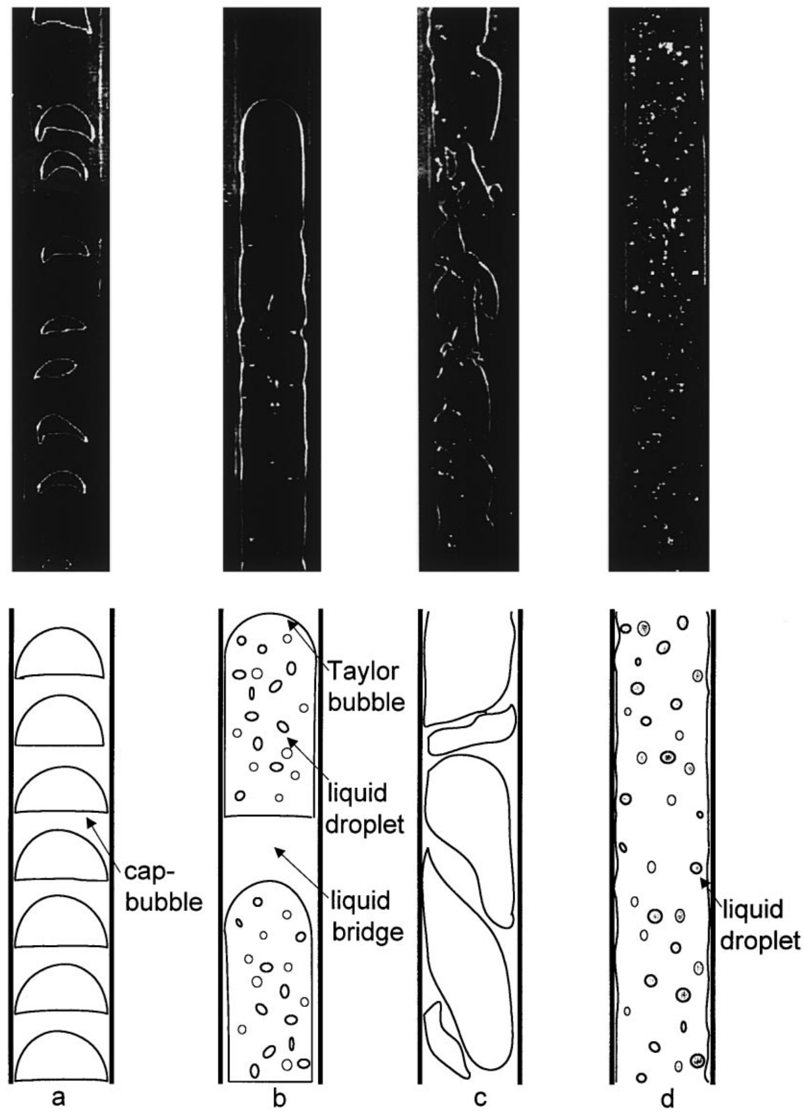


Fig. 6. Flow regimes in the channel with the gap of 0.3 mm. (a) Cap-bubbly flow; (b) slug-droplet flow; (c) churn flow; (d) annular-droplet flow.

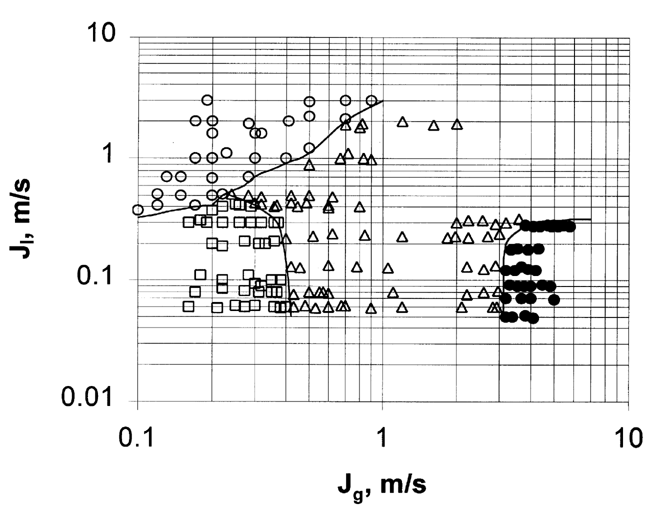


Fig. 7. Flow regime map in vertical rectangular channel with w = 12 mm, s = 0.3 mm. ○ cap-bubbly flow; □ slug-droplet flow; Δ churn flow; ● annular-droplet flow.

2. The flow regimes in the channels with the gaps of 1.0 and 0.6 mm are similar to those performed in channels with medium sizes, and consist of bubbly, slug, churn and annular flow. However, in rectangular channels with mini gaps, any bubbles are flattened and two-dimensional in shape.
3. In channels with mini gaps, the transition lines from bubbly to slug flow, slug to churn flow, and churn to annular flow shift to left. Especially for the channel with the gap of 0.6 mm, bubbly flow covers a small region. This is because the small bubbles are squeezed in the gap to be merged with each other. The reason that the transition from slug to churn flow shifts to the left is mainly because the increased friction shear stress. Annular flow is formed at low gas flow rate. This is also due to the increased wall and interface shear stresses.
4. In the channel with the gap of 0.3 mm, the flow structures are different from the classical flow structures in channels with medium sizes and in the channels with the gaps of 1.0 and 0.6 mm. Two important phenomena are found: bubbly flow was never observed; at low liquid flow rate, liquid droplets are always attached on the wall surface and are pushed by the gas phase. The flow regimes consist of cap-bubbly, slug-droplet, churn, and annular-droplet flow.

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