Study on Transient Void Behavior During Reactivity Initiated Accidents Under Low Pressure Condition

- Development and Application of Measurement Technique for Void Fraction in Bundle Geometry - *

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Abstract

Series of out-of-pile experiments to obtain the knowledge on the transient void behavior during reactivity initiated accidents are in progress at JAEA. In the present series of experiments, the transient void behavior in a test section of 2 x 2 bundle geometry under atmospheric pressure condition was measured using an impedance technique. The measuring areas and the arrangement of electrodes for the impedance technique were defined on the basis of numerical analyses and scaled model experiments. The comparison was made between the impedance and differential pressure techniques for steady boiling experiments to estimate the accuracy of the impedance technique. The impedance technique showed a good agreement with the void fraction estimated from the differential pressure. The transient void behavior in the bundle geometry was measured using the impedance technique. The void fraction distribution in the bundle cross-section could be quantitatively obtained by the impedance technique. It could be properly confirmed that the transient void behavior depended on both the subcooling of inlet water and the heat generation rate of simulated fuel rods.

Key words: Reactivity Initiated Accidents, Transient Void Behavior, Bundle Geometry, Impedance Technique

1. Introduction

In order to avoid mechanical energy generation due to fuel melting and to avoid loss of core coolability during postulated reactivity initiated accidents (RIAs), in regulation of nuclear safety, maximum fuel enthalpy is required to be lower than the upper limit specified in the regulatory guide. The increment of the fuel enthalpy during RIAs depends strongly on the amount of reactivity inserted into fuels. However, current safety evaluation estimates the fuel enthalpy using conservative methodology without taking into account the negative feedback of coolant vapor voids to the reactivity. This methodology can result in the

unrealistic underestimation of margin of fuels to the upper limit of the fuel enthalpy during RIAs. Especially, for high burn-up fuels, it is important to accurately predict the fuel enthalpy because high burn-up fuels melt at lower enthalpy than fresh or low burn-up fuels, which could induce the generation of mechanical energy if the molten fuels ejected into the surrounding coolant at the cladding failure.

In order to reasonably evaluate the negative void feedback, technical knowledge on fast transient void behaviors is necessary. Several experimental studies have been performed in industry and universities⁽¹⁻⁴⁾. In those studies, a single cylindrical pin or plate simulating a fuel rod was sharply heated in water under low-pressure conditions. Additional knowledge is required for transient void behaviors in bundle geometry and at higher pressures to assess the applicability of thermal hydraulic models for predicting void fraction into RIA analyses.

Japan Atomic Energy Agency (JAEA) has conducted out-of-pile experiments to investigate the transient void behaviors caused by the power excursion during RIAs. The experimental study consists of several series with a single simulated fuel rod or bundle geometry at the atmospheric or higher pressures up to 7MPa. The experiments at the atmospheric pressure or 7MPa simulate the condition of cold shutdown or hot shutdown, respectively. In the first series of experiments, the applicability of the impedance technique for void fraction measurement, in which void fraction was quantified through measured electrical resistance of gas-liquid two-phase flow, was confirmed and the transient void behaviors were measured in the flow channel with a single simulated fuel rod at the atmospheric pressure⁽⁵⁾.

In the present series of experiments, the measuring target was the transient void behavior in the flow channel of 2 x 2 bundle geometry under atmospheric pressure condition. The impedance technique was improved to measure the void fraction distribution in the bundle geometry. The applicability of the improved impedance technique was investigated and the transient void behavior in the bundle geometry was measured using this technique under various thermal-hydraulic conditions expected in low-pressure and low-temperature RIAs.

2. Experimental Facility

The schematic of an experimental facility is shown in Fig.1. The experimental facility mainly consists of a test section and a water heating system connected to a water circulation loop, an electric power source, and control and data acquisition systems. Maximum voltage, current and current increasing rate of the electric power source are 40 V, 10 kA and 500 A/ms, respectively.

The test section consists of four simulated fuel rods arranged in 2 x 2 bundle, flow channel, and upper and lower plenums, simulating a part of the 9 x 9 BWR fuel assembly in rod length (4163 mm), outer diameter (11.2 mm) and rod pitch (3.2 mm). The structure and major dimension of the test section around heat generation part is depicted in Fig.2. The heat generation part of the simulated fuel rod is made of Inconel, vertically placed in a transparent polycarbonate square channel, and electrically heated by direct current. Heat generation length and thickness of the rod are 310 mm and 0.5 mm, respectively. The inner dimension of the polycarbonate pipe is 31.8 x 31.8 mm.

Eight thermocouples and an electromagnetic flowmeter are installed in the water circulation loop to control the flow in the facility. In the test section, thermocouples measuring fluid temperature and inner wall temperature of the rods, pressure transducers and differential pressure gauge are installed. Void fraction in the flow channel is measured using the improved impedance technique detailed in the next section. Transient void behavior is visually observed using high-speed video cameras.

Fig. 1 Schematics of Experimental Facility

Fig. 2 Structure and Major Dimension of Test Section

3. Technique of Void Fraction Measurement

3.1 Measurement Principle

Void fraction of homogeneous liquid-gas two-phase fluid can be evaluated from the measured impedance of the two-phase fluid between two electrodes. The evaluation is based on the Maxwell equation⁽⁶⁾ describing the relation between void fraction and impedance as follows:

$$\frac{R_{\alpha}}{R_0} = \frac{1 + 0.5\alpha}{1 - \alpha}, \quad (1)$$

where, α is void fraction, R_{α} is electric resistance of two-phase fluid and R_0 is that of liquid. Because the resistance of fluid depends on the fluid temperature, it is necessary to measure the temperature distribution between the electrodes in addition to the electric current to evaluate the void fraction.

3.2 Requirements for Void Fraction Measurement in Bundle Geometry

The impedance technique for void fraction measurement had been already applied to single-rod experiments⁽⁵⁾. In the single-rod experiments, one of electrodes had been a heater-rod itself, and another had been a curved plate placed near the wall. Averaged void fraction in the flow channel could be obtained using one pair of electrodes for such simple geometry. However, it is impossible to measure the averaged void fraction in the bundle geometry using such simple arrangement of electrodes because of geometry complexity. Therefore, for the void fraction measurement in the bundle-type flow channel, the cross-section of flow channel should be divided into several measuring areas, and several pairs of electrodes must be installed at appropriate position in respective areas. In the present study, we divided the cross-section of flow channel into three areas, i.e., the central area surrounded by the four rods (called area-C), an area between two adjacent rods (area-R) and an area between two rods and the wall of flow channel (area-W) as shown in Fig.3, in which the methodology of division was discussed in a later subsection.

Fig. 3 Three Measuring Areas

3.3 Preliminary Experiments

To investigate the appropriate length of measuring region for void fraction measurement in the flow direction, several experiments were carried out, in which line-type electrodes and thermocouples were arranged as shown in Fig.4. Length of the electrodes was 10mm, 20mm and 40mm, respectively. Void signals were obtained by measuring the resistance between each electrode and four rods. In the time variation of the measured void signals, there were terms in which the signal was almost lost because almost all the part of electrode was covered with large void(s). However, the length of such term decreased with increase of the length of electrode. Furthermore, using long electrode, the averaged void fraction utilized directly for general thermal-hydraulic numerical codes can be measured more accurately because all the vapor bubbles which have broad distribution in their size can be caught.

Since the impedance of water depends on the temperature, the distribution of water temperature in the measuring region must be measured accurately to obtain the void fraction using impedance technique. To investigate the vertical temperature distribution in the measuring region, several thermocouples were installed as shown in Fig.4. From the results, temperature difference between at the both ends of electrode was enough small to neglect for all electrodes. On the basis of these results, the electrodes in the length of 40mm were adopted and the thermocouples were arranged around the center of measuring region in the flow direction in all subsequent experiments.

Considering the symmetry of the cross section of the bundle-type test section, it can be

divided into eight congruent or inverted congruent areas as shown in Fig.3. If the temperature distribution in the cross section is also symmetrical, we can concentrate the thermocouples in one of those areas. To investigate the symmetry of temperature distribution in the cross section, several preliminary experiments were performed, in which the electrodes were arranged bilaterally-symmetrically as shown in Fig.5. Since the temperatures measured by two thermocouples arranged symmetrically each other were nearly equal, we considered that the temperature distribution in the cross section was approximately symmetrical.

Fig. 4 Arrangement of Electrodes and Thermocouples for Investigation of Measuring Length

Fig. 5 Arrangement of Thermocouples for Investigation of Symmetry of Temperature Distribution

3.4 Numerical Analyses

To measure the void fraction in the bundle-type flow channel, multiple pairs of electrodes must be installed at the appropriate position because of geometry complexity. The shape and arrangement of electrodes requires following conditions as far as possible:

- (i) Ease to identify the measuring area
- (ii) Uniformity of the induced current density distribution
- (iii) Small influence on the motion of water and voids.

The condition (i) can be achieved by surrounding the measuring area with electrodes if possible. To satisfy the condition (ii), the ratio between the surface areas of electrode pair should be as small as possible. To satisfy the condition (iii), the size of electrode should be as small as possible. The shape and spatial arrangement of electrodes satisfying these properties were designed based on computational analyses of the electric field in area-C, R and W using a commercial FEM (Finite Element Method) code, ABAQUS Ver.6.4.

For area-C, we adopted a combination of a coil-type and line-type electrodes arranged as shown in Fig.6. Diameter and length of the coil were 11.2mm and 40mm, respectively. Thickness of wire forming the coil was 0.2mm so as not to disturb the water flow. Winding number of the coil was 16. Thickness and length of the line-type electrode were 1mm and 40mm, respectively. The electric current density distribution calculated by three-dimensional analysis is shown in Fig.7(a) for the horizontal cross-section and Fig.7(b)

for the vertical cross-section. Because of symmetry of this arrangement, the analysis was performed in the area shown in these figures. Generally, the sensitivity of the impedance technique to voids is low in the area with low current density. These figures show the current density in most part of the inner area of the coil-type electrode was relatively large and, therefore, this pair of electrodes would have sufficient sensitivity. However, the sensitivity for void fraction measurement would depend on the position of voids because the value of current density around the line-type electrode was larger than that in other area. This effect of sensitivity was investigated by scaled experiments explained in the next section. The result in the vertical section displayed the substantially uniform distribution of current density.

Fig. 6 Arrangement of Electrodes and Thermocouples

For area-R, we adopted a combination of three line-type electrodes and two simulated heater rods. Thickness and length of the electrodes were 1mm and 40mm, respectively. Pitch between the electrodes was 2mm. The result of two-dimensional analysis is shown in Fig.8. There was sufficient current density in this area to measure the void fraction. The density distribution was slightly inhomogeneous; however, there was virtually no problem to measure the void fraction since the void fraction in this area would be approximately uniform because of narrow width of this area (3.2mm).

For area-W, we adopted a combination of a plate-type electrode and two heater rods. Width of the plate-type electrode was the same as that of the flow channel (32mm) and height of it was 40mm. The result of two-dimensional analysis is shown in Fig.9. There was

sufficient current density in this area. The value of current density around the left side of the heater rods was large, and therefore the sensitivity of void fraction measurement would be higher in that region.

Fig. 7 Calculated Current Density Distribution in Area-C

Fig. 8 Calculated Current Density Distribution in Area-R

Fig. 9 Calculated Current Density Distribution in Area-W

3.5 Scaled Experiments

Scaled experiments were performed to evaluate the capability of void fraction measurement using the electrodes of which shape and spatial arrangement were determined above. In these experiments small plastic balls with 6mm diameter dispersed in water to simulate vapor bubbles.

Fig. 10 Scaled Model for Area-C

Fig. 11 Resistance Ratio versus Averaged Void Fraction

Figure 10 shows the scaled model to evaluate the measurement in area-C. The cross-sectional dimension of the model was 15 times larger than that of the actual bundle-type test section. The height of the model was 150mm, which simulated about 1/4 of the test section; therefore, the winding number of simulated coil-type electrode was 4. To investigate the relation between void distribution and measured void fraction, the area between the center and coil electrodes was separated into three layers in radial direction, in which the layers were called layer-1, layer-2 and layer-3 in ascending order of distance from the center electrode. According to the visual observations on the preliminary heating experiment with the actual test section, voids in the area-C hardly concentrated around the center or coil electrode. However, to comprehend the measurement property of the electrode arrangement, three situations in terms of void distribution were investigated, in which voids were only in layer-3, in layer-2 and 3, and in all layers, respectively. Figure 11 shows the measured resistance ratio versus void fraction averaged in the measuring area. A solid line in the figure means theoretical value derived from the Maxwell equation. When voids were in all layers, the measured value agreed well with the theoretical one. The result obtained in

the case where void were in layer-3 were similar to that obtained in the case where void were in layer-2 and 3; each results were larger than the theoretical value and therefore they underestimated the void fraction. The reason for this underestimation is that there was no void around the center electrode where the current density was larger. With similar scaled experiments for area-R and area-W, the capability of the measurement technique and the measuring area were evaluated for respective areas.

3.6 Steady Boiling Experiment

Void fraction in the bundle-type test apparatus was measured using a differential pressure gauge and the impedance technique on steady boiling condition to estimate the accuracy of the impedance technique for measuring cross-sectional averaged void fraction. Based on the estimations by numerical analyses and scaled experiments, the cross-section of flow channel was divided into three areas as illustrated in Fig.3. Since local void fraction was not uniform, the measured void fractions in these areas were different from each other as shown in Table.1. To compare with the void fraction measured by differential pressure gauge, averaged void fraction in the cross-section of flow channel was calculated from the local void fractions obtained by the impedance technique in the three areas with taking the area difference into account. The comparison between the results obtained by the differential pressure gauge and the impedance technique is plotted in Fig.12. The results of impedance technique showed a good agreement with the void fraction estimated from the differential pressure method. The error of the impedance technique against the differential pressure method was within 5% under present experimental condition. In addition, this technique should have sufficient accuracy on transient boiling condition because the impedance technique for single-rod experiments, adopted the same measuring principle as the present technique, had been compared with X-ray technique on transient boiling condition and had been confirmed having sufficient accuracy⁽⁵⁾.

Table 1 Local Void Fraction

Cross-sectional averaged void fraction (Differential pressure)	Local void fraction (Impedance measurement)		
	Area-C	Area-R	Area-W
0.433	0.655	0.395	0.444
0.261	0.273	0.233	0.270

Fig. 12 Comparison between Measured Cross-sectional Averaged Void Fractions Obtained by Differential Pressure Gauge and Impedance Technique

4. Results and Discussion

The transient void behavior in the bundle geometry was measured using the impedance technique in the similar way as the steady boiling experiment. The measuring region in the flow direction was around the top of the test section, in which the top end of the coil-type electrode was at the distance of 5mm upstream of the top end of the heat generation part. Void fractions in the three divided areas were calculated by substituting the measured resistance R_α into Eq.(1). The resistance of single-phase water, R_θ , in Eq.(1) strongly depends on temperature; therefore, we investigated the relation between the resistance and temperature of water from the measured value at the time when no void was observed in the test section confirmed from the movie of high-speed camera. The approximate expressions of the relation in the three areas are as follows:

$$\begin{aligned} R_c &= 0.275(T_c - 393)^2 + 1620 \\ R_R &= 0.105(T_R - 393)^2 + 621 \\ R_W &= 0.225(T_W - 393)^2 + 1240 \end{aligned} \quad (2)$$

where, subscripts C, R and W mean the respective measuring area, and T means averaged water temperature. To calculate the local void fraction, corresponding resistance was used instead of R_θ in Eq.(1).

Fig. 13. Measured Values in Bundle Geometry

Figure 13 shows the variation of heat generation rate, local void fraction, pressure and local subcooling with saturation temperature for a typical experiment with subcooling and velocity of inlet water of 34 K and 0.3 m/s, respectively. During the initial phase of the experiment, the void fraction in area-R slightly increased and oscillated because small voids would grow and collapse on the surfaces of the simulated fuel rods. After that, the pressure gradually increased, and then, at about 0.3sec, the void fraction abruptly increased. The pressure gradually decreased while high void fraction was maintained. However, there was not necessarily an apparent relation between the pressure and void fraction because the pressure was influenced by the subcooling in the upstream of the measuring region, the inertia of the water in the downstream of the measuring region, etc. The saturation temperature also decreased synchronizing with the pressure decrease and influenced on the transient void behavior. For instance, the abrupt increase of void fraction occurred at the same time as the abrupt decrease of local subcooling due to the drop of pressure, i.e., flashing. The abrupt increase of local void fraction in area-C and area-R occurred simultaneously. On the contrary, the increase of local void fraction in area-W occurred later and more moderate than that in other areas because, in area-W, the ratio of the flow area to the length of heat transfer edge was larger than that of other areas and so the water temperature could not increase much..

Averaged void fraction was estimated in a similar way on the steady boiling experiment. Figure 14 shows the dependence of averaged void fraction on heat generation rate with velocity of inlet water of 0.3 m/s. Subcooling of inlet water was 34K for Fig.14(a) and 54K for (b). As the heat generation rate increased, the averaged void fraction increased and the initiation of abrupt increase in void fraction was moved forward. Furthermore, by comparing between Fig.14(a) and (b), the increase of subcooling caused the decrease of the void fraction and the delay of abrupt increase of void fraction. Using the impedance technique proposed in this study, it could be properly confirmed that both the heat generation rate and the subcooling influenced on the transient void behavior.

Fig. 14 Dependence of Averaged Void Fraction on Heat Generation Rate

5. Conclusions

Series of out-of-pile experiments to obtain the knowledge of the transient void behavior during reactivity initiated accidents are in progress. In the present series, the measuring

target was the transient void behavior in the flow channel of 2 x 2 bundle geometry under atmospheric pressure condition. To measure the void fraction in the bundle geometry, we improved the impedance technique which had been applied to the geometry with single simulated fuel rod. The applicability of the improved impedance technique was verified and the transient void behavior in the bundle geometry was measured using this technique.

The essentials of the improved impedance technique for the bundle geometry were multi-area and multi-electrode measurement. The horizontal cross-section of flow channel was divided into three areas to measure the void fraction independently because of geometry complexity. The void fraction in three areas was measured using three couples of electrodes installed in respective areas. The spatial arrangement of the electrodes was defined through numerical analyses of the electric field and scaled experiments. Averaged void fraction in the cross-section of flow channel could be evaluated from the measured void fractions in three areas with taking the difference of area size into account.

To evaluate the accuracy of the impedance technique, the results were compared with those of the differential pressure technique for steady boiling experiments using the actual bundle-type test section. The impedance technique showed a good agreement with the void fraction evaluated by the differential pressure technique.

The transient void behavior in the bundle geometry was measured using the impedance technique. The impedance technique could quantitatively measure the void fraction distribution in the bundle cross-section. The local void fraction in the area adjacent to the wall was often lower than that in other areas because the local void fraction was influenced by the ratio of flow area to heat transfer area of the simulated fuel rod. It could be properly confirmed by the impedance technique that the transient void behavior depended on both the subcooling of inlet water and the heat generation rate of simulated fuel rod.

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