# Two-Phase Air-Water Flow Regime and Transition Criteria For Vertical Upward And Vertical Downward Flow Direction In A Narrow Rectangular Channel

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## 1. Introduction

Air-water two-phase flow through a narrow vertical rectangular channel has drawn an increased research interest in recent decades owing to its numerous applications such as in high heat-flux compact heat exchangers, plate type research reactors, high performance micro-electronics and space applications. In the narrow rectangular flow channel, the two-phase flow characteristics is different from those in conventional channels, largely because the bubbles are being sandwiched between the two surfaces. A thorough understanding of this phenomenon needs extensive research.

From this point of view, the authors did the adiabatic air-water flow experiment in vertical upward and downward direction in narrow rectangular channel with the aim of (1) measuring void fraction and differential pressure, (2) plotting the flow regime maps for both the flow directions based on visual observation and the void fraction, and (3) analysis and comparison of the present results with the previous studies.

## 2. Experimental Apparatus

### *2.1 Experimental set-up*

Schematic of the experimental set-up is shown in Fig. 1. The set-up consists of a vertical rectangular test section, a water tank, a pressurizer, a centrifugal pump, an air compressor coupled with an air dryer, an air-water separator, water and air piping, measurement and control instruments, and a control and data acquisition system.

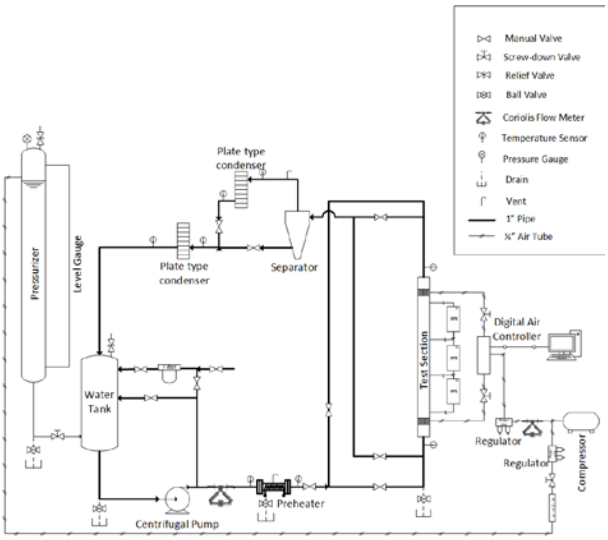


Fig. 1. Schematic of the experimental set-up

### *2.2 Test procedure and data analysis*

The experiment was performed at 28°C room temperature. Measurements were made for the superficial gas velocity ranging from 0.02 to 7.0 m/sec and for superficial liquid velocity ranging from 0.2 to 3.5 m/sec for the vertical upward flow and vertical downward flow, respectively.

A high speed digital video camera was used to record the two-phase flow pattern inside the test section and recording was done at a frequency of 5,000 fps and at 1280 x 512 pixel resolution. The shadowgraph imaging technique was used to visualize and capture the two-phase flow.

Digital image analysis was carried out with Matlab (1) and Fiji (2).

## 3. Results And Discussion

Flow regime map for the vertical upward flow and for the vertical downward flow direction is shown in Fig. 4(a) and Fig. 4(b), respectively.

Following flow regimes are observed in vertical upward direction.

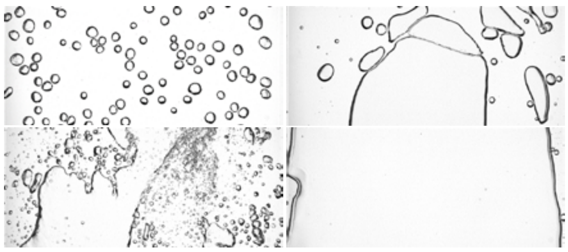

Fig. 2. Upward flow patterns (From top, left to right) (a) Bubbly flow at $J_L = 1.3$ m/s, $J_G = 0.3$ m/s, (b) Slug flow at $J_L = 0.4$ m/s, $J_G = 0.8$ m/s, (c) Churn flow at $J_L = 2.0$ m/s, $J_G = 2.5$ m/s, and (d) Annular flow at $J_L = 0.3$ m/s, $J_G = 6.0$ m/s

<u>Bubbly Flow</u>: Small circular shaped air bubbles of various size are dispersed in continuous liquid phase (Fig. 2(a)). It was observed that the transition from bubbly to slug flow occurs at void fraction of approximately 20%.

<u>Slug Flow</u>: It consists of Taylor bubbles and liquid slugs separating them. These Taylor bubbles have an approximate semi-circular nose and wide body of width closer to the test section width (Fig. 2(b)). The void fraction was observed in the range of 20 to 40% in the entire slug flow region.

<u>Churn Flow</u>: At higher superficial gas and liquid

velocity, the flow is so chaotic that it becomes frothy (Fig. 2(c)). In churn flow region, the void fraction was measured to be ranging from approximately 40 to 65 %.

Annular Flow: With further increase in gas flow rate, the liquid slug is destroyed and a continuous gas core is formed (Fig. 2(d)). In annular flow, the liquid flow is not enough to maintain the bridging liquid slug. The transition from churn to annular flow was observed to be taking place at around 65 % of void fraction.

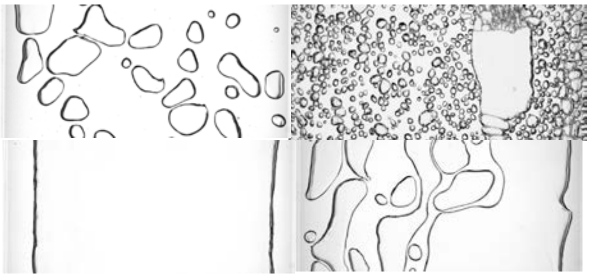

Fig. 3. Downward flow patterns (From top, left to right) (a) Large-bubbly flow at $J_L$ = 0.8 m/s, $J_G$ = 0.4 m/s, (b) Cap bubbly flow at $J_L$ = 2.3 m/s, $J_G$ = 1.7 m/s (c) Falling film flow at $J_L$ = 0.3 m/s, $J_G$ = 0.0 m/s, and (d) undefined flow at $J_L$ = 0.4 m/s, $J_G$ = 0.6 m/s

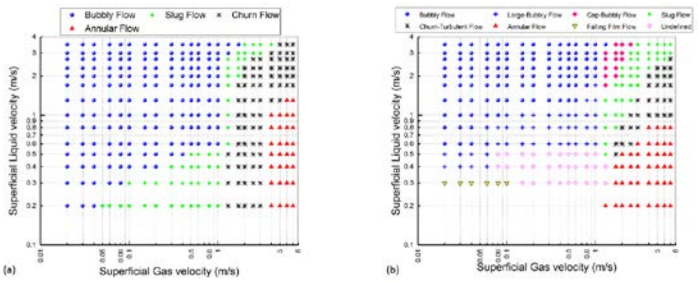


Fig. 4. Flow regime map for (a) vertical upward flow and (b) vertical downward flow in rectangular 2.35 mm test section

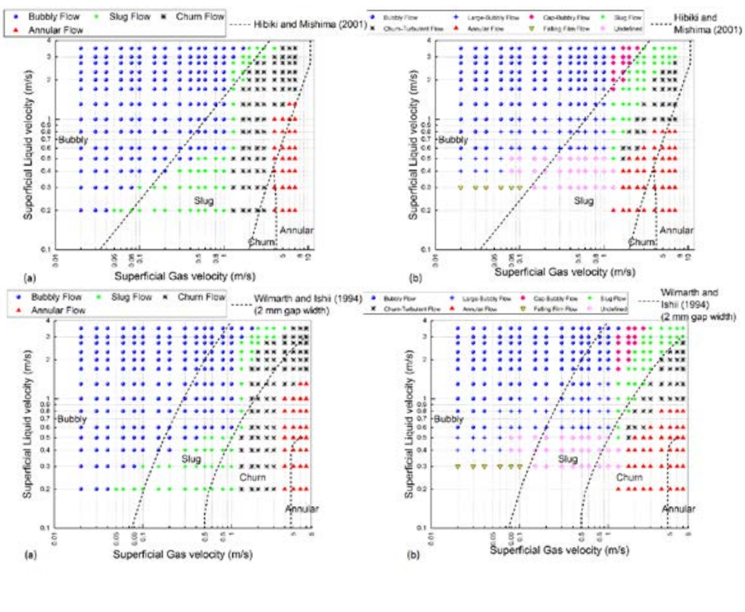


Fig. 5. Comparison with Hibiki et al. (2001) and Wilmarth et al. (1994)

In vertical downward direction, the bubbly flow is more or less similar to that in vertical upward flow, but the inertia and buoyancy force act in opposite direction. Apart from the four flow regimes as explained earlier, following flow regimes are also observed in vertical downward direction and are shown in Fig. 3.

Large-bubbly Flow: At intermediate superficial liquid velocity, with increasing gas flow rate, the bubbly flow transitions to large-bubbly flow. Two or more smaller bubbles coalesce to form larger bubbles which are laterally elongated and pressed between the narrow gap (Fig. 3(a)).

Cap-bubbly Flow: At higher superficial liquid velocity, the bubble density in bubbly flow is very high. With increasing gas flow rate, more and more bubbles coalesce to form large distorted bubbles which look like inverted caps as shown in Fig. 3(b). The bubbly flow to cap-bubbly flow transition appears to happen at void fraction of 20 to 30 %.

Falling Film Flow: Falling film flow is a gravity flow where a continuous thin layer of liquid glides smoothly on the edges of the width of the test section and air flows at the center of the test section (Fig. 3(c)). At low air flow rate and low liquid flow rate when the liquid flow is not enough to fill the entire test section, the liquid falls down the test section as a thin layer close to the width surface.

Undefined Region: At intermediate superficial liquid and gas velocities, the flow was observed to be exhibiting the mix of two or more different flow patterns and was impossible to classify as one specific flow pattern. It is shown in Fig. 3(d)

Current flow regime maps are compared with the flow regime maps proposed by Hibiki et al (3) and Wilmarth et al (4) for the vertical upward flow in round pipe and rectangular test section, respectively and are shown in Fig.5. In case of upward flow, Wilmarth et al.'s flow regime map is more in agreement with current flow regime map. In downward flow case, bubbly flow region conforms well with the compared flow regime maps, but other regions either lay out or are widely spread. This is because of the opposite direction of flow in present study and compared studies.

In case of large-bubbly flow in downward direction, a significant buoyant force acts on these large bubbles which results in slowing them down significantly. While at some instances, the inertia force, wall shear and buoyant force acting on the large bubbles is in equilibrium. Because of this equilibrium, for example, at $J_G$ = 0.1 m/s and $J_L$ = 0.6 m/s, the bubbles appear to be stationary in the field of view for a longer time while the liquid phase is continuously moving downwards. The downward movement of liquid phase can be observed with very small bubbles moving past these large bubbles. Because of the liquid motion past them, the large bubbles are displaced laterally as well as angularly. Snippets for this phenomenon is shown in Fig. 6. Air bubbles, in this case, A, B, C and D are remaining relatively stationary in the field of view. Bubble A is seen to be breaking into bubbles A1 and A2 while arrows indicate the forthcoming merger of two bubbles to form a larger bubble.

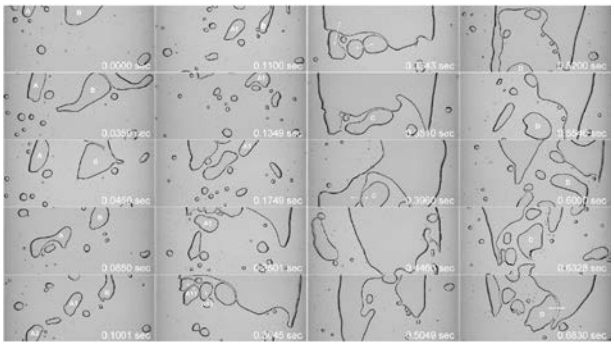

Fig. 6. Large-bubbly flow snippets at mentioned time intervals. Air bubbles, in this case, A, B, C and D remaining relatively stationary in the field of view. Bubble A is seen to be breaking into bubbles A1 and A2. Arrows indicate the forthcoming merger of two

## 4. Conclusion

Four different flow patterns, namely bubbly flow, slug flow, churn flow and annular flow are identified for the vertical upward flow direction and seven flow patterns, namely bubbly flow, large-bubbly flow, cap-bubbly flow, slug flow, churn-turbulent flow, falling film flow and annular flow are identified for the vertical downward flow direction.

Falling film flow is absent in vertical upward flow direction and is observed in only vertical downward flow direction at low superficial liquid and gas velocities.

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