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An Experiment on Measuring Void Fraction using Impedance Meter in 3×3 Rod Bundle consisting of Metal Filter

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Abstract

The two-phase flow in fuel rod bundle has been actively studied to understand the characteristics of coolant and vapour behavior on accident conditions. The accurate measurement of void fraction is required to monitor the heat removal capability of the coolant in rod bundle. In order to measure the void fraction, several methods have been applied by using wire-mesh, impedance meter, X-ray and etc. This paper tries to investigate volumetric void fraction by using impedance meter for vertical upward two-phase flow in rod bundle. Generally, gas flow is injected from bottom of test section. Especially, bubbles are generated from surface of rods made from metal filter which replaces simple rod in fuel assembly. An experimental set consists of a 3×3 rod bundle inside a rectangular acrylic duct of 1m height. The three electrode sets including guard electrodes are installed at the three positions of the acrylic duct encasing the rod bundle. Pitch length between the rods is 19 mm, and diameter of the rod is 14 mm to satisfy the pitch to diameter (P/D) of 1.35. This experiment is conducted under room temperature and atmospheric pressure air/water flows. In this condition, impedance is measured by changing the air and liquid flow rate about from 0 to 467 lpm and from 0 to 221 lpm, respectively, which indicate the superficial gas velocity j_g of 3.17 m/s and the superficial liquid velocity j_f of 1.5 m/s covering the churn flow regime. The preliminary analysis of test data is presented to study feasibility and performance of the metal filter to construct a two phase flow in a rod bundle.

Keywords: two-phase flow, void fraction, impedance meter, rod bundle

1. Introduction

A large number of research on measuring void fraction in rod bundle have been being steadily conducted with various measurement methods. Each valid experimental data on void fraction distribution in a rod bundle is important basis for correlations used in safety code or for validation of CFD analysis result. Especially, this study focuses on a non-intrusive measurement method and high similarity in bubble generation at the rod surface with metal. In view of experimental method, there are difficulties in the measurement of dynamical characteristics of flow which is generated at core of PWR under high heat flux condition. The boiling phenomenon has intrinsic complexity and it is hard to measure certain flow characteristics in the narrow and complex region. Nonetheless, experimental database on the flow dynamics is highly important in that it becomes the basis for various prediction method for momentum/heat transfer in the flow.

In this study, this group wanted to construct experimental data on the flow of volumetric void fraction in a rod bundle. To remove interaction between flow and sensor, impedance method is selected. To increase the similarity between the flow in test section and the real flow, bubbles are generated through metal filters. In the table 1, experimental works conducted by other research groups are arranged [1-3].

2. Methods and Results

2.1. Experimental setups

A variety of measurement techniques have been being used to measure several types of void fraction such as local void fraction, chordal void fraction, cross-sectional void fraction and volumetric void fraction. The volumetric void fraction that this study focuses on was measured by using the installed several pairs of electrode sets, which are able to transfer ions in test section.

Table 1. Experimental database of rod bundle conducted by research groups

Reference	j_f (m/s)	j_g (m/s)	$<\alpha>$ (-)	Pressure (MPa)	D_{rod} / Pitch (mm)	Fluids
Anklam and Miller (1982)	0.00-0.11	0.03-3.56	0.07-0.82	4, 7-8	9.5 / 12.7	Steam / Water
Kumamaru et al (1994)	0.00-0.13	0.01-4.99	0.04-0.92	3, 7, 17	9.5 / 12.6	Steam / Water
Qazi et al (1994)	0	0.08-0.40	0.07- 0.36	0.1	9.5 / 17.0	Steam / Water
Kamei et al (2008)	0	0.06-8.86	0.14- 0.91	0.1	10.0 / 12.3	Air / Water
Yang et al (2012)	0.09-1.40	0.07-8.33	0.25-0.88	0.1, 0.3	10.3 / 16.0	Air / Water
Collin Clark et al (2014)	0.00-1.00	0.06-6.33	0.15-0.70	0.1	12.7 / 16.7	Air / Water

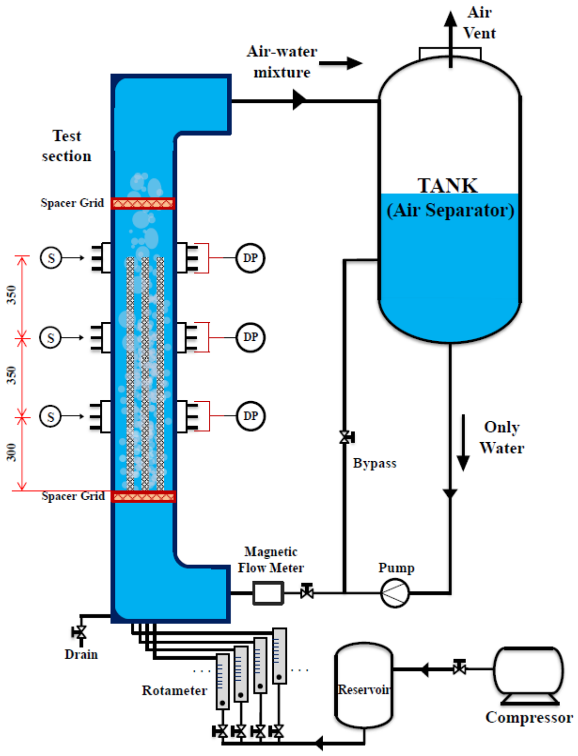


Figure 1. Schematic of 3×3 rod bundle and circulation system

Figure 1 represents the schematic of facility for this experiment. The facility was designed with consideration for pressure loss assuming the flow state as homogeneous model [5]. There are three measurement parts containing impedance meter and circulation system. To acquire more accurate information on a volume-averaged void fraction, mutual guard electrode sets which block external electric signal from other measurement parts and electronic equipment are installed at each height [4]. Each part includes two pairs of guard electrodes and one pair of measuring electrodes. From these parts, each AC signal passing two mixed fluids in test section transferred information of impedance between two electrodes. In order to substitute real fuel rod, 50μm of porous metal filter was set up in the rectangular acrylic duct and bubbles are generated on the surface of nine rods.

In order to make the Pitch to Diameter (P/D) equal to 1.35 which is the standardized value in PLUS7 that is one of APR1400 models, the length of diameter and pitch are settled in accordance with table 2.

Table 2. Geometric dimensions of two rod bundle models

	PLUS7	Experimental Model
Rod Diameter [mm]	9.50	14.00
Pitch [mm]	12.85	19.00
(P/D) [-]	1.35	1.35
Hydraulic Diameter (D_H) [mm]	12.64	18.83
Flow Area [m^2]	5.825	0.002458

2.2. Calibration

At the each measurement height, volume-averaged void fraction, $<\alpha>$ had to be calibrated using the correlation between differential pressure and conductance which is the reciprocal of impedance. 5 kHz AC signal was applied because frequency range of 2 kHz $< f <$ 1MHz is essential to prevent polarizing phenomenon and minimize the capacitance effect in water [4]. Acquisition was conducted with 1 kHz of sample rate for 5 second. Simultaneously, data processing was also progressed with DAQ and MATLAB simulator. Calibration was conducted by using the normalized conductance with equation (1).

$$<\alpha_G>= 1 - G^* = 1 - \frac{G_X - G_g}{G_w - G_g} \qquad (1)$$

The G_X is the conductance value measured by impedance meter when two fluids coexist. The G_g and G_w are conductance measured when only gas or water exists. The calibrated void fraction α_G is compared with the α_{dP} , empirical real void fraction, extracted by differential pressure obtained from equation (2)

$$<\alpha_{dP}>= 1 - \frac{dP_{meas}}{dP_w} = 1 - \frac{dP_{meas}}{\rho g \Delta H} \qquad (2)$$

In these two correlations (1) and (2), calibration curve was extracted and plotted in figure 2 through the collected data at each measurement height. In this graph which includes Maxwell correlation, experimental data distribution has a tendency to be below $\alpha_G = \alpha_{dP}$ graph.

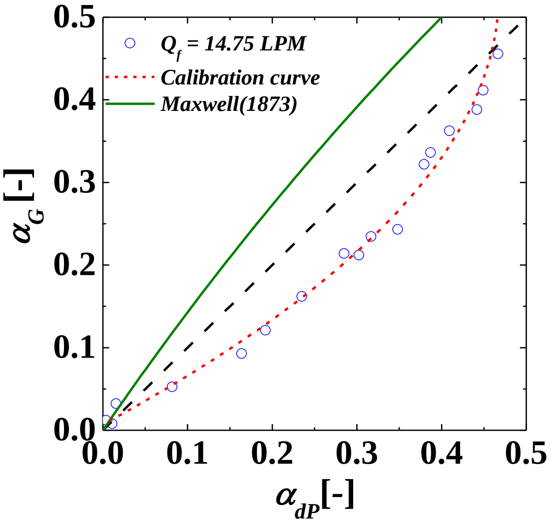


Figure 2. Calibration curve between α_G and α_{dP}

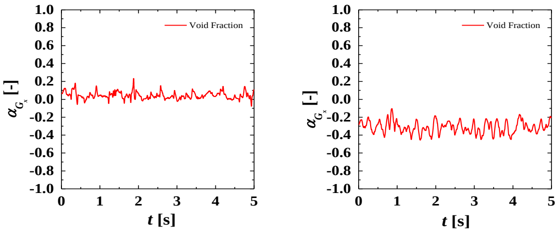
The calibration curve follows the equation (3) and the norm of residual is 0.054677.

$$\alpha = -1.7224\alpha_G^2 + 1.8185\alpha_G - 0.012669 \qquad (3)$$

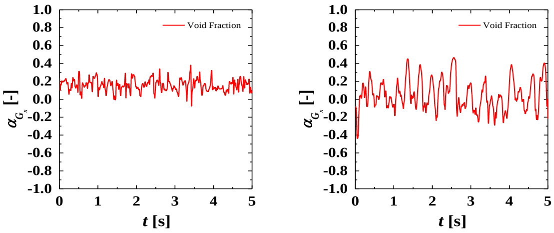
Since the calibration method through differential pressure is generally applied with low liquid flow state which is negligible frictional differential pressure, the process was conducted in the low liquid condition of $Q_f = 14.65\ lpm$.

2.3. Void fraction

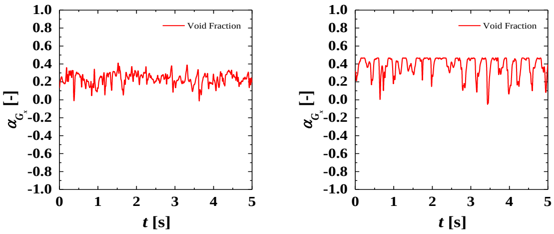
Through the calibrated void fraction equation (3), the dynamic characteristic of volumetric void fraction is represented in figure 3.



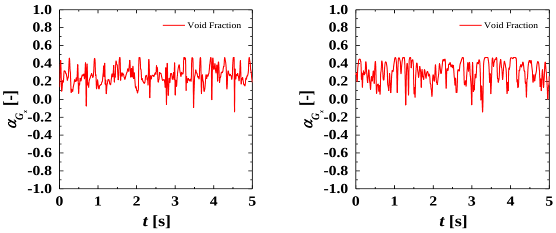
(a) $(Q_f,\ Q_g)$ = (14.75, 187.06) [lpm]



(b) $(Q_f,\ Q_g)$ = (36.87, 280.59) [lpm]



(c) $(Q_f,\ Q_g)$ = (14.75, 342.95) [lpm]



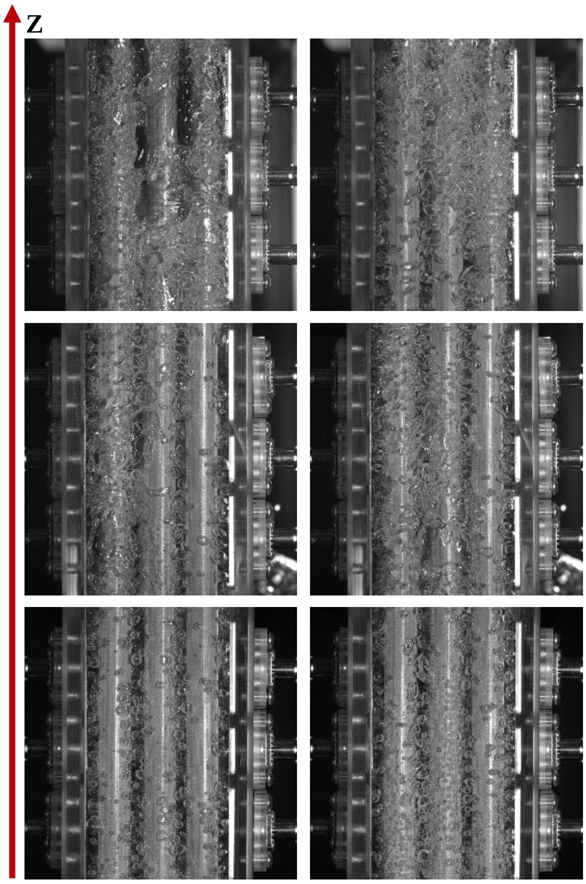
(d) $(Q_f,\ Q_g)$ = (73.75, 467.65) [lpm]

Figure 3. Dynamic characteristics of void fraction. (Measurement height: 650 mm (left), 1000 mm (right))

Each shape of graph depends on flow patterns such as bubbly, slug and churn flow. Especially, at the height of 1000 mm, it is shown that the change of shape is the most distinct and there is higher frequency in higher gas flow rate. However, at the same measurement height, a non-physical phenomenon that void fraction has negative value occurs because the current which has to flow through guard electrodes enters measuring electrode during the low gas is injected.

2.4 Visualization

In order to visualize the flow patterns at each flow rate condition, the high speed camera was used on a state of 500 pps and 2 second of recording time. Figure 4 shows the flow patterns along the height z.



(Left side: $(Q_f,\ Q_g)$ = (14.75, 234) [lpm])
(Right side: $(Q_f,\ Q_g)$ = (36.87, 252) [lpm])
Figure 4. Visualized flow patterns of two-phase flow

As can be seen from figure 4, the higher location, the larger void fraction is observed in test section. It means that the interfacial interaction is on quick action in higher place. Moreover, there is an effect of using the metal filter to satisfy similarity to real boiling phenomenon in rod bundle. The existing adiabatic experiments conducted by research groups have mostly used the air injector or bubble generator at the bottom in test section. On the other hand, metal filter makes non-homogeneous flow like real boiling phenomenon, which means that bubble-generated time and places are not irregular. Therefore, it is required to prove the similarity of void fraction distribution between results in this study and that of other boiling experiments in rod bundle.

3. Conclusions

Applying the impedance meter for measuring void fraction was appropriate to acquire data. Furthermore, the bubbles generated on the surface of a metal filter rod describing an actual fuel rod represented real boiling phenomenon in the test section. However, it remains as a task to prove similarity between the bubble distribution formed from the metal filter and actual boiling phenomenon. In addition, unlike previous studies having the gas bubble generator at the bottom of test section, this experiment was conducted in the condition of non-homogeneous bubble generation along the height. Because of this fact, the value of j_g varies in vertical height, not fixed. Thus, it is also required to calculate the exact local j_g profile.

At low gas flow rate, a phenomenon that bubbles are concentrated on upper guard electrode caused the void fraction to be negative, which is non-physical data.

Nonetheless, the shape of graph plotting data of dynamic void fraction follows the flow patterns and has the meaningful tendency depending on alteration of gas and liquid flow rate. In the future studies, measuring volumetric void fraction with impedance meter and metal filter will be technique to extract more accurate data by building a better environment such as enhanced measuring circuit and test structure.

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