Annals of Nuclear Energy 114 (2018) 384–394

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Visual observations of flow patterns in downward air-water two-phase flows in a vertical narrow rectangular channel

Tae Hyeon Kim[b], Vikrant Siddharudh Chalgeri[a], Woosung Yoon[a], Byong Jo Yun[a], Ji Hwan Jeong[a,*]

[a] *School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea*
[b] *Korea Hydro & Nuclear Power Company Central Research Institute (KHNP-CRI), 70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejeon, Republic of Korea*

ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 21 December 2017
Accepted 23 December 2017

Keywords:
Flow regime map
Downward flow
Rectangular channel
Two-phase flow

ABSTRACT

Flow patterns in downward air–water two-phase flows in a narrow rectangular channel were visually observed. A test section was constructed using transparent acrylic plate with a test channel 2.35 mm thick, 66.6 mm wide, and 780 mm long. The experiments determined that at high liquid velocity the flow patterns for downward flow are similar to those observed in upward flow. However, at low liquid velocity some significant differences were observed between downward and upward flows. The new flow patterns, falling film flow, large-bubbly flow, and intermediate flow, were identified in the low liquid velocity region, where buoyancy force is influential. A flow regime map for downward flow in a narrow rectangular channel was constructed using the experimental data and analyses.

1. Introduction

Downward flow in a narrow rectangular channel is a phenomenon that can be observed in the plate type nuclear fuel of research reactors Lee et al. (2013), the heat transfer tubes of heat exchangers Yun and Jeong (2016), and various thermal energy conversion systems (Faizal et al., 2016). For example, coolant flows downward through narrow rectangular channels in the KIJANG research reactor, which uses plate type nuclear fuel. The subchannels of the plate type nuclear fuel are usually designed to have a gap of a few millimeters. To conduct an enhanced safety analysis of research reactors that utilize plate type nuclear fuels, the thermal-hydraulic characteristics inside the narrow rectangular channel, such as pressure loss and heat transfer, need to be determined. To characterize the thermal-hydraulics, it is necessary to identify the flow pattern and construct a flow pattern regime map.

In the last 50 years numerous studies have been conducted to investigate two-phase flows in vertical channels. Most of these studies have focused on upward flows in vertical circular and annular channels. In the open literature, it is rare to find research on downward two-phase flow in narrow rectangular channels. The behavior of a gas-liquid two-phase flow inside a narrow rectangular channel should be different from that in a circular tube because the two-phase flow in a narrow rectangular channel is confined by the two flat walls which comprise the narrow channel. Furthermore, the behavior of a two-phase mixture flowing downward in a channel will be somewhat different from that of an upward flow because the flow direction is opposite to the direction of gravity.

A number of previous researchers have investigated the flow pattern of an upward two-phase flow in a rectangular channel. Wilmarth and Ishii (1994, 1997) experimentally investigated the flow regime of an upward two-phase flow in rectangular channels that had gap widths of 1 and 2 mm. They conducted a comparative analysis for their data using the flow regime transition criteria for a circular tube suggested by Mishima and Ishii (1984); and proposed a new distribution parameter needed for the boundary of bubbly-slug flow. Xu (1999) performed an experimental study on adiabatic upward air–water two-phase flow in rectangular channels with gap widths of 0.3 mm; 0.6 mm and 1.0 mm. At low gas flow rates, the flow regime in the 0.3 mm gap width channel was quite different from that of the larger gap channels. Hibiki and Mishima (2001) measured flow regime, void fraction, the velocity of a slug bubble and pressure drop in rectangular channels with gap widths of 1.0 mm, 2.4 mm and 5.0 mm. They also developed new flow regime transition criteria and compared them with the previous experimental data for two-phase flow in narrow rectangular channels with various gap widths from 0.3 mm to 17 mm. They obtained experimental results that were different from those of a circular tube, due to an increase in void fraction and interfacial area concentration. Transition lines in particular shifted to lower gas velocities, and flow regime regions were changed in the narrow rectangular channel.

---

* Corresponding author.
E-mail address: jihwan@pusan.ac.kr (J.H. Jeong).

https://doi.org/10.1016/j.anucene.2017.12.053
0306-4549/

Two-phase downward flows have also been investigated using circular and annular channels. Oshinowo and Charles (1974) investigated a two-phase downward flow in a vertical annular channel and categorized the flow patterns into six groups, then developed a model with various fluid properties. Both Martin (1976) and Kulov et al. (1979) performed experimental research on the transition from bubbly to slug flow and slug to annular flow for downward flow. Flow regime maps for downward two-phase flows in circular tubes covering a wide range were proposed by Usui and Sato (1989); Spedding and Nguyen (1980), Barnea et al. (1982), Kendoush and Al-Khatab (1994), Usui (1989), Goda et al. (2003) and Julia et al. (2013). They proposed flow regime transition criteria based on a drift-flux model, or experimental results such as the void fraction and chord length distributions of the bubbles. Swanand and Afshin (2012) experimentally observed differences in appearance between the upward and downward two-phase flow regime in terms of the flow patterns and the void fraction. They reported that bubbly and slug flow regimes were significantly different for the upward and downward flows. They also reported that churn flow was not observed, while falling film flow appeared in the downward flow. They concluded that the differences between the upward and downward flows were caused by interactions between the liquid's inertia and the buoyancy force.

Two-phase flow behaviors in a channel with rod bundles and annulus have also been investigated. Paranjape et al. (2011) experimentally investigated two-phase flow in a sub-channel surrounded by rod bundles, while Sun et al. (2004) and Julia et al. (2011) performed experiments with an annulus flow channel. Unlike most previous studies, they classified the cap-bubbly flow as a common, independent flow regime. These studies clearly showed that the shape of a channel changes the flow regimes.

As introduced above, numerous studies have focused on identifying two-phase flow patterns and constructing flow regime maps, but there has been scarcity of study in the open literature on downward two-phase flow in narrow rectangular channels. The behaviors of two-phase flow in a narrow rectangular channel differ from those in a circular channel, and from upward flow, in terms of interactions between the forces of buoyancy, gravity and liquid inertia.

In this study, experiments were performed to investigate the flow patterns of downward two-phase flow in vertical rectangular channels with a gap width of 2.35 mm (the same width as the gaps between plate type fuels in the KIJANG research reactor). The behavior of the downward two-phase flow in the rectangular channel was visually observed using a high-speed camera, and the captured images were analyzed to obtain the values of the associated parameters. Based on these analyses, a flow regime map for the downward two-phase flow in a rectangular channel was constructed.

2. Experimental apparatus and methods

2.1. Experimental apparatus and procedure

In order to observe the flow pattern of a downward air-water two-phase flow in a narrow rectangular channel, a closed-loop experimental apparatus was constructed. Fig. 1 shows a schematic of the closed-loop experimental apparatus and the test section. The experimental apparatus consists of a vertical rectangular test section, a centrifugal pump made of stainless steel, a pre-heater, a condenser, a cooler, a degassing system, measurement devices, and control and data acquisition systems. The flow direction of the working fluids in the test section could be switched between upward and downward directions by closing or opening the valves labeled V1 and V2. The water flow rate was regulated by a manual control valve, V3. The test section was constructed with two transparent acrylic plates and two stainless steel side walls so that the flow channel was 2.35 mm thick, 66.6 mm wide, and 780 mm long.

The two-phase mixers are installed in between the top-end of the test section and the upper plenum and between the bottom-end of the test section and the lower plenum. For the downward flow experiments, water and air were supplied to the test section through the two-phase mixer installed between the test section and the upper plenum. Fig. 2 shows a schematic of the two-phase mixer. Water is supplied downward from the upper plenum while air is supplied through a porous metal which has a pore size of 1.0 μm. The porous metal screen was employed so that the air can be supplied to the channel as evenly as possible and prevent the flow of water back into air ducts via the porous metal screen. The air is mixed with the water and the air–water mixture flows downwards into the test section. The flow of bubbles was observed at various locations using a high-speed camera and distribution of void fraction across the channel width was calculated. The distributions of void fraction at various distances from the channel entrance are displayed in Fig. 3. The distribution of void fraction appeared to be fairly uniform across the channel width.

Air bubbles generated inside the upper two-phase mixer are dragged downwards by the downward water flow. After running through the test section, the air-water mixture flows into a two-phase separator where the air is separated and discharged into the atmosphere while the water returns to a water storage tank. A Coriolis flowmeter and a thermal mass flowmeter were used to measure the air flow rate while another Coriolis flowmeter was used to measure the water flow rate. Temperatures at various locations in the experimental apparatus were measured using copper-constantan (T-type) thermocouples. One static pressure transmitter and three differential pressure transmitters were installed to read pressure across the test section. The uncertainties in the measurements of flow rate, temperature, and pressure were 0.1% of reading, 0.3 °C, and 0.05% of span (3.0 kPa), respectively.

Experiments to observe the two-phase flow behavior inside the channel and to identify the flow pattern were conducted in the following sequence. At first, the air flow rate was set at a minimum level to prevent water from entering the air supply line. Secondly, the liquid flow regulating valve was opened and the liquid flow rate was set at a pre-determined level. Thirdly, the gas flow rate was increased in a stepwise manner. Then, the apparatus was visually observed until the two-phase flow reached a quasi-steady state. Video images were captured using a high-speed camera during this quasi-steady state. When the video image recording was finished, the gas flow rate was increased and the third step was repeated. When the air flow rate reached a maximum level, the level of liquid flow rate was increased and the sequence was repeated from the second step.

Concerning the dominant force on a two-phase flow through a narrow channel, a confinement number (Co) can be used as a measure to consider the effect of channel size (Cornwell and Kew, 1993).

$$Co = \frac{\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}}{d_h} \tag{1}$$

where σ, g, ρ_l and ρ_g are the surface tension, gravitational acceleration, and the density of the liquid and gas phases, respectively. d_h is the hydraulic diameter of the channel, defined as $d_h = 4A/P$, where A and P represent the cross sectional area and perimeter, respectively. Co represents the ratio of surface tension force to gravitational force. Generally, the value of Co is larger for micro/mini channels because of the dominant surface tension force. Suo and Griffith (1964) suggested that the effect of buoyancy is negligible when the confinement number is larger than 3.3. The confinement