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Flow patterns of vertically upward and downward air-water two-phase flow in a narrow rectangular channel

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A B S T R A C T

Considering the importance of two-phase flows in narrow rectangular channels and their use in various applications, the hydrodynamics of a co-current air-water two-phase flow in a vertical narrow rectangular channel has been studied. Experiments have been carried out and flow regime maps for vertical upward and vertical downward flows have been plotted based on measured data sets. Flow regimes were identified and classified based on visual observation and void fraction data. Flow visualization was performed using a high speed camera, while a void fraction analysis was done using the electrical impedance method and a digital image analysis. Four different flow patterns were identified for the vertical upward flow and seven flow patterns were identified for the vertical downward flow. The flow regime map for the vertical upward flow was compared with previous studies and also with the flow regime map obtained for the vertical downward flow in this study.

Nomenclature

$\propto$	time-averaged void fraction*
$\underline{f}_{i,j,k}$	image frame at time k*
$f_{i,j,k}$	mean image of the stack*
i, j	image co-ordinates*
J_L	superficial liquid velocity (m/s)
J_G	superficial gas velocity (m/s)
k	time (s)
$stdDev$	standard deviation (Gray scale value)
V_m	voltage signal from electronic circuit for a given void fraction (V)
V_{air}	voltage signal from electronic circuit for only air (V)
V_{water}	voltage signal from electronic circuit for only water (V)
Y^*	normalized admittance*
Y_m	instantaneous two-phase mixture admittance (siemens, S)
Y_{air}	admittance of only air (siemens, S)
Y_{water}	admittance of only water (siemens, S)

*Dimensionless.

1. Introduction

Among the 243 operational research reactors worldwide [1], some use plate type fuel. For example, the KIJANG Research Reactor (KJRR), being developed by The Korea Atomic Energy Research Institute (KAERI), plans to use low enriched uranium (LEU) plate type fuel with vertical downward flow of the coolant through narrow rectangular channels. The KJRR will be mainly used for isotope production for industrial and medical purposes, neutron transmutation doping (NTD), and research related activities [2]. It is necessary to study the two-phase flow inside vertical narrow rectangular channels for safety analysis of the plate type nuclear fuels. Despite its importance, research on two-phase flows in narrow rectangular channels is very limited in the open literature whereas there have been numerous works concerning two-phase flow behavior inside circular tubes, annulus, and sub-channels in rod-bundle assemblies. The two-phase flow in a narrow rectangular channel has drawn increased research interest in recent decades owing to its numerous applications such as in high heat-flux compact heat exchangers [3–5], plate type nuclear fuels [6–10], and high performance micro-electronics [11,12]. In a narrow rectangular flow channel, the two-phase flow characteristics are different from those in conventional channels because bubbles are confined between narrow side walls.

One of the major difficulties in the study of two-phase flow is the understanding of mass, momentum, and energy transfer and its sensitivity to the geometric distribution or topology of the two-phase flow. The topology heavily influences the interfacial area available for mass, momentum, and energy transfer between two phases. Also, the flow of each phase is dependent on the phase's geometric distribution. The articulation of the geometric distribution, also called the flow patterns, thus becomes an

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appropriate starting point in two-phase flow study. From this point of view, many studies on generating flow regime maps have been conducted. The following is a brief summary of these recent studies on flow regimes in circular and narrow rectangular channels. Sadatomi et al. [13] carried out vertical upward two-phase flow experiments in rectangular (17, 10 and 7 mm gap width), triangular, and annular channels and presented flow regime maps. They concluded that the channel geometry has little influence on the flow pattern transitions in non-circular channels when the hydraulic diameter is greater than 10 mm. Mishima and Ishii [14] suggested void fraction based flow regime classification for a two-fluid model. Transition criteria were developed and a flow regime map was plotted based on these new criteria and compared with the experimental datasets for the upward two-phase flow inside circular pipes with good agreement. Usui and Sato [15,16] investigated the vertical downward two-phase flow of an air-water mixture in an inverted U-tube of circular tubes with inside diameter of 16–38 mm. Bubbly, slug, falling film, and annular flow regimes were observed. In part I of the paper, they observed that the average void fraction in the vertical downward flow depended highly on the flow regimes compared to that in the vertical upward flow, especially in slug and falling film flows. This is because, in a downward flow, the gravity force acts in the direction of the flow, while the buoyant force acts in the opposite direction of the bubble flow. In part II of the paper, Usui proposed transition criteria for bubbly, slug, and annular flow regimes in vertically downward two-phase flows inside the inverted U-tube used in part I. They found that the transition from bubbly to slug flow occurs at an average void fraction of 0.25 to 0.30, which also confirmed the transition criteria of 0.30 proposed by Mishima and Ishii [14]. It is noteworthy that Usui and Sato did not classify the churn flow as an independent regime, but instead they included it in the slug flow regime even though the churn flow can be visually distinguished from that of the slug flow.

Ali et al. [17] investigated an adiabatic co-current air-water flow through a narrow rectangular passage between two flat plates with gap widths of 0.778 mm and 1.465 mm for six different orientations including vertical upwards and downwards, inclined and horizontal. The electrical conductivity method was used to measure the local and average void fractions and flow regime maps for all the orientations were plotted. Two-phase flow patterns, void fraction, and friction pressure drop in the narrow rectangular passages were found to be similar for all the orientations except the horizontal flow condition. Interestingly, they observed minimal change in these parameters with the change in gap width. Mishima et al. [18] measured void fraction, slug bubble velocity, and pressure loss for vertical upward flows in rectangular ducts with narrow gaps of 1.0–5.0 mm and plotted flow regime maps with bubbly, slug, churn, and annular flows identified. They observed that small bubbles, cap bubbles, and slug bubbles were crushed in the narrow gap, and they thereupon determined the flow regime based on the shape characteristics of the bubbles. The transition line between slug and annular flow was well reproduced by the Jones-Zuber equation while the churn flow was found to be missing for the channel gap of 1.0 mm. Another study of two-phase air-water vertical upward flows with 1.0 mm and 2.0 mm gap width was carried out by Wilmarth and Ishii [19]. As with the previous studies, they observed four flow regimes (bubbly, slug, churn-turbulent, and annular flow) and three transition regions (cap bubbly, elongated slug flow, and churn-turbulent to annular region). The transition criteria of Taitel et al. [20] and another by Mishima and Ishii [14] were also validated against the experimental data. They observed that the theoretical transition lines were situated slightly to the right of the plotted transition lines; i.e. the models predict that the transition occurs at high gas superficial velocity.

Xu et al. [21] proposed a flow regime transition model for a vertical upward two-phase flow in a rectangular channel. This model was tested with the experimental results obtained from two-phase flows in rectangular channels with gap width of 0.3, 0.6 and 1.0 mm. Flow regimes for 0.6 and 1.0 mm channel gaps were found to be similar to those for the conventional large gaps. However, for mini-gap width of 0.3 mm, the flow regime was significantly different and a bubbly flow was not observed at very low gas flow rates. They concluded that the two-phase flow in the mini-gap width of 0.3 mm necessitates the development of a new model. Hibiki and Mishima [22] developed flow regime transition criteria for a vertical upward flow in narrow rectangular channels based on the same principles of Mishima and Ishii [14] for vertical round tubes. They documented the effect of the distribution parameter on the flow regime transition criteria. They summarized that the newly developed transition criteria showed satisfactory agreement with the experimental data for mini-rectangular channels, but were considerably inaccurate in the prediction of a two-phase flow inside channels having a gap width less than 1.0 mm. Kim et al. [23] studied an adiabatic vertical downward air-water two-phase flow inside a round pipe with 25.4 and 50.8 mm internal diameter. They observed that the flow regime boundaries were highly dependent on the flow area in the vertical downward flow, unlike in a vertical upward flow. In a bubbly flow, the bubbles were observed to be migrating towards the center of the pipe, a phenomenon called "coring". Also, the bubble velocity was less than the surrounding liquid phase velocity. It was also concluded that the mechanisms of the bubble coalescence and disintegration were similar to those in a vertical upward two-phase flow.

Bhagwat and Ghajar [24] investigated flow patterns and carried out void fraction measurements for vertical upward and downward two phase flows in a 12.7 mm internal diameter pipe using an air and water mixture. Significant differences in the appearance of the bubble and slug flow regimes were observed in the flow

Fig. 1. Two-phase flow experimental setup with 2.35 mm test section.