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Experimental study for flow regime of downward air-water two-phase flow in a vertical narrow rectangular channel

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1. Introduction

There have been many studies of two-phase flow in vertical tube or channel in various purposes for 50 years. Studies were mostly about flow in upward flow in medium size circular tube. Although there are great differences between upward and downward flow, studies on vertical upward flow are much more active than those on vertical downward flow in a channel. In addition, due to the increase of surface forces and friction pressure drop, the pattern of gas-liquid two-phase flow bounded to the gap of inside the rectangular channel is different from that in a tube. The downward flow in a rectangular channel is universally applicable to cool the plate type nuclear fuel in research reactor. The sub-channel of the plate type nuclear fuel is designed with a few millimeters. In this study, the flow regime on downward two-phase flow in narrow rectangular channels is proposed.

2. Experimental Apparatus and Methods

2.1 Experimental Apparatus

The observation of the air water two-phase flow pattern was performed in the closed loop apparatus. There are a vertical rectangular main test section, a pump, a pre-heater, a condenser, a cooler, a degassing system, measurement devices, and a control and data acquisition system in the test apparatus. The main test section consists of two bubble generators in up and down plenums and two transparent acrylic windows whose vertical lengths are 780 mm with the depths of 2.35 mm between them. Air is supplied by a compressor to a test section through a bubble generator that involves a porous media with the pore size of 1 μm. The air is mixed in the water at the bubble generators and the air-water mixture moves downward into the test section.

2.2 Visualization and Image Analysis

The bubble images in the test section were recorded using a high speed digital video camera with a double laser sheets source. The shadow image technique is applied for obtaining both the shape and the location of individual bubbles. In the test section, a high speed camera is utilized for performing the measurement of both phases. The trigger timings of the laser and a high speed camera are synchronized using a pulse generator supported by laser generation system. The basic recording speed and image size of the camera were set to 5,000 frames per second and 1024 × 512 pixels.

RGB images were captured by the high speed cameras, but the extraction of bubble parameters required the binary images, so it's necessary to transform the initial RGB images with noise to binary images that apply for filtering methods. In this process, many kinds of digital images processing methods were used, such as type conversion of image, noise filtering, painting algorithms and edge detection. Images are stored as a matrix in which every element is the pixel value. In RGB images, pixel color consists of three components, grayscale images only have the strength information in the images and binary images only have black and white which are referred using 0 and 1 respectively. In order to automate the image acquisition and data processing procedure, an in-house routine was developed using Matlab image processing toolbox. With this technique it was able to process a large number of bubbles and properly estimate bubble behavior.

3. Experimental Results and Discussion

2.1 Flow Regime Classification

Also similar to the upward flow regimes, downward two-phase flow regimes are usually classified into four or five regions. But it is important whether downward two-phase flow regimes have considered differences with upward flow regimes, with the sectional shape change of the sub-channel. In this paper, the flow regime was classified into six patterns by the line averaged void fraction such as large bubbly, bubbly, cap-bubbly, slug, churn-turbulent and annular flows using image processing with the high speed camera image.

Falling film flow and large bubble (LB) In low mass flow rates of gas and liquid, the falling film flow that the liquid phase streamed is observed at down near the wall. The flow pattern turns to be the annular flow with increasing the gas flow rates. When the liquid velocity increases, the bubbles gather together and flow pattern turns into the slug flow. On the contrary to this, the flow pattern becomes the bubbly flow when the liquid flow rates increases. When the superficial liquid velocity is less than 0.8 m/s and the superficial gas velocity is below 0.2 m/s in the bubbly flow development process, the bubble diameter for large bubble is close to the width of the channel. The bubbles sometimes coalesce into the large bubbles at a center of the channel. The large bubbles tend to stay at the center of the channel when the drag force and the inertia force working on the bubble are equilibrium. Figure 1 shows the averaged void fraction line of downward flow in rectangular channel.

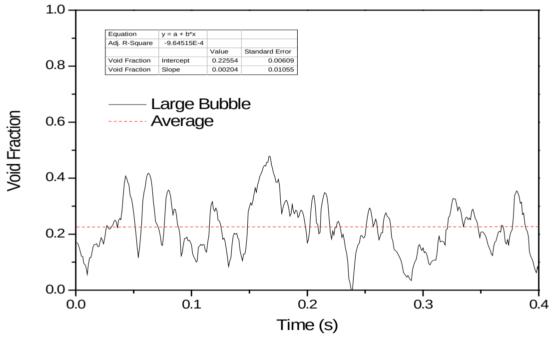

Figure 1 Void fraction of large bubbly flow

Bubbly flow (B) Due to the superficial liquid velocity increase, the large bubbles are dispersed into small bubbles. The bubbly flow is similar to that of the upward flow in circular tube. It is the significant difference observed in the bubbles in downward flow that the size is smaller than the gap of rectangular channels, and average void fraction is less than 0.25. Figure 2 show the line averaged void fraction of downward flow in rectangular channel, respectively.

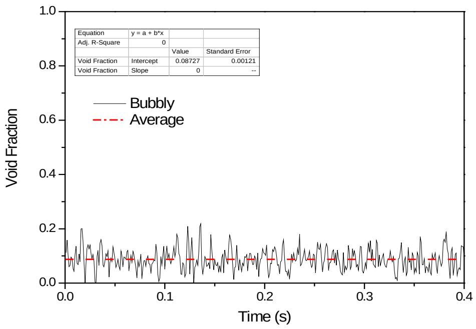

Figure 2 Void fraction of bubbly

Cap-bubbly flow (CB) In vertical downward flow, the buoyancy force is produced in opposition to the direction of gravity in the mean flow. While the low gas and liquid flow rates, the small slug bubbles shows similar shape of overturned caps. The transition from cap-bubbly to slug flow occurs at the void fraction of approximately 0.7. Figure 3 show the line averaged void fraction in downward rectangular channel.

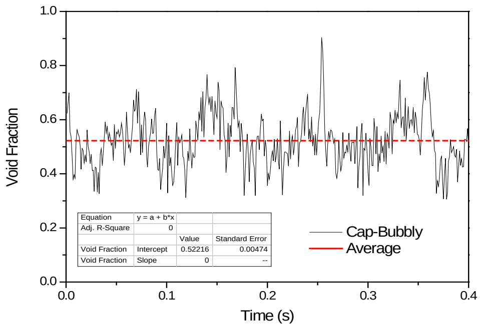

Figure 3 Void fraction of cap-bubble flow

Slug flow (S) The bubbly to slug flow transition criteria is generally used in a circular tube occurs at the void fraction of approximately 0.3 [1][2][3][4]. The slug flow observed in this study is far different from that observed in the upward flow at the narrow rectangular channel. Due to the small depth and relatively wide width of channel, the cap-bubble to slug transition occurs at the line averaged void fraction of approximately 0.7. The line averaged void fraction of slug flow was fluctuated by liquid slugs that bridge the test section. Figure 4 show 4 the line averaged void fraction in downward rectangular channels.

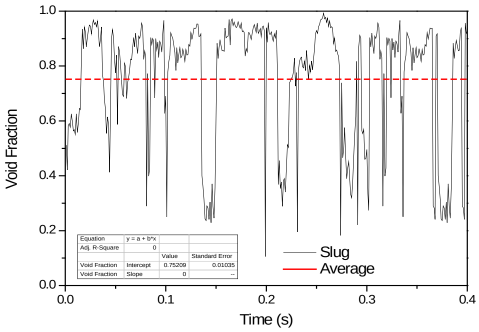

Figure 4 Void fraction of slug flow

Churn-turbulent flow (CT) When the gas flow rates increases, a breakdown in the slug flow makes the flow regime unstable. The combined liquid band is often broken up. This destroyed liquid lumps is accumulated, builds a bridge and is lifted by the gas again. Churn-turbulent flow usually shows this quicksilver liquid. The line averaged void fraction of churn-turbulent flow is close to slug flow .However churn-turbulent flow is lots more irregular, frothy and disordered than that of slug flow. Figure 5 show the line averaged void fraction in downward rectangular channel.

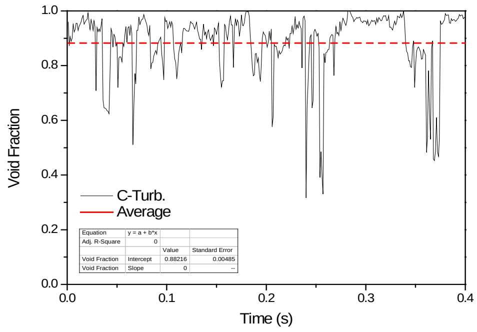

Figure 5 Void fraction of churn-turbulent flow

Annular flow (A) The gas phase flow is located in the center of the channel in an unbroken line and the liquid phase flow near the widely side wall of the channel makes film. The gas flow entrains the liquid phase as small droplets, but it is quite uncommon for bubbles to be entrained in the liquid side. Figure 6 show the line averaged void fraction in downward rectangular channel.

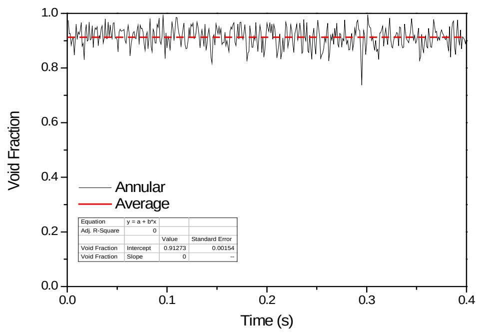

Figure 6 Void fraction of annular flow

2.2 Flow Regime Map

Flow regime map in the rectangular channel with the depth of 2.35 mm is separated into six regions using void fraction as shown above. In the flow regime map, the 60 cases of downward flow conditions with superficial gas velocity ranging from 0.02 to 8 m/s and superficial liquid velocity ranging from 0.5 to 2.5 m/s were analyzed. Figure 8 shows the flow regime map. Dot lines on the flow regime map are transition criteria of the vertical upward flow in the narrow rectangular channel suggested by Hibiki and Mishima [5]. The general transition criteria aspect of the experimental results is similar to above research.

Figure 7 shows the experimental data of the transition criteria by Hibiki and Mishima [5]. The experimental result of the downward flow regime in rectangular channel in this study is similar to transition criteria suggested by Hibiki and Mishima [5] investigated in vertical upward flow though they are in opposing directions. The flow regime studied in recent years showed that the transition criteria in the upward flow could be substitutable for that in the downward flow in relatively high superficial liquid velocities over 1 m/s.

However, at superficial liquid velocity below 0.8 m/s, a new model is needed for the criteria in the flow regime for the downward flow in narrow rectangular channel. Furthermore, the results in this experimental study showed that the cap-bubbly flow region appears in the region that is classified into slug flow region by Hibiki and Mishima [5]. Moreover, the cap bubbles in downward flow are formed in lower gas fraction than in the upward flow. This phenomenon is occurred because the opposite direction between inertial and buoyancy force that increases the bubble coalescence in downward flow. Barnea [6] researched modified model for the transition affected by inclination angle. According to his study, at superficial liquid velocity below 1 m/s, the two-phase flow is affected by the buoyancy force. In recent study said that at superficial liquid velocity approximately 0.3 m/s, the gas phase flow is continuous at center of the channel. And the liquid phase flows following both sides of the wall of channel. When the superficial liquid velocity is from 0.5 to 0.8 m/s, the bigger bubble size and the lower bubble velocity are observed while the superficial liquid velocity is over 1.0 m/s on the wall.

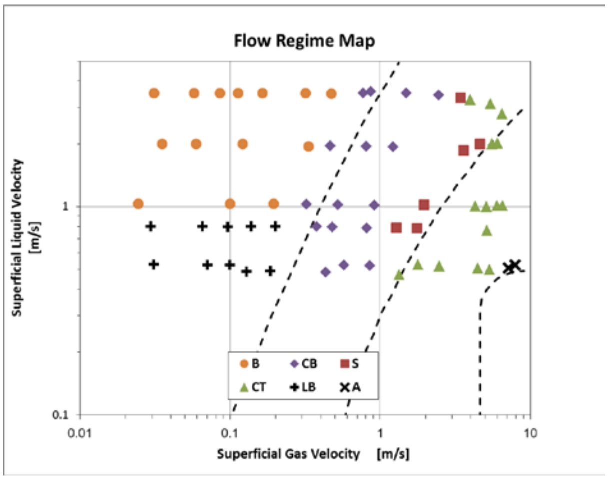

Figure 7 Two-phase flow regime map for downward flow in rectangular channel

4. Conclusions

Downward air-water two-phase flow in vertical rectangular channel was experimentally observed. The depth, width, and length of the rectangular channel is 2.35 mm, 66.7 mm, and 780 mm, respectively. The test section consists of transparent acrylic plates confined within a stainless steel frame. The flow patterns of the downward flow in high liquid velocity appeared to be similar to those observed in previous studies with upward flow. In downward flow, the transition lines for bubbly-slug and slug-churn flow shift to left in the flow regime map constructed with abscissa of the superficial gas velocity and ordinate of the superficial liquid velocity. The flow patterns observed with downward flow at low liquid velocity are different from those with upward flow. Bubbles grow much larger than channel depth at very low liquid and gas flow velocities. The large bubbles would not move upward or downward but stay in the middle of the test section for a long time. The flow regime transitions in high liquid and air velocity regions are in good agreement with transition criteria developed by Hibiki and Mishima [5] even though their model was developed for upward flow. However, it was found that new criterion should be developed for flow pattern transition in low velocities of liquid and air.

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