EXPERIMENTAL INVESTIGATION OF HYDRODYNAMIC PHENOMENA IN VERTICAL-UPWARD ADIABATIC TWO-PHASE FLOW CONDITIONS

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Abstract

In order to investigate on hydrodynamic phenomena in two-phase flow conditions in nuclear safty analysis, a series of two-phase flow experiments were conducted using a single flow channel in which air and water were simultaneously injected into the test section. The experiments under atmospheric pressure condition were carried out with the water velocity and the air velocity covering the ranges from 0.2 to 1.5 m/s and 0.05 to 0.2 m/s respectively. The technique of two-sensor conductivity probe was used for the measurement of bubble parameters The experimental results presented in this study are the local time-averaged void fraction, bubble velocities at three axial positions L/D = 10, 50 and 70.

Keywords: *two phase flow regime, two phase flow experiment, conductivity probe method.*

1. Introduction

From an engineering viewpoint, the final objective of studying two-phase flow is to determine the heat transfer and pressure drop characteristics of a given flow. A particular situation of this kind, which is of special interest to nuclear engineers, is analyzing and predicting two-phase flow transients in nuclear power reactors under various operational transients or accident conditions, e.g. LOCA (Loss-of-Coolant-Accident). The two-phase flow may exist in parallel flow channels as in the reactor core, or in a large pipe and connections as in the cooling loops. The adiabatic flow with head addition is a coupled thermodynamic problem in which heat transfer cause phase change and hence a change of phase distribution and flow pattern; on the other hand, it causes a change in the hydrodynamics, such as a pressure drop along the flow path that affects the heat transfer characteristics. Futhermore, a single-component, two-phase flow in a channel can hardly become fully developed at low pressure because of the shape change in large bubbles and the inherent high complexity in adiabatic two-phase flow, where a local or point description is insufficient without knowledge of the previous “history” of the flow. Additional complexities are introduced by the hydrodynamic instabilities and the occasional departure from thermodynamic equilibrium between the phases [L.S. Tong and Y.S. Tang]. To avoid such complexities, a relatively large amount of experimental work have so far been conducted that are based on the assumptions of fully developed flow patterns and without heat addition to the flow, the so-called adiabatic two-phase flow. Through these research works, the flow structure of air-water two-phase flow was figured out, and many flow-pattern maps have been proposed using dimensional coordinates based on the liquid and gas superficial velocities. All of these maps are based on experimental data; and, therefore, the big question is whether these maps can be extrapolated to a wider range of tube diameters, fluid properties and flow patterns or not.

For a few decades, a considerable amount of works on the measurements of local two-phase flow parameters has been successfully performed by many investigators since Neal & Bankoff (1963)’s work on the measurement of local void profile in air-water flow condition [1]. However, it is true that there is not enough data to adequately support a wide range of continuing efforts in calibration and validation of advanced models and codes [Nam Dinh, NURETH-15].

With new approach of data-driven concept in experimentation, modeling, and analysis of CFD appplications for Nuclear Reactor Safety, the present work is an experimental investigation of various local parameters of cocurrent air-water two-phase flow, flowing upward in a vertical circular tube of 25.4 mm i.d. under nearly atmospheric pressure. Due to constraints on the financial and human resource issues, emphases are put on the following: 1) Description of some statistical and hydrodynamic characteristics of flow patterns transition in vertical-upward air-water flow; 2) Measurment of the local parameters of two-phase flow for validation of CFD code.

2. Experimental aparratus

The experiment was installed at VINATOM for studing two-phase flow regime, transition phenomena, and measurement of two-phase flow parameters such as void fraction, bubble velocity. The principle of the experiment is shown in Figure 1. It consits of test section, bubble generator, water supply system, air supply system and data accquisition system. Test section is a vertical transparent tube with the inner diameter of 25.4 mm and the height of 2 m. Two-sensor conductivity probe is located at three positions L/D = 10, 50 and 70 for measuring the two-phase flow parameters. In order to measure the pressure of the system, an absolute pressure and a differential pressure are installed. The Rosemount 3051C absolute pressure is connected to the L/D = 10 while the Rosemount 2880 differential pressure is connected to the L/D = 50 and 70.

Air is supplied by air compressor with the capacity of 1 HP. After passing the test section, the gas is released to the environment through a separator while the water is returned to the Water tank. The water flow rate is measured by a coriolis flow meter with the range of 0-3000 kg/h and the error of 0.2% - 0.5% for the entire operating range, while air flow rate is measured by rotameter with the range from 0.2 - 30 l/m and the error of ± 2%. The bypass water flow was also measured by the rotameter with the measuring range of 6 l/h to 60 l/h. The data collection and processing system includes a signal conditioner, A/D signal converter, and a computer with LabVIEW software. The visualization of the two-phase flow is achieved through high-speed camera with the maximum frame rate of 1000 and Xenon lamps.

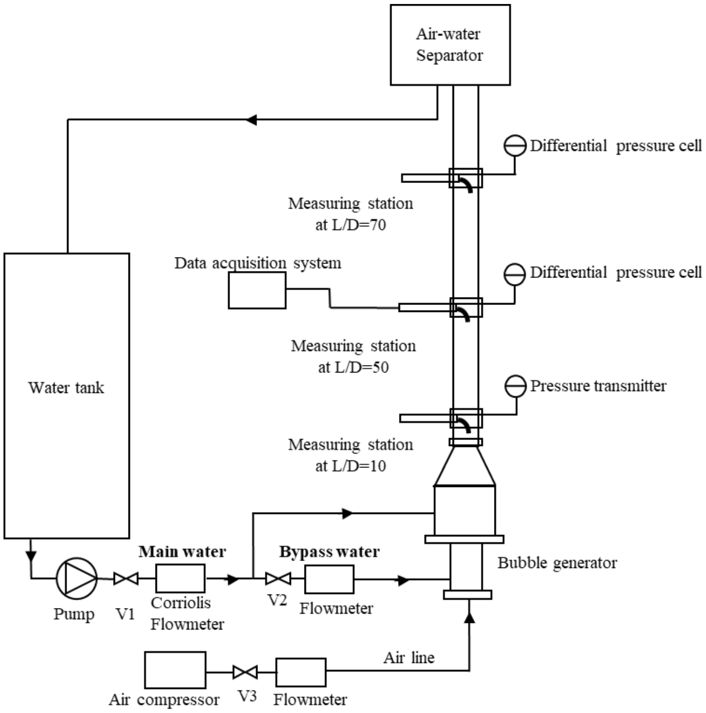

Figure 1. Schematic of test facility

3. Signal processing technique of local two-phase flow parameters

3.1. Two-sensor conductivity probe

The conductivity method was first proposed by Neal and Bankoff to determine the void fraction and bubble velocity in air - water two-phase flow. This method has been developed by many researchers. Two-sensor conductivity probe is based on the continuous value of local conductivity in two-phase flow with each sensor tip acting as an electrode. The circuit made up of sensor tips is in "Open" or "Close" state depending on the sensor tip contacted with the water or gas.

In this study, the two-sensor conductivity probe is mounted L/D= 10, 50 and 70 upstream of the bubble generator. As shown in Figure 2, it is possible to change the radial position of the probe in the cross-section by means of a traversing mechanism. By performing measurements at different radial locations, radial profiles of time-averaged two-phase flow parameters can be measured.

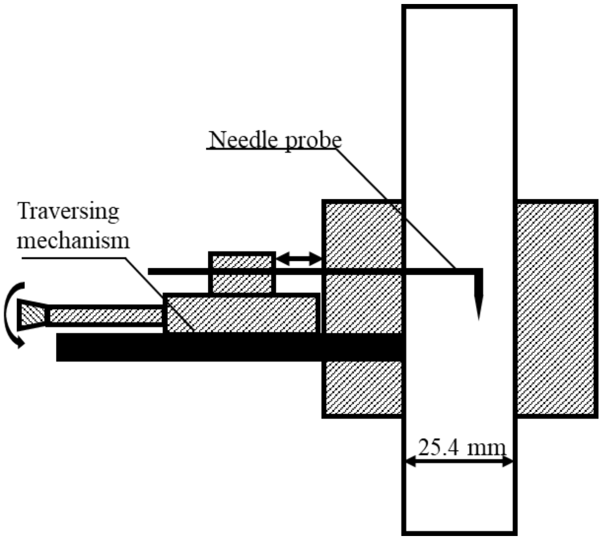

Figure 2. Instrumentation set-up

A sketch of the two-sensor probe is shown in Figure 3. Two sensor tips is made by thermal couple wire type K with cross section of 0.2 mm. Sensor tips will be sharpened to the cone shape.

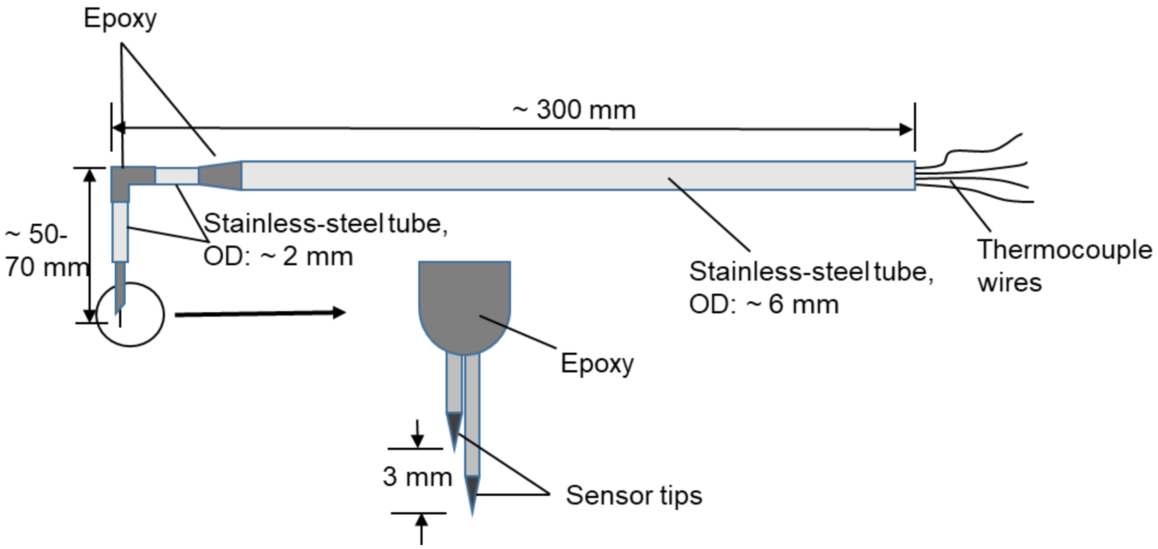

Figure 3. Sketch of the two-sensor conductivity needle-probe

3.2.Signal processing

The sensor probe is initially placed in the water with the low voltage signal. When the sensor contact with the gas, a higher voltage level is obtained. The signal form is very different from the ideal square wave since each sensor has a finite size and time delay due to wetting and rewetting phenomenon. Therefore, it is necessary to make a signal-processing program for obtaining exactly the necessary information from the raw signal. The signal-processing program was developed on LabVIEW software combined with MATLAB language with 4 main parts: signal reading & nomanization; making cut-off level; transrectangle & filting and bubble statics.

First, signals from rear and front sensors will be read and standardized. The goal is to eliminate high frequency noise signals. Then the cut-off value is set to trigger a square signal. As Yun (1992), it is extremely important to determine the appropriate cut-off level for obtainning the value of the void fraction and bubble velocity accurately. Threshold level is calculated based on the standard level of pulse amplitude and standard level of the slope edge, in which these standards can vary with each bubble, instead of being assigned by a given constant for all bubbles.

After determining the cut-off value, the signal will be converted into square signal and filter out unsuitable parts of square pulse in the part of Signal TransRectangle&Filtering. This process is based on the algorithms of Yun [15] and Euh [20]. Finally the two-phase flow parameters is calculated in the part of Bubble Statics.

From the square wave signal, the number of bubbles that hit the sensor can be measured by counting the number of pulses in the signal. The interfacial velocity of each interface can be obtained by using the distance to the different tips of the two-sensor probe, and time delay between the upstream and downstream signal. Local parameters of the two-phase flow has been calculated as below.

- *Local time-averaged void fraction:*

The time-averaged void fraction is a function of the total sampling time - Ω, and the accumulated pulse widths of the upstream sensor during the sampling period. Thus, this time-averaged void fraction is simply the accumulated time the sensor is exposed to the gas phase divided by the total sampling time of the sensor.

$$\bar{\alpha}^t = \frac{1}{\Omega}\sum_{j}^{N_t}(t_{TF} - t_{TR})_j$$

Where, N_t is the number of bubbles that strike the sensor; $(t_{TF} - t_{TR})_j$ is the time that the sensor is exposed to the gas phase.

- *Local interfacial velocity:*

The interfacial velocity can be computed by taking into account the span among the tips of the front and rear sensor and the time difference between the front and rear signal. Thus, the time-averaged interfacial velocity is given as:

$$\left|\vec{v}_{szj}\right| = \frac{1}{N_{tv}}\sum_{i}^{N_{tv}}\frac{\Delta s}{t_{RR} - t_{TR}}$$

Where, Δs is the distance between the front and rear sensor; $t_{RR} - t_{TR}$ is the relative time between the bubble striking the front and rear sensor.

4. Prelininary results and Discussion

Experiment data was collected at 8 radial measurement points with each point distance of 1.5 mm along three axial positions (L/D = 10, L/D = 50, L/D = 70). The temperature is 45°C. All the flow conditions is summeried Table 1.

Table 1. Experimental flow condition

Parameter	Run 1-5	Run 6 -10	Run 11-13	Run 14-16	Run 17-19	Run 20-22	Run 23-25
Superficial gas velocity, j_g [m/s]	0.05	0.10	0.20	0.30	0.50	0.80	1.00
Superficial water velocity, j_f [m/s]	0.2	0.2					
	0.3	0.3	0.2	0.2	0.2	0.2	0.2
	0.5	0.5	0.3	0.3	0.3	0.3	0.3
	1.0	1.0	0.5	0.5	0.5	0.5	0.5
	1.5	1.5					
Mass Flow rate of Gas, W_g [g/s]	0.032	0.065	0.129	0.194	0.323	0.517	0.647
Mass Flow rate of Water, W_f [kg/s]	0.10 0.15 0.25 0.51 0.76 0.10	0.10 0.15 0.25 0.51 0.76 0.10	0.10 0.15 0.25	0.10 0.15 0.25	0.10 0.15 0.25	0.10 0.15 0.25	0.10 0.15 0.25

Experiments carried out are represented in the flow regime map shown in figure 4.

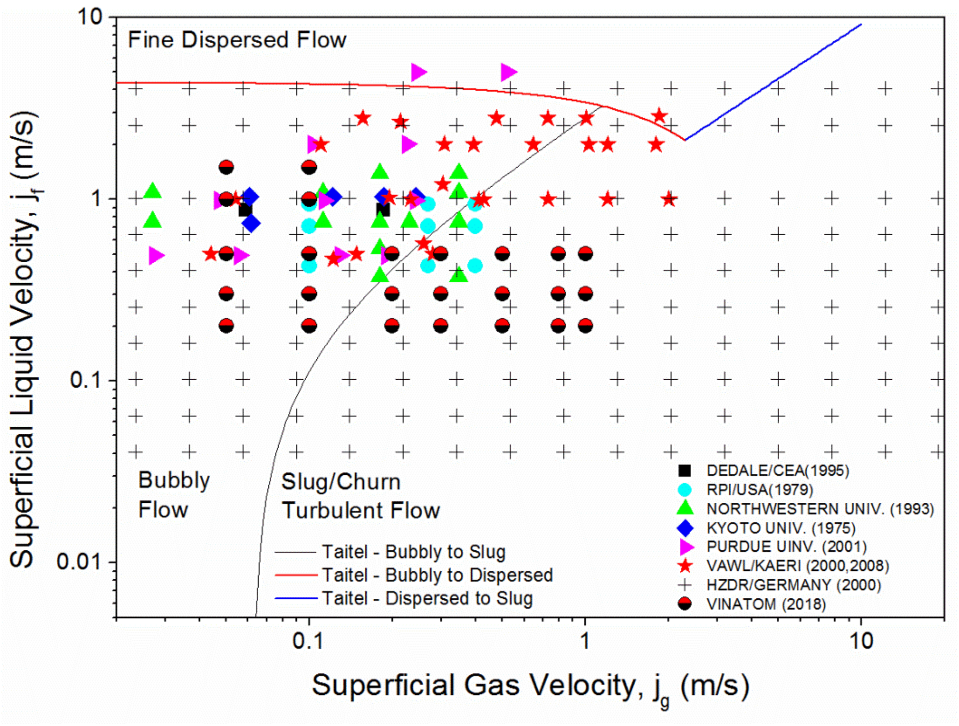

Figure 4. Test conditions on flow regime map

4.1.Data verification

In order to ensure accuracy of measurement results, the image technique is appled using the high-speed camera with xenon lamp for observing and recording the time of bubbles passed through the conductivity probe. Independent small-scale experimental system was built. Test Section is a shape square acrylic box with the size of 2x2 cm and the length of 40 cm. A small steel tube are used to generate a single bubble with a diameter of 2 to 5 mm. It is possible to determine the velocity of each bubble through the image processing software developed by the research team of Hanoi University of Science and Technology. Figure 5 presents the results of comparison of the velocity measured by the imaging technique and conductivity probe. The difference between two measurement techniques is within ± 15%. This result is a good and suitable for use in two-phase flow experiment.

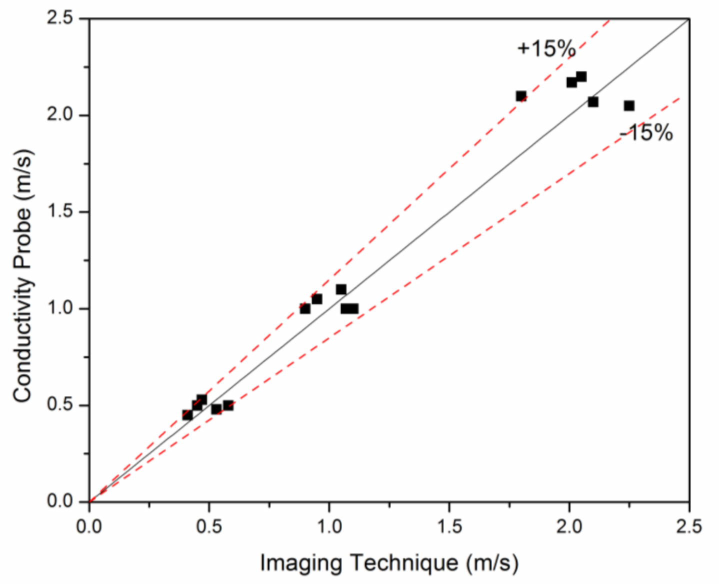

Figure 5. Comparison of bubble velocity obtained by Imaging Technique and Conductivity Probe

4.2.Local time-averaged void fraction

a. Bubbly

In order to present better local parameter distribution and transport characteristics, the results of bubbly flow test condition Run 4 is selected. The time-averaged local void fraction and bubble velocity profiles at all three axial locations are given in Fig. 6. Each row from bottom to top represents the result at L/D = 10, 50, and 70, respectively.

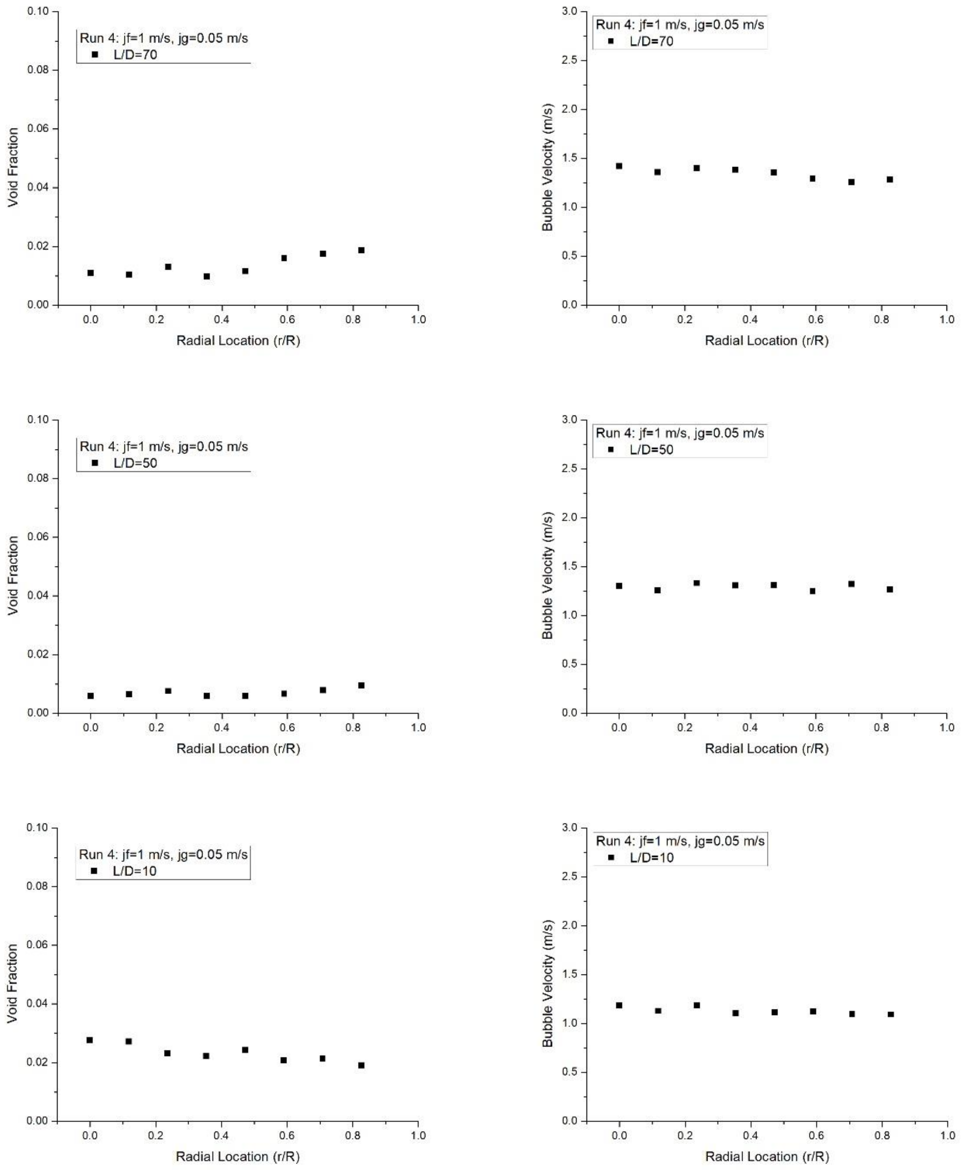

Figure 6. Local profile for run 4: j_f = 1 m/s, j_g = 0.05 m/s

In Run 4, the void distribution experiences a change process of center peak (L/D = 10) – transition (flat) (L/D = 50) – wall peak (L/ D = 70). This is explained by bubble breakup mechanism. At inlet position (L/D = 10), wake entrainment mechanism is dominant, small bubbles coalescence to larger bubble and drive bubbles toward pipe center. Along the flow path, the liquid velocity is high, bubbles will be break up to smaller bubbles due to the turbulent effect and forced toward wall by lift force, resulting wall peak void distribution. This bubble interaction mechannisms also result small amount change of void fraction at two upper axial position. This phenomena matches this measurement result in the work of Dang [26] and KEARI [2005].

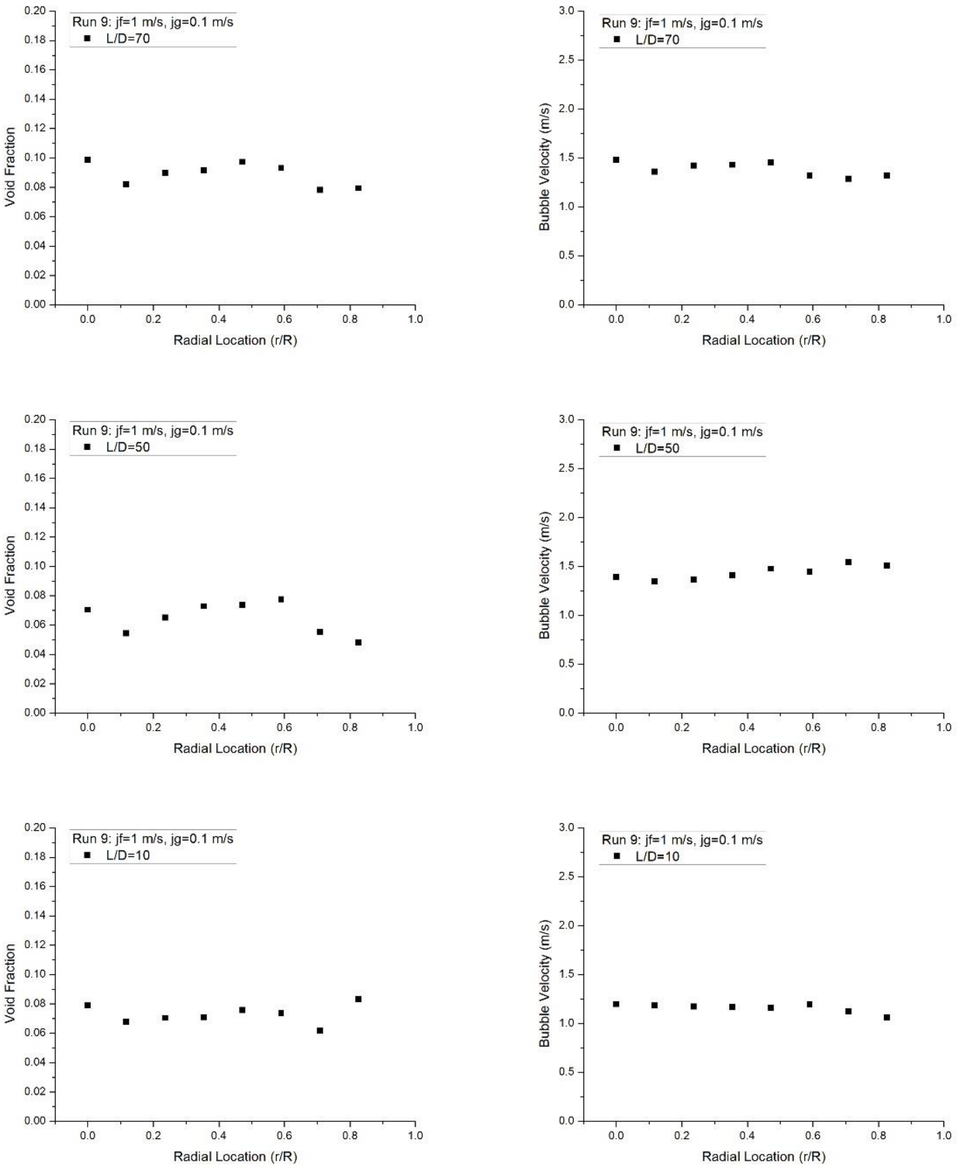

Figure 7. Local profile for run 9: j_f = 1 m/s, j_g = 0.1 m/s

When flow rate of gas is higher in run 9, the bubbles are distributed uniformly in the radius at the first measurement position. Along the flow path, the bubble coalescence to form larger bubbles and concentrates at the center pipe region. This is shown in Figure 7, void fraction at two upper measuring positions is higher than that of position measurement first and void fraction at region near wall is lesser than that of the center pipe region.

b. Slug

The local profiles of Run 13 is given in Figure. 8. In this flow condition, the major bubble shape is slug and they cover the entire flow channel. Thus, group void distribution matches the shape of a slug bubble. At the inlet position, bubbles coalescense to form larger bubble. At sencond measuring position the void distribution is affected by slug bubbles that small bubbles follows the slug bubbles, distributing in the slug bubbles' wake regions. Besides, the effect of shear off mechanism start to contribute the amount of small bubbles near wall region. According to shear off mechanism, when slug bubbles are large enough, they are sheared at the rim and many small bubbles show up. This could lead void fraction increase near the wall.

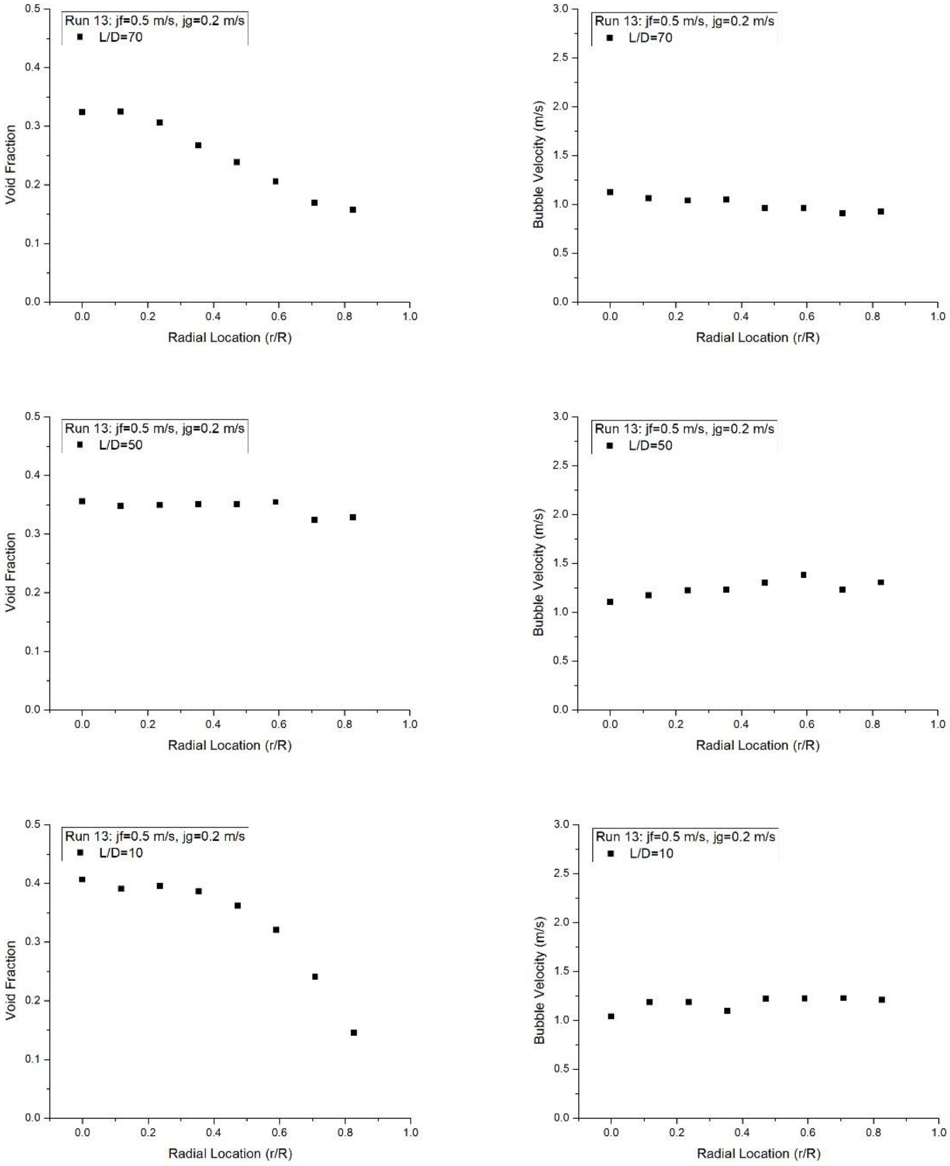

Figure 8. Local profile for run 13: j_f = 0.5 m/s, j_g = 0.2 m/s

4.3.Bubble Velocity

In bubbly flow (run 4 and run 9), Hibiki [2] shown that the interfacial velocity is distributed corresponding to the single phase velocity profile. The liquid velocity profile will be flattened when the gas is added. From the result, the value of bubble velocity is approximately equal to the sum of superficial velocities. As the bubbles flow along the channel, the bubbles experience an acceleration by a buoyancy force and a deceleration by a drag force. Therefor, the bubble velocity at two upper measuring positions are higher than the first position. Also, near to the wall region the velocity of the bubbles is strongly fluctuated due to wall friction and turbulent intensity.

In slug flow (run 13), the bubble velocity profile is similar to that of run 9. However, the channel-averaged velocity at third measuring position is slightly lower than that at the second measuring position. This phenomenon occurs in the case of low water supperficial velocity and therefore drag force is domination. As the bubble grows, bubble is normally accelerated by the effect of buoyancy force. However, due to the effect of drag force, velocity in run 13 is suitable.

5. Conclusion

The experimental investigation on local interfacial parameters for vertical upward air-water two-phase flow was performed in this study. Two-sensor conductivity probe was used for the measurement of 25 flow conditions that covers from bubbly flow to slug flow. The local parameters included are time-averaged void fraction and bubble interfacial velocity. A data acquisition frequency of 10 kHz and sampling time of 60 s were applied.

From the local experiment result, the mechanisms on radial and axial profiles of void fraction and interfacial velocity were discussed in detail. The differences of local parameter distribution were caused by the bubble interaction mechanisms. For high liquid supperficial velocity (j_f), the effect of buoyancy force is dominant and bubble break up phenomena is observed. On the contrary, for low liquid supperficial velocity (j_f), the effect of drag force is dominant and bubble interaction mechanism will change from bubble break up to bubble coalescence.

The data set obtained in this study are expected to be used for the development and checking CFD codes which are used in modeling two-phase flow, especially in the design of reactors more safe and efficient.

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KHẢO SÁT THỰC NGHIỆM CÁC HIỆN TƯỢNG THỦY ĐỘNG LỰC HỌC TRONG CÁC ĐIỀU KIỆN DÒNG CHẢY HAI PHA ĐOẠN NHIỆT KÊNH DẪN ĐỨNG THEO CHIỀU TỪ DƯỚI LÊN TRÊN

Tóm tắt

Để nghiên cứu các hiện tượng thủy động lực học trong các điều kiện dòng chảy hai pha sử dụng trong phân tích an toàn hạt nhân, một loạt các thí nghiệm dòng chảy hai pha đã được thực hiện trên một kênh dòng chảy trong đó không khí và nước được đưa đồng thời vào test section. Các thí nghiệm dưới điều kiện áp suất khí quyển được thực hiện với vận tốc nước và vận tốc khí tương ứng từ 0.2 đến 1.5 m/s và 0.05 đến 0.2 m/s. Kỹ thuật đầu đo độ dẫn hai cảm biến được sử dụng để đo các thông số của bong bóng. Kết quả thí nghiệm được trình bày trong nghiên cứu này là tỷ phần trăm pha hơi và vận tốc bong bóng cục bộ, trung bình theo thời gian tại ba vị trí dọc kênh dẫn L/D = 10, 50 và 70.

Từ khóa: dòng chảy hai pha nước-khí, đầu đo độ dẫn điện, tỷ số phần trăm pha hơi, vận tốc bong bóng.