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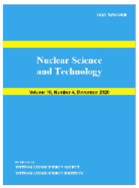

Experimental investigation of hydrodynamic phenomena in vertical-upward adiabatic two-phase flow conditions

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Abstract: In order to investigate hydrodynamic phenomena in two-phase flow conditions in nuclear safety 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 conditions 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 and analyzed in this study are the local time-averaged void fraction and bubble velocities at three axial positions L/D = 14.4, 51.2 and 71.3.

Keywords: *Two phase flow regime, Two phase flow experiment, Conductivity probe method.*

I. INTRODUCTION

In order to determine the heat transfer and pressure drop characteristics of a given flow in nuclear power reactors under various operational transients or accident conditions, e.g., LOCA (Loss-of-Coolant-Accident), studying two-phase flow plays a very important role. The hydrodynamics and heat transfers are a coupled thermodynamic problem in which single phase flow is changed. Therefore, phase distribution, flow pattern and heat transfer characteristics are also affected. Furthermore, due to the shape change in large bubbles, two-phase flow in a channel can hardly become fully developed at low pressure. So, with the inherent high complexity, a local description of the adiabatic two-phase flow is insufficient if there is not knowledge of the previous “history” of the flow. The hydrodynamic instabilities and the thermodynamic equilibrium between the phases are extremely complicated until now [1]. To avoid such complexities, a relatively large amount of experimental work has 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

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since Neal & Bankoff's work (1963) on the measurement of local void profile in air-water flow condition [2]. However, there are not enough data to adequately support a wide range of continuing efforts in the calibration and validation of advanced models and codes.

Based on the current practice in experimentation, modeling, and analysis of two-phase flow in nuclear reactor safety, the present work is an experimental investigation of various local parameters of concurrent air-water two-phase flow, flowing upward in a vertical circular tube with inner diameter 25.4 mm under nearly atmospheric pressure. Due to constraints on the financial and human resource issues, emphases are put on the following: 1) Measurement of the local parameters of two-phase flow which are the local time-averaged void fraction and bubble velocities at three axial positions using two-sensor conductivity probe. 2) Description of some statistical and hydrodynamic characteristics of flow patterns as bubbly and slug in a vertical-upward air-water flow; 3) Checking the effect of changing the air and water flow rate as in Run 4 ($j_f = 1$ m/s, $j_g = 0.05$ m/s), Run 9 ($j_f = 1$ m/s, $j_g = 0.1$ m/s) and Run 13 ($j_f = 0.5$ m/s, $j_g = 0.2$ m/s) on the results.

II. EXPERIMENTAL APPARATUS

The experiment was installed at VINATOM (Vietnam Atomic Energy Institute) for studying two-phase flow regime, transition phenomena, and measurement of the two-phase flow parameters such as void fraction, bubble velocity. The principle of the experiment is shown in Figure 1. It consists of test section, bubble generator, water supply system, air supply system, and data acquisition system. The test section is a vertical transparent tube with an inner diameter of 25.4 mm and a height of 2 m. Two-sensor conductivity probe is located at three positions L/D = 14.4, 51.2, and 71.3 for measuring the two-phase flow parameters [3]. In order to measure the pressure of the system, absolute and differential pressures are installed. The Rosemount 3051C absolute pressure is connected to the L/D = 14.4, while the Rosemount 2880 differential pressure is connected to the L/D = 51.2 and 71.3.

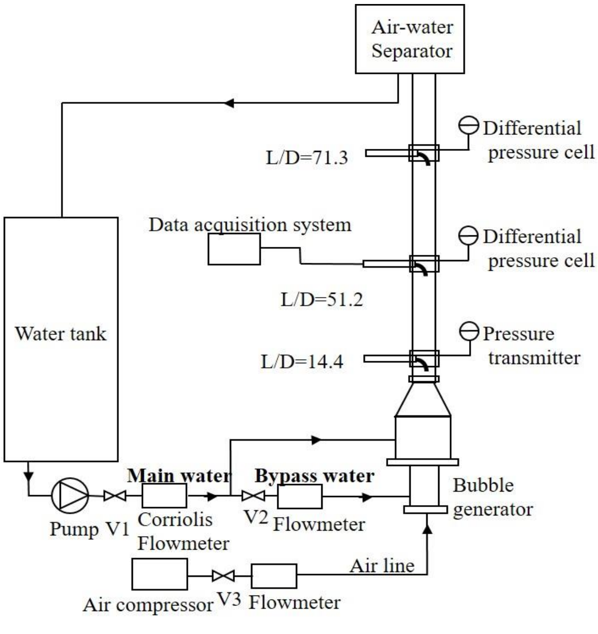


Fig. 1. Schematic of test facility

Air is supplied by an air compressor with a capacity of 1 HP (Horse Power). 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 the air flow rate is measured by a rotameter with the range from 0.2 - 30 l/m and the error of ± 2%. The rotameter also measured the bypass water flow with the measuring range of 6 l/h to 60 l/h. The data collection and processing system includes a signal conditioner, A/D (Analog/Digital) signal converter, and a computer with LabVIEW software. The visualization of the two-phase flow is achieved through the high-speed camera with a maximum frame rate of 1000 and Xenon lamps.

III. SIGNAL PROCESSING TECHNIQUE OF LOCAL TWO-PHASE FLOW PARAMETERS

A. Two-sensor conductivity probe

The conductivity method was first proposed by Neal and Bankoff [2] to determine the void fraction and bubble velocity in air-water two-phase flow, and thereafter many researchers have developed this method *[4,5]*. The 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 the "*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= 14.4, 51.2 and 71.3 upstream of the bubble generators. As shown in Figure 2, it is possible to change the radial position of the probe in the cross-section using a traversing mechanism. By performing measurements at different radial locations, radial profiles of time-averaged two-phase flow parameters can be measured.

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

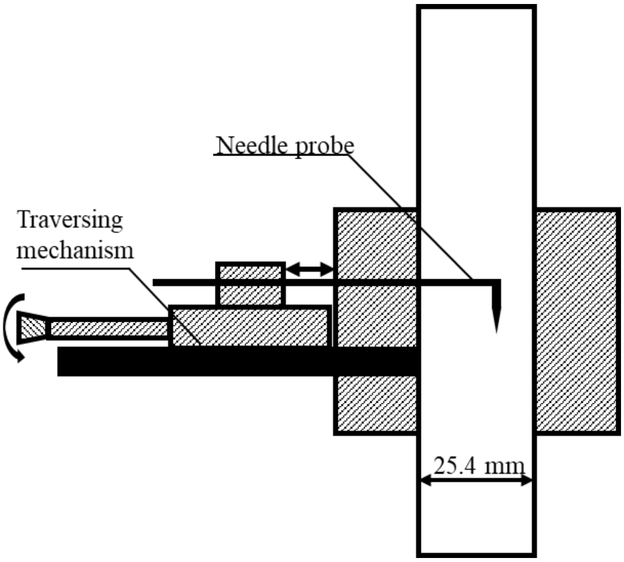


Fig. 2. Instrumentation set-up

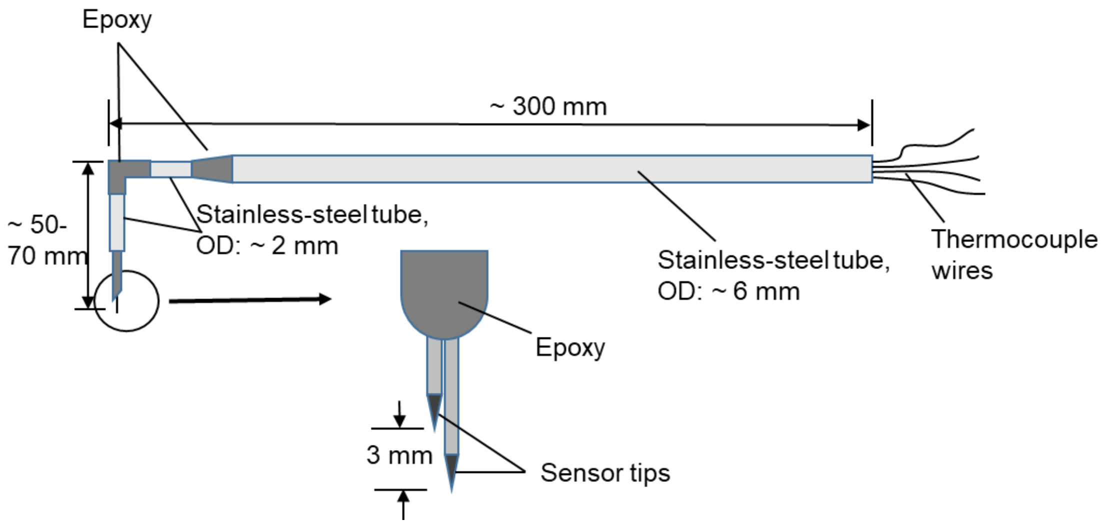


Fig. 3. Sketch of the two-sensor conductivity needle-probe

B. Signal processing

The sensor probe is initially placed in the water with a low voltage signal [6]. When the sensor contacts 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 the wetting and rewetting phenomenon. Therefore, it is necessary to make a signal-processing program for obtaining exactly the necessary information from the raw signal [7,8]. The signal-processing program was developed on LabVIEW software combined with MATLAB language with four main parts: signal reading & normalization; making cut-off level; trans-rectangle & filtering; and bubble statics as illustrated in Figure 4. [9].

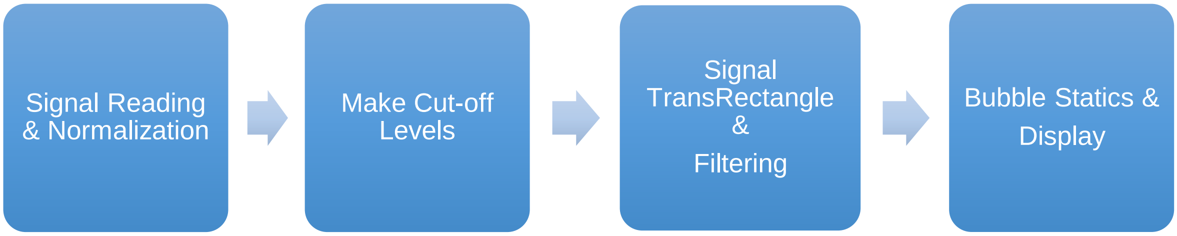


Fig. 4. The structure of the signal-processing program

First, signals from the 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 [10,11]. As Yun [12], it is crucial to determine the appropriate cut-off level for obtaining the value of the void fraction and bubble velocity accurately. The 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 is converted into square signal and filter out unsuitable parts of a square pulse in the part of Signal TransRectangle & Filtering. This process is based on the algorithms of

Yun [12] and Euh [13]. Finally, the two-phase flow parameters are 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 the time delay between the upstream and downstream signals. The parameters of the two-phase flow have been calculated as below [14].

- *The 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.

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

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.

- *The time-averaged 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 signals. 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.

IV. PRELIMINARY 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 = 14.4, L/D = 51.2, L/D = 71.3). All the flow conditions are summarized in Table I.

Table I. 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					

Experiments carried out are represented in the flow regime map shown in figure 5 [15]. According to the flow map it can be seen that, when studying measurement of two-phase flow parameters, the authors measured with wider ranges based on the liquid and gas superficial velocities. However, it is still not possible to cover the entire. Therefore, the experimental system built at VINATOM with the measurement range shown in Figure 5 is expected to contribute to the missing experimental data on the flow regime map.

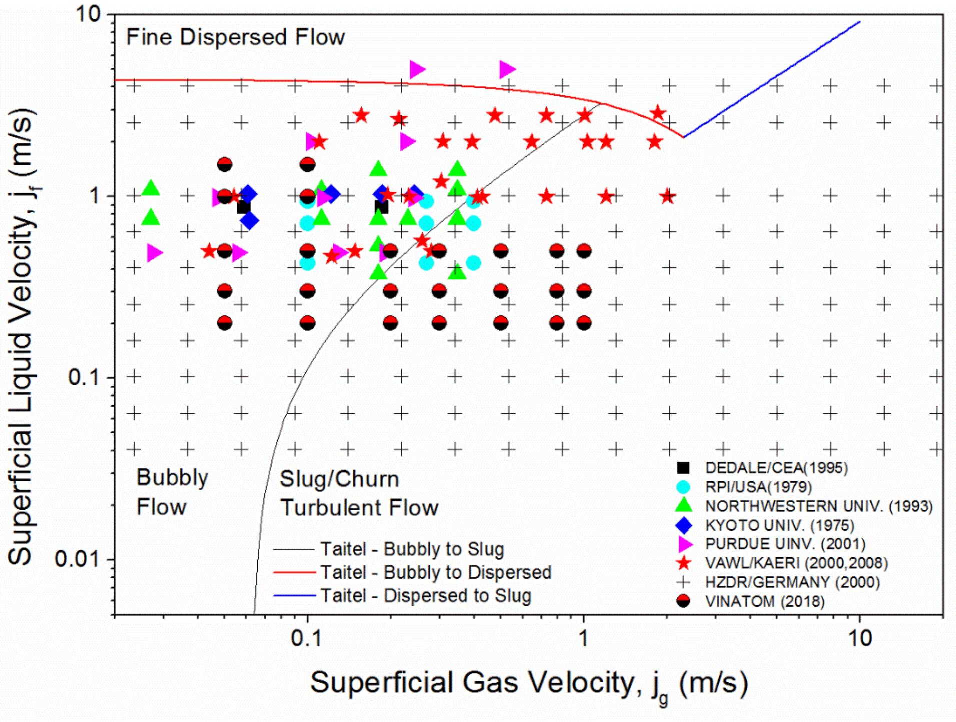


Fig. 5. Test conditions on flow regime map

A. Signal processing verification

In order to ensure the quality of conductivity probe and the signal processing, the imaging technique is applied using the high-speed camera with xenon lamp for observing and recording the time of bubbles passed through the conductivity probe [16,17]. An independent small-scale experimental system was built. Test Section is a shape square acrylic box with a size of 2 × 2 cm^2 and a length of 40 cm. A small steel tube is 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 6 presents the results of the comparison of the velocity measured by the imaging technique and conductivity probe. The difference between the two measurement techniques is within ± 15%. This result is good and suitable for use in the two-phase flow experiment.

B. Local time-averaged void fraction

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 Figure 7. Each row from top to bottom represents the result at L/D = 14.4, 51.2 and 71.3, respectively.

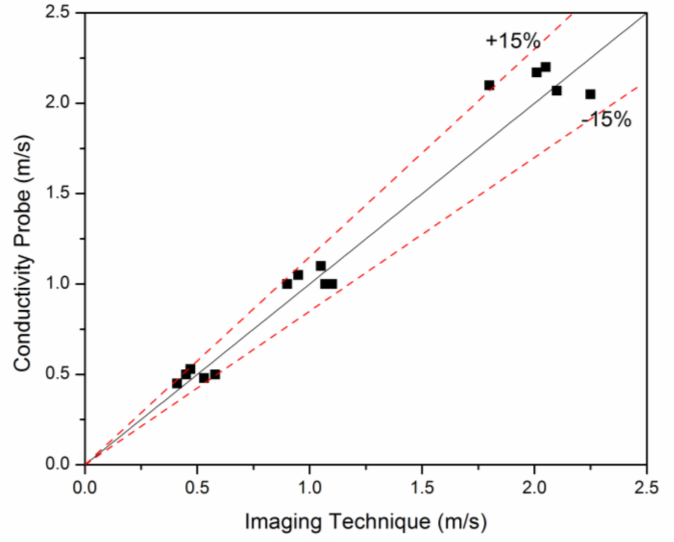
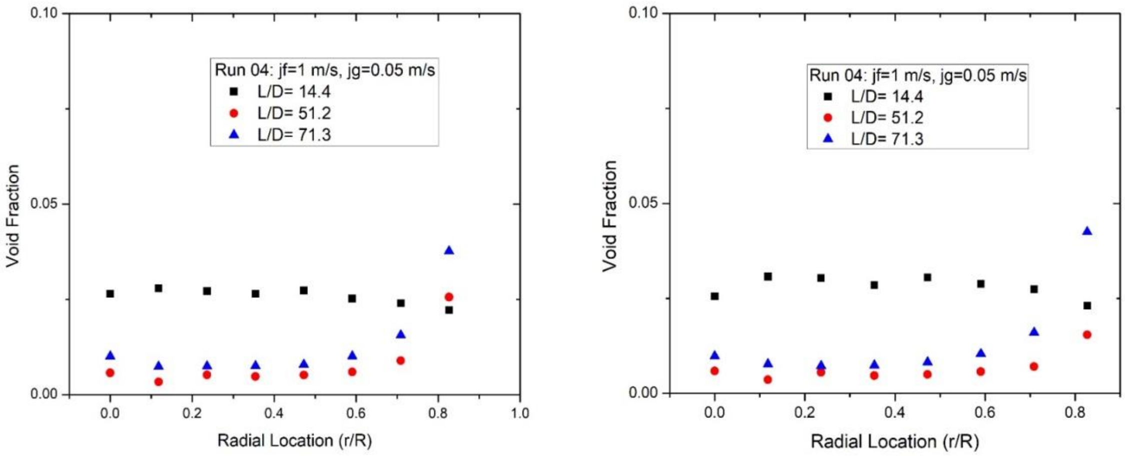


Fig. 6. Comparison of bubble velocity obtained by Imaging Technique and Conductivity Probe

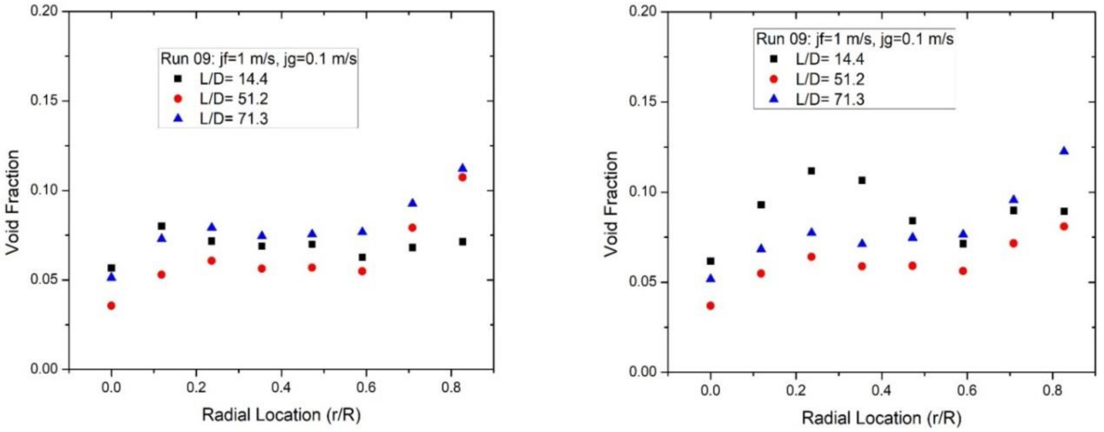


(a) *(b)*

Fig. 7. Local profile of void fraction for run 4: $j_f = 1$ m/s, $j_g = 0.05$ m/s
(a) Front Sensor; (b) Rear Sensor

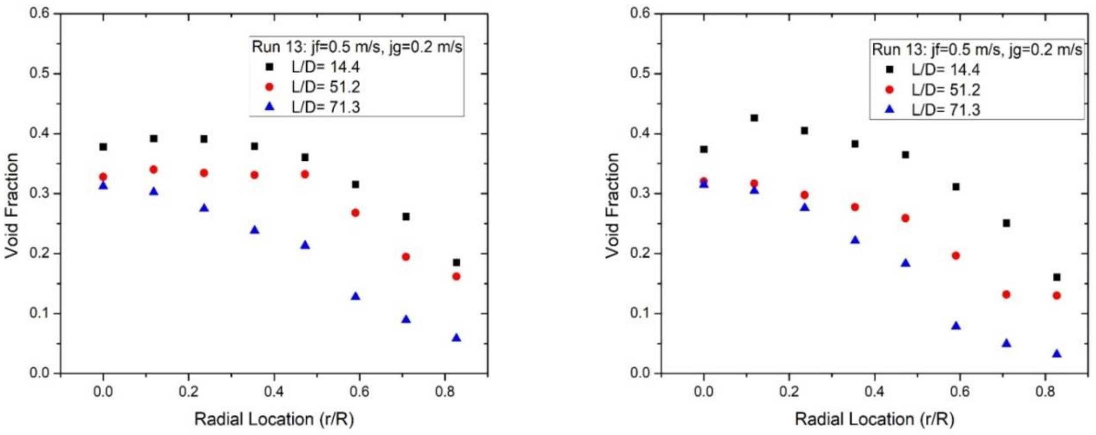
In Run 4, the void distribution experiences a change process of transition (flat) (L/D = 14.4) – wall peak (L/D = 51.2 and 71.3). This reason is explained by the bubble breakup mechanism. At inlet position (L/D = 14.4), wake entrainment mechanism is dominant, small bubbles coalescence to larger bubble, and drive bubbles toward pipe center. Along the flow path, the liquid velocity is high, and bubbles will be break up to smaller bubbles due to the turbulent effect and forced toward the wall by lift force, resulting in the wall peak void distribution. This bubble interaction mechanism also results in small amount change of void fraction at two upper axial positions. This phenomenon matches the measurement result in the work of Dang [5].

When the flow rate of gas is higher in run 9, the bubbles are fluctuated at the first measurement position. Therefore, the void fraction at Front Sensor and Rear Sensor are quite different. Along the flow path, the bubble breakup to form smaller bubbles and concentrates at the wall region (Figure 8). Therefore, the void fraction in the wall region, at two upper measuring positions are higher than that of position measurement first.



(a) *(b)*

Fig. 8. Local profile of void fraction for run 9: $j_f = 1$ m/s, $j_g = 0.1$ m/s
(a) Front Sensor; (b) Rear Sensor

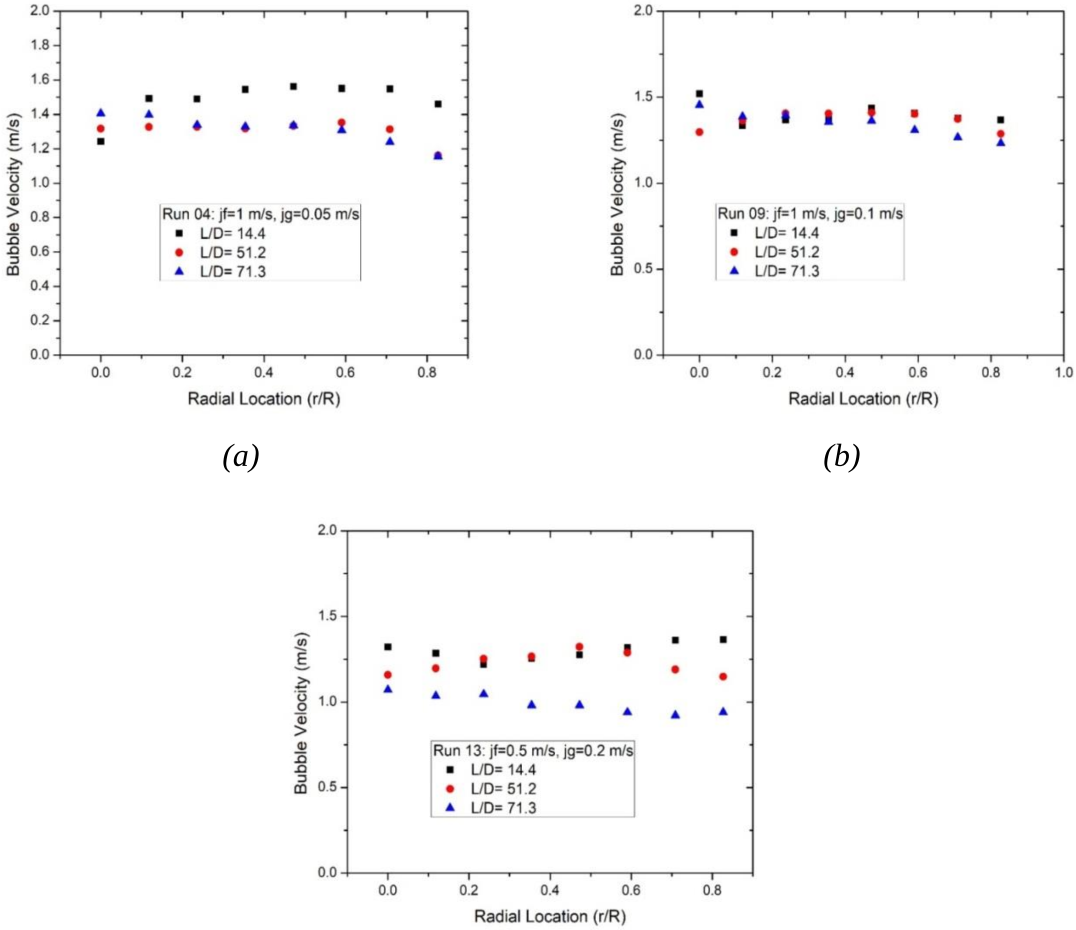


(a) *(b)*

Fig. 9. Local profile of void fraction for run 13: $j_f = 0.5$ m/s, $j_g = 0.2$ m/s
(a) Front Sensor; (b) Rear Sensor

The local profiles of Run 13 are given in Figure 9. In this flow condition, the major bubble shape is a slug and they cover the entire flow channel. Thus, group void distribution matches the shape of a slug bubble. However, under the same flow condition, the bubbly regime was recorded in previous study [15]. This experimental data was located near the boundary between bubbly and slug flow regime in Figure 5. Therefore, the difference can be explained by the fluctuation of air flow rate during the experiment, thus the flow regime was shifted from bubbly to slug flow. At the inlet position, bubbles coalescence to form larger bubbles. At second measuring position, the void distribution is affected by slug bubbles that small bubbles follow the slug bubbles, distributing in the slug bubbles' wake regions. Besides, the effect of shear off mechanism starts to contribute to the number 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.

C. Bubble Velocity



(a)

(b)

(c)

Fig. 10. Local profile of bubble velocity:
(a) Run 4; (b) Run 9; (c) Run 13

In run 4 and run 9, the interfacial velocity is distributed corresponding to the single-phase velocity profile and this agrees with Hibiki [18]. The liquid velocity profile is flattened when the gas is added. As shown in Figure 10, the value of bubble velocity is approximately equal to the sum of superficial velocities. When bubbles enter the wake region, they will accelerate and may collide with the leading one. Therefore, the bubble velocity at first position is slightly higher than the two upper measuring positions. In addition, near to the wall region, the velocity of the bubbles is strongly fluctuated due to wall friction and turbulent intensity.

In Run 13, the channel-averaged velocity at the higher measuring positions are gradually decreased and are distributed almost uniformly in the radius. This phenomenon occurs in the case of low water superficial velocity, and drag force is domination. As the bubble grows, the bubble is normally accelerated by the effect of buoyancy force. However, due to the effect of drag force, velocity in run 13 is suitable.

V. CONCLUSIONS

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 a time-averaged void fraction and bubble interfacial velocity. The data acquisition frequency of 10 kHz and the sampling time of 60 s were applied.

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

When changing the flow conditions, the void fraction distribution changes from wall peaking at Run 4 and Run 9 to center peak at Run 13. The reason might be due to the uncertainties in the measured results that need to be carefully considered and reduced in future works. In conclusion, the test facility, the experimental methods, and the preliminary experimental results obtained in this study can be helpful to study and comprehend the fundamental two-phase flow phenomena. For practical application in nuclear reactor safety, they are envisaged to be further improved and applied to verification and validation of calculation methods and codes, e.g., CFD codes, in modeling of two-phase flow.

NOMENCLATURE

D – pipe diameter
g – acceleration of gravity
L – length
l_{chord} – chord length
N – number of bubble
p – pressure
t – time
t_{delay} – delay time
u – velocity
V – Volume
Greek Symbols
α – void fraction
μ – viscosity
ρ – density
σ – deviation standard
Ω – total sampling time
Subscripts
b – bubble
f – liquid
g – gas

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