Boiled-up level and boiling two-phase flow dynamics in 5×5 heated rod bundle during boil-off process under atmospheric pressure conditions

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ABSTRACT

In the case of an accident and when a water level of a reactor core falls below the top level of active fuel, the cooling limit height becomes a key factor for determining the accident mitigation procedure. To predict the cooling limit height, it is important to clarify a two-phase mixture level in a rod bundle during the boil-off process. The two-phase mixture level depends on the collapsed level and void fraction distribution. During the boil-off process, a boiling two-phase flow in the rod bundle exhibits multidimensional and complex flow structures. The paper addresses a three-dimensional void fraction distribution and a two-phase mixture level in 5×5 heated rod bundles during the boil-off process, under atmospheric pressure conditions. The heated rod length is 3.7 m, which is the same as the fuel rod in boiling water-reactor (BWR). The 5×5 rod bundles have an axially and radially uniform power profile, and eight pairs of sheath thermocouples are embedded in the heated rod to monitor their axial surface temperature profiles. The diameter of the heated rod is 10 mm, and the rod pitch is 13 mm. The void fraction distributions were acquired with eight pairs of subchannel void sensors (SCVS) as time series data. The two-phase mixture level was evaluated by side-viewing images acquired with two high-speed digital video cameras. The experimental result exhibits a relationship of the boiling two-phase flow dynamics to the two-phase mixture level, and the void fraction during the boil-off process.

KEYWORDS
Boiling two-phase flow, 5×5 heated rod bundle, void fraction, two-phase mixture level, boil-off

1. INTRODUCTION

When the water supply function is lost in a reactor in the case of an accident, the reactor's water level falls and a fuel rod bundle may be partially exposed. A two-phase mixture level may form owing to boiling behavior in the rod bundle. Below the two-phase mixture level, the fuel rod is sufficiently cooled and maintained at the water saturation temperature. However, the temperature of the exposed fuel rod to the vapor environment can rise during the boil-off process. To evaluate the coolability of the fuel rod during the boil-off process, it is important to predict the two-phase mixture level. The two-phase mixture level depends on the void fraction in the reactor core. Since the void fraction in the reactor core has a spatial distribution related to the development of a boiling two-phase flow, it is necessary to clarify the void fraction distribution in a reactor core in detail.

During the boil-off process, the two-phase mixture level fluctuated periodically owing to the passage of vapor bubbles and slugs as shown in Fig. 1. The boiling two-phase flow exhibits multidimensional and transient flow dynamics, and droplets, liquid slugs, and liquid film, can be generated near the two-phase mixture level. Therefore, it is important how to determine and predict the effective cooling level of the heated rod. The effective cooling level can be related to the two-phase mixture level behavior.

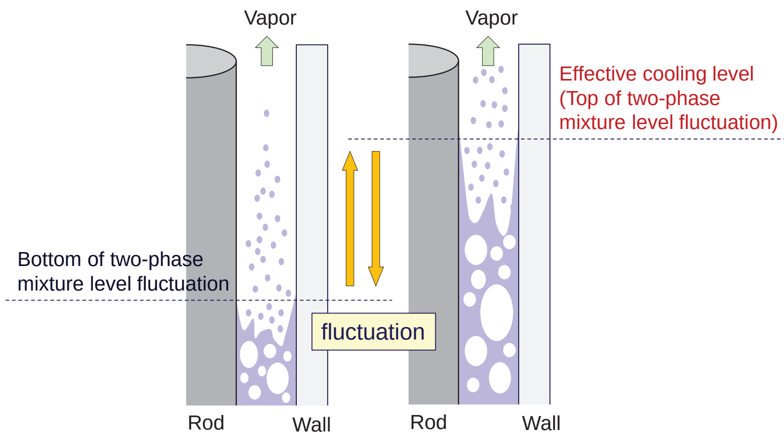


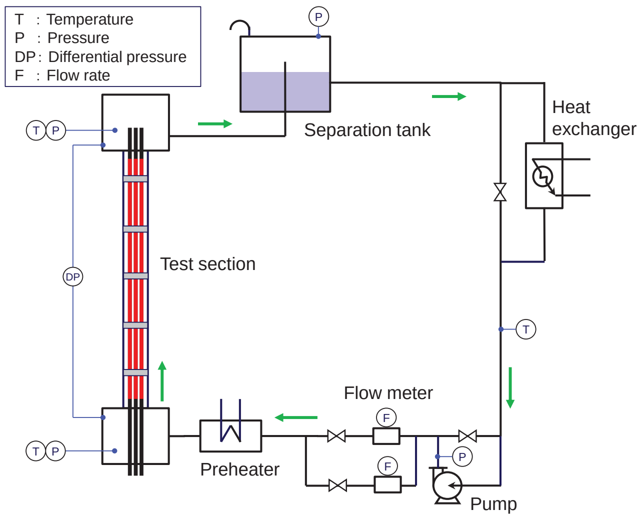
Figure 1. Effective cooling level during boiled-off process.

In previous studies, boil-off experiments had been conducted to acquire the void fraction in the rod bundle, and time series data of the rod-surface temperature [1–7]. A two-phase mixture level has also been estimated based on the temperature of the rod surface and the local differential pressure. Anklam et al. conducted boil-off experiments under high pressure conditions (4.0–7.5 MPa) using an 8×8 rod bundle to simulate PWR flow conditions [6]. The two-phase mixture level was estimated by a dryout of the heated rod, which was detected using thermocouples in the rod. Seedy et al. conducted a boil-off experiment under high pressure conditions (approximately 1.4–5.5 MPa) using an 8×8 rod bundle to simulate the BWR flow conditions [7]. The two-phase mixture level was estimated based on the dryout of the heated rod and the local differential pressure. However, there is insufficient knowledge about the relationship between the effective cooling level and the two-phase mixture level behavior especially under atmospheric pressure conditions. In the present study, a rod bundle boil-off experiment was conducted to clarify the effective cooling level and the void fraction in the rod bundle.

2. EXPERIMENTS

Figure 2 shows a schematic diagram of the test loop, which comprises a circulation water pump, flow meters, a preheater, a rod-bundle test section, a separation tank, and a heat exchanger. The system pressure is atmospheric pressure since the separation tank is open to the atmosphere. Water is supplied to the bottom of the test section by the circulating pump and the preheater. A boiling two-phase-flow goes up and is divided into vapor and water by the separation tank, while the water is recirculated through the heat exchanger and the vapor is condensed in a reservoir. The test fluid is water that has traversed an ion-exchange resin whose electrical conductivity is controlled by the periodic water exchange in order to maintain the reproducibility of the void measurement using subchannel void sensors (SCVS).

Figure 3 shows a schematic of the test section. The geometry of the test section is a 5×5 rod bundle. The heated rod diameter is 10 mm and the rod pitch is 13 mm. The heated length of the rod bundle is 3.7 m and its lower end is defined as a reference position (z = 0 mm). The rod bundle is installed in the rectangle vessel made of polycarbonate. Ferrule spacers are installed at eight height levels. The main measurements are the void fraction, rod surface temperature, fluid temperature, pressure, and differential pressure.



Test fluid	Water
System pressure	Atmospheric pressure
Maximum design temperature	120 ºC
Maximum design flow rate	4.8 m^3/h

Figure 2. Schematic of test loop.

To measure the rod surface temperature distribution, eight sheathed-thermocouples of outer diameters of 0.5 mm are embedded in five heater rods, respectively. Heater rods with thermocouples are also arranged in the central, side, and corner regions of the rod bundle, respectively. The axial positions at which the temperature measurements were conducted at the rod surface are z = 1981, 2493, 3005, 3281, 3517, and 3690 mm, which are downstream of the spacers or at the middle position between them.

The SCVS is a void fraction measurement sensor, capable of acquiring a multidimensional void fraction distribution in a rod bundle at a high-sampling rate [8, 9]. Figure 4 shows a partial cutaway view of the SCVS. Wires (6×6) are inserted in the gaps between the rods and act as independent electrodes. The six wires of both layers intersect at 90° with a gap of 2 mm. The diameter of the wire electrodes is 0.2 mm. The unique feature of the SCVS is the 5×5 heated rods are used as independent electrodes. All the spacers have insulated coverings, which allow the heater rods to be used as individual rod electrodes. For the 5×5 heated rod bundle, the SCVS can acquire both the 32 points (= 6×6-4) in the central subchannel region and the 100 points (= 5×5×4) near the surface region of the rod of the void fraction distribution. This means that the SCVS can measure 132 points of the local void fraction as the cross-sectional distribution. The local void fraction is estimated by the electric potential acquired by the SCVS, while the signal-processing technique of the wire mesh sensor (WMS) [10] was applied to the SCVS signal processing. Pairs of SCVS are located at eight height levels, z = 198, 709, 1220, 1731, 2242, 2753, 3264, and 3775 mm. The height levels of the SCVS correspond to the middle position between the spacers.

Since the flow condition in the experiment is a low-flow rate, equivalent to that of natural circulation, it is important to ensure adequate measurement accuracy in the low-flow region. Accordingly, two types of coriolis flow meters were used (Micro Motion ELITE sensor by Emerson Electric Co.), with different measurement ranges and with a ± 0.1% accuracy. The local differential pressure was measured by a differential pressure transmitter (DPharp EJX110 by Yokogawa Electric Co.) with a ±0.1 % accuracy over the full-scale range and a 0.1 s response. Visual observations are conducted by two high-speed digital video cameras (Vision Research Inc., Phantom V1210).

According to the experimental conditions, the outlet pressure is atmospheric, while the experimental parameter is the bundle thermal power. The bundle thermal power Q varies from 3.8 to 15 kW corresponding to approximately 0.25 – 1% of the rated thermal power of the fuel rod in BWR. The radial and axial distributions of the rod-bundle power are uniform. The inlet flow rate is zero, which corresponds to the pool boiling condition.

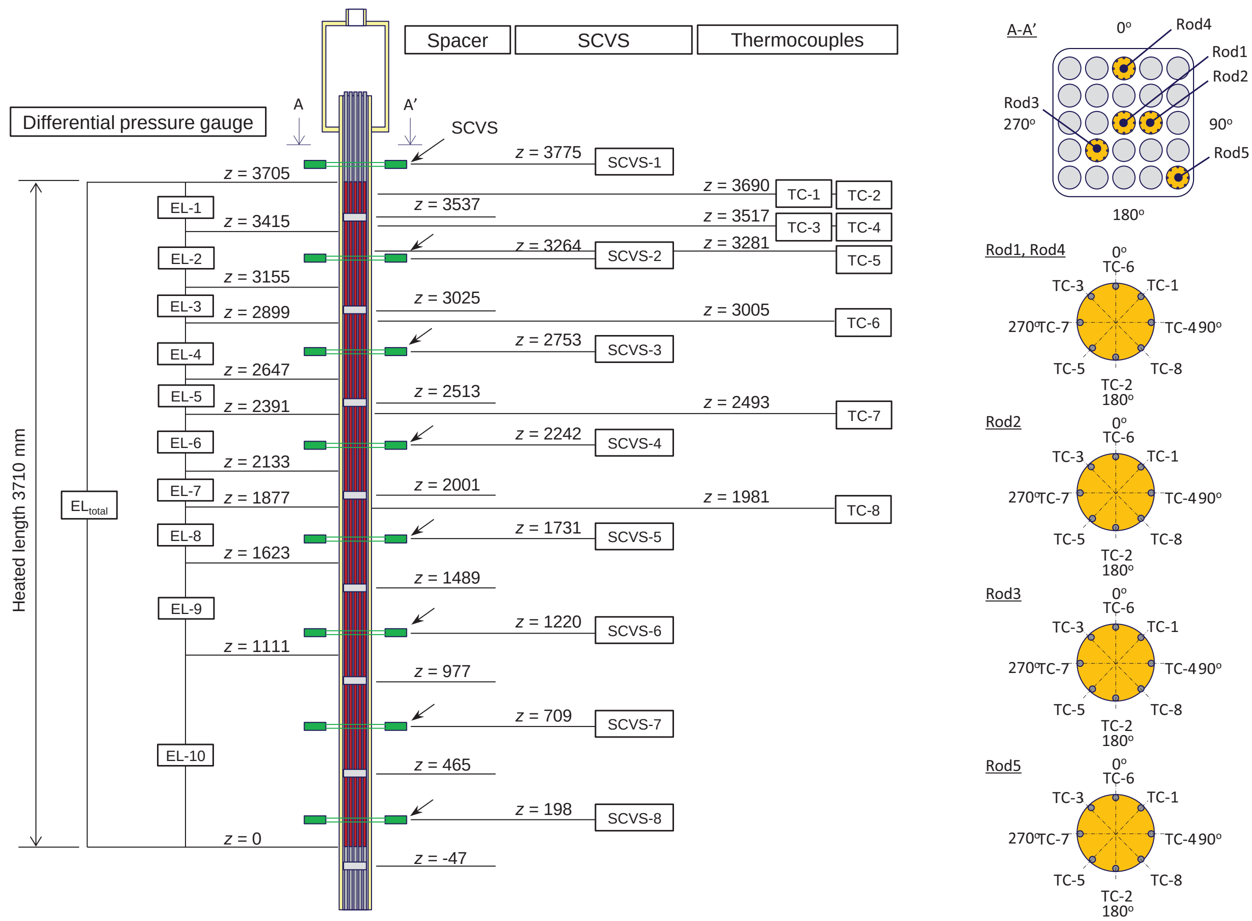


Figure 3. Schematic of test section.

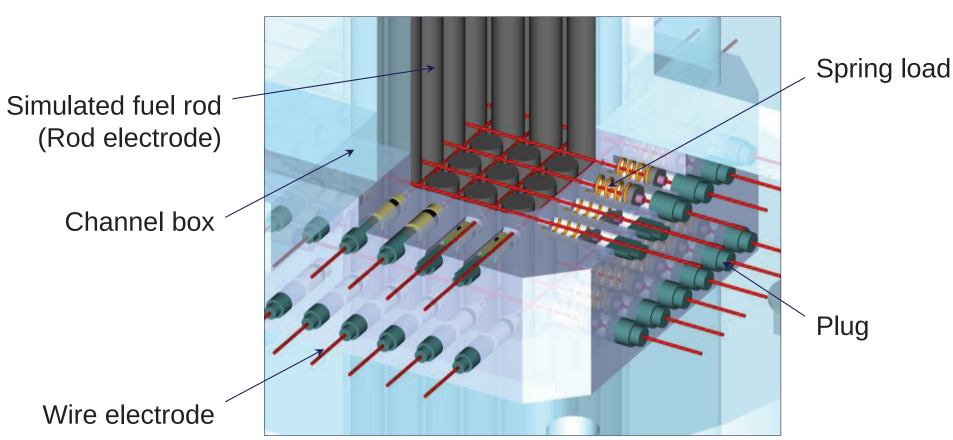


Figure 4. Partial-cutaway view of the SCVS.

3. RESULTS AND DISCUSSIONS

Figures 5–10 show the experimental results with a bundle thermal power of 5.6 kW under the pool boiling condition. The boiling two-phase flow behavior was acquired using the eight pairs of the SCVS, the thermocouples embedded on the rod's surface, the local differential pressure gauges, and the high-speed digital video camera. The two-phase mixture level was evaluated by each measurement results.

Figure 5 shows the successive images observed from the side of the test section. The observation area is near the top of the heated part of the rod bundle. The start time (t = 0 s) is defined as that when the two-phase mixture level reached a level of approximately z = 3.7 m. The yellow arrow shows the two-phase mixture level. Near the two-phase mixture level, large vapor slugs covering two or more channels blew off periodically with liquid slugs and films. The two-phase mixture level decreased over time and reached the bottom of the observation area at 450 s. Figure 6 shows a two-phase mixture level variation obtained from side-view images. Herein, the two-phase mixture level was extracted by the difference in intensity between the neighboring two images. To detect the two-phase mixture level, a background image was eliminated from the original and the extracted image was binarized to emphasize the two-phase mixture level. The result shows that the two-phase mixture level fluctuated with a magnitude of approximately 300 mm, in accordance to the blow off of the vapor slugs, and gradually declined owing to the evaporation of water.

Figure 7 shows the variation over time of the cross-sectional average void fraction with the SCVS located at the four height levels. The cross-sectional average value was calculated as a weighted mean value based on the division of the flow channel area, as shown in Fig. 8. The region near the rod surface is divided into four subregions and assigned by four measuring points near the rod surface. The rest of the flow area is assigned by the central subchannel region. The corner region is calculated as an average of two neighboring regions near the rod surface. Since large vapor slugs periodically traversed the flow channel, the void fraction sharply fluctuated with a value of approximately ±0.2, downstream of the test section. When the two-phase mixture level approached the measuring height level, the void fraction increased and finally reached 1.0. At z = 3264 mm, the void fraction gradually increased after 380 s. The time at which the void fraction firstly reached the value of 1.0 was defined as the instant at which the bottom of the two-phase mixture level fluctuation reached the measuring position, while the time at which there was no fluctuation of the void fraction at a value of 1.0 was defined as the instant at which the top of the two-phase mixture level fluctuation reached the measuring position.

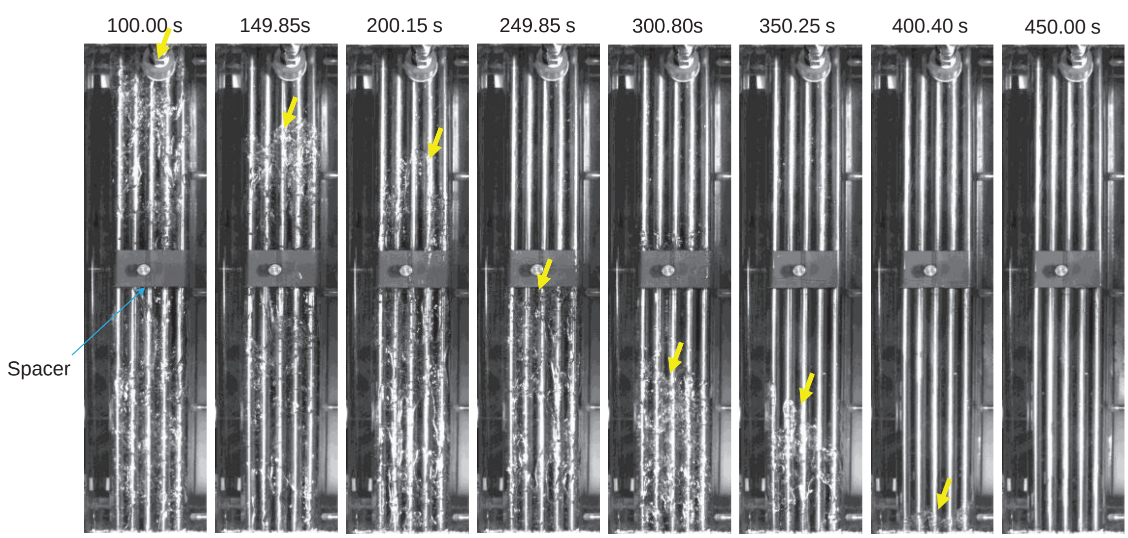


Figure 5. Successive images during the boil-off process (*Q* = 5.6 kW, pool condition).

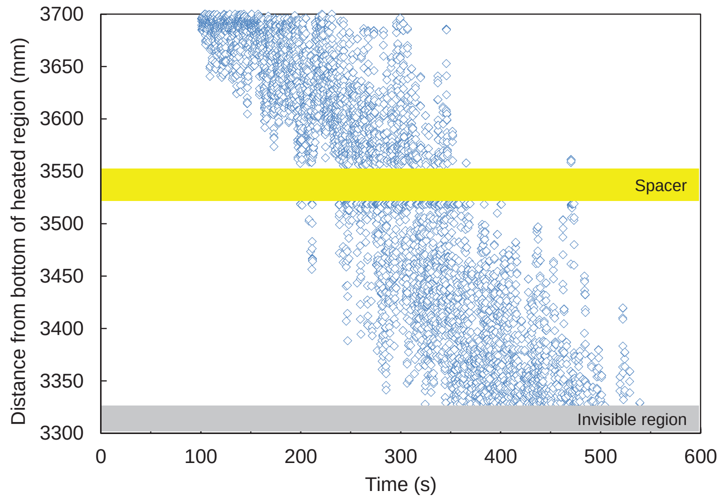


Figure 6. Two-phase mixture level extracted from the observed images (*Q* = 5.6 kW).

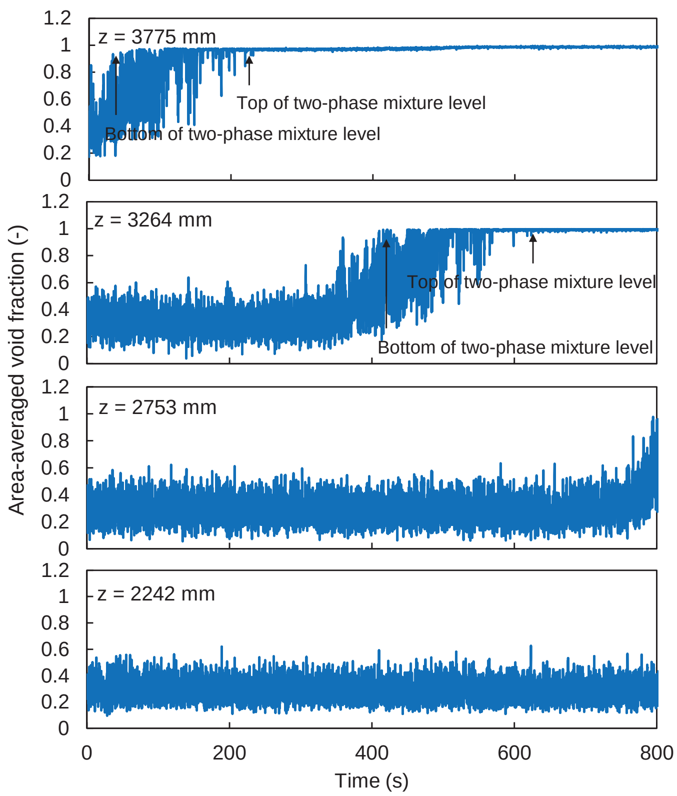


Figure 7. Void fraction distribution acquired by SCVS. (*Q* = 5.6 kW)

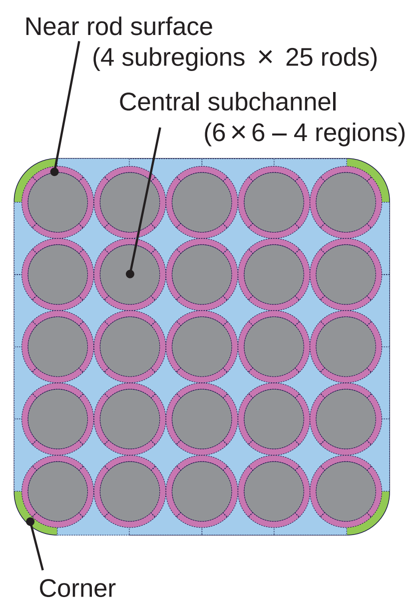


Figure 8. Regional division of flow area.

Figure 9 shows the variation over time of the volume-averaged void fraction at seven intervals evaluated by local differential pressure data. The volume-averaged void fraction was estimated by the measured differential pressure since the axial pressure profile is primarily governed by the hydrostatic head of the water under the pool boiling condition. When the two-phase mixture level reached a measuring interval of differential pressure, the void fraction increased and approached 1.0. The time when the void fraction reached 1.0 was defined as the instant when the two-phase mixture level reached the lower height of the measuring interval.

Figure 10 shows the variation over time of the rod-surface temperature in the side, corner, and center of the rod bundle. Below the two-phase mixture level, the heated rod was sufficiently cooled and the rod surface temperature was maintained at the saturated water temperature. As the two-phase mixture level declined, the rod surface temperature started increasing from the top of the rod. The start time at which the rod surface temperature increased from the saturated water temperature was defined as the time at which the two-phase mixture level reached the measuring height level. The reason why the rate of the temperature rise at z = 3690 mm was relatively slower than in any other position is that the height z = 3690 mm is the upper end of the heated area, and the axial heat conduction to the upper nonheated rod can affect the rod surface temperature.

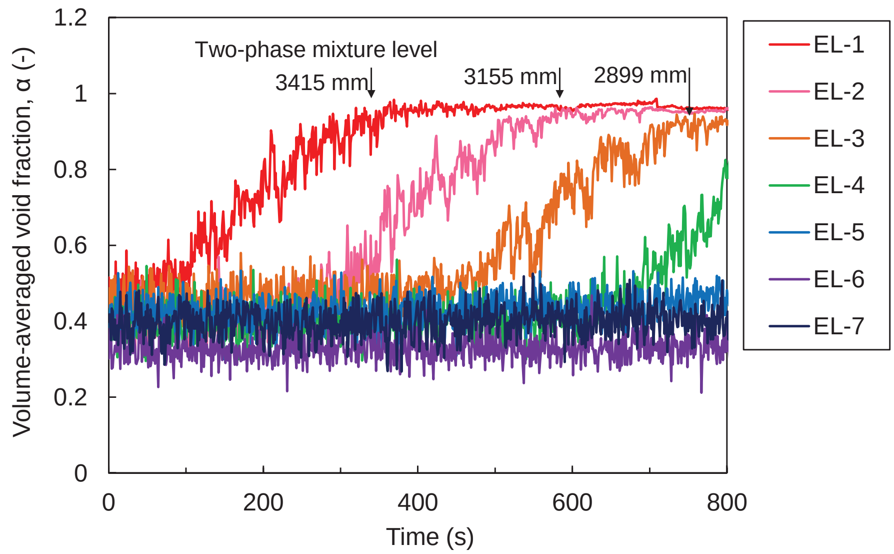


Figure 9. Two-phase mixture level evaluated by the differential pressure (Q = 5.6 kW).

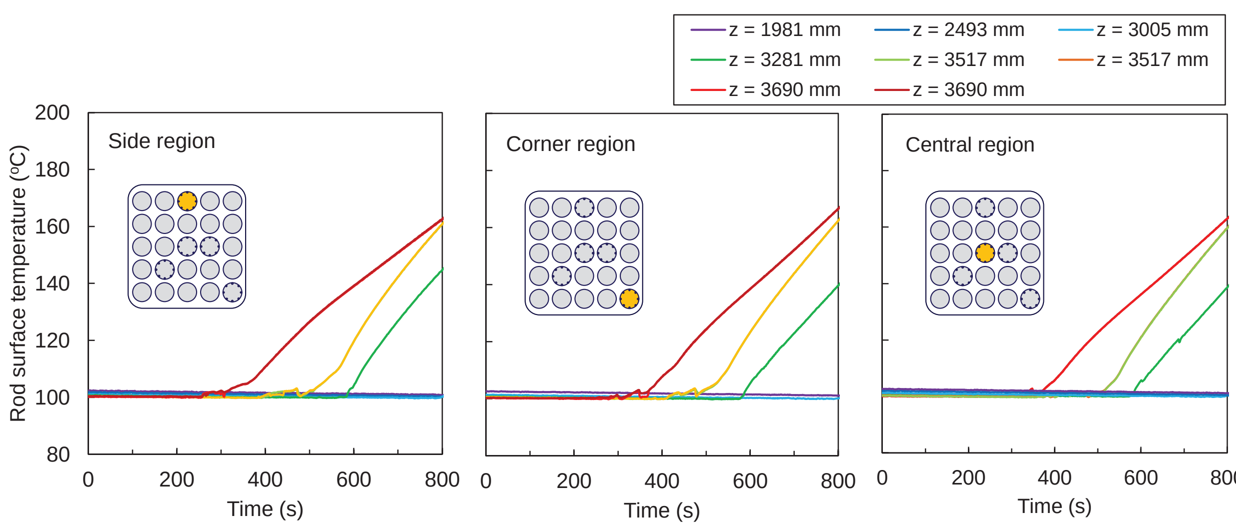
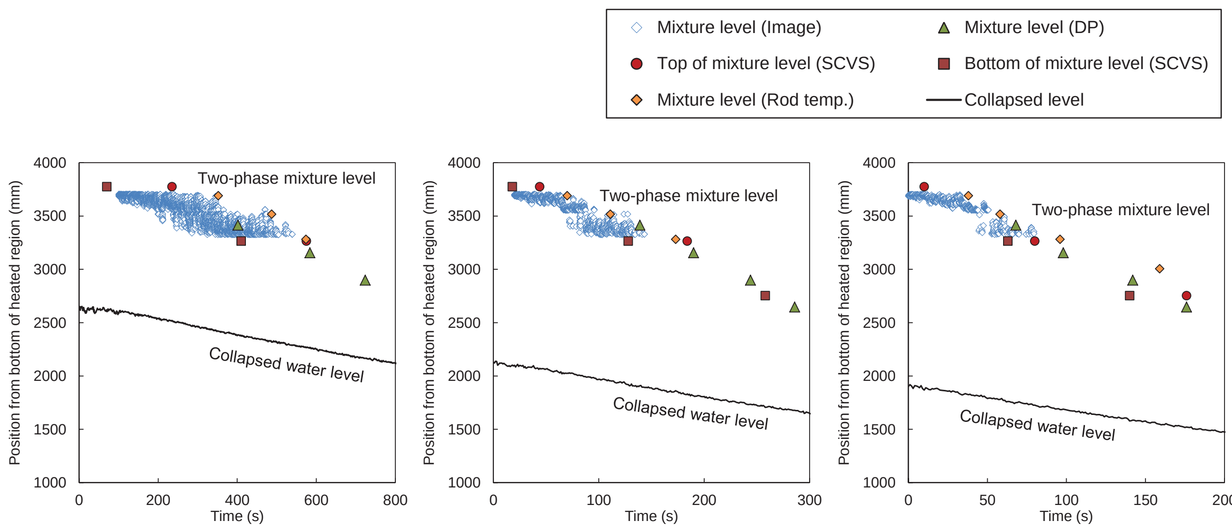


Figure 10. Two-phase mixture level evaluated by the rod surface temperature (Q = 5.6 kW).

Figure 11 shows a comparison of the collapsed water level and the two-phase mixture level obtained by each set of measurements. The bundle thermal power levels are 5.6, 11, and 15 kW, respectively. The two-phase mixture level sharply changed in magnitude of approximately 300 mm under any thermal power condition. The top and bottom fluctuations of the two-phase mixture level based on the observation images were in good agreement with those based on SCVS measurements. Conversely, the two-phase mixture level obtained by measuring the differential pressure was located at the lower end or at the middle position of the fluctuation value. This is because it is difficult to detect locally supplied liquid slugs and liquid films following differential pressure variations. The two-phase mixture level based on the rod surface temperature rise was in agreement with the top of the two-phase mixture level variation. Therefore, the top of the two-phase mixture level fluctuation is equivalent to the effective cooling level during the boil-off process. The result indicates that the rod bundle can be cooled even if a droplet or a liquid film is supplied periodically on the rod's surface. However, once the rod surface temperature increases, occasional water, supplied in the form of droplets, hardly affects the coolability of the partially exposed rod.



(a) Q = 5.6 kW **(b) Q = 11 kW** **(c) Q = 15 kW**

Figure 11. Effect of bundle thermal power on boiling two-phase flow during the boil-off process.

Based on the experimental results, the existing model predicting two-phase mixture level in the reactor core was validated. When the two-phase mixture level or the void fraction in the core are evaluated based on the safety analysis code, there are various void fraction correlations, such as one-dimensional and lumped parameter models. In the present study, the experimental results were compared to the prediction by the void fraction correlation for the boil-off condition implemented in the severe accident analysis code MAAP. The void fraction correlation in MAAP is modeled as a lumped parameter system. The void fraction correlation is a function of the superficial vapor velocity. In the present experiment, the volume-averaged void fraction can be calculated by:

$$\bar{\alpha} = 1 - \frac{Z_c}{Z_m} \tag{1}$$

where Z_m is the two-phase mixture level and Z_c is the collapsed water level. The two-phase mixture level fluctuated in accordance to the blow off of vapor slugs, and it then gradually declined owing to the evaporation of water under any bundle thermal power condition. The time-averaged two-phase mixture level was evaluated with the results obtained by image processing for side-view images. The superficial vapor velocity can be calculated by the amount of the evaporation. Just above the two-phase mixture level, the superficial vapor velocity is given by:

$$j_g = \frac{\rho_{l,sat}}{\rho_{g,sat}} u_d \tag{2}$$

where u_d is the decrease rate of the collapsed water level, and ρ the density. The subscripts g, l, and sat denote vapor phase, liquid phase, and saturated condition respectively. Saturated thermo-physical properties are evaluated at the outlet pressure.

Figure 12 shows the comparison of the void fraction between the experimental results and the predicting value of the correlation in MAAP 5.01 [11]. The existing test data are also plotted in the figure as a reference although the pressure conditions are different. There are two types of experimental results, such as the full-length and the short-length. The full-length results mean that the rod bundle test section is 3.7 m in heated length, and the short-length results mean that the rod bundle test section is 2 m in heated length [12]. The experiment using the short-length rod bundle simulated the boil-off process in which the two-phase mixture level is considerably below the TAF in the actual height of the rod bundle. When the water level declined and the rod bundle was partially exposed to the vapor atmosphere, the superficial vapor velocity decreased since the effective heated length, which contributed to the evaporation of water, decreased. Comparing the experimental result of the short-length and full-length rod bundle, the void fraction with the short-length rod bundle was larger than that of the full-length rod bundle. During the boil-off process, the volume-averaged void fraction depends on the surface heat flux of the rod bundle. On the other hand, the superficial vapor velocity depends on the total thermal power of the rod bundle. When the total thermal power of the rod bundle is equal in all these rod bundles, the superficial vapor velocity will attain the same value if the entire heated rod contributes to the vaporization of water. However, the void fraction become larger since the surface heat flux of the short-length rod bundle is larger than that of the full-length rod bundle. Although the correlation overestimated the void fraction under a slower superficial vapor velocity condition, the predicted value was in agreement with

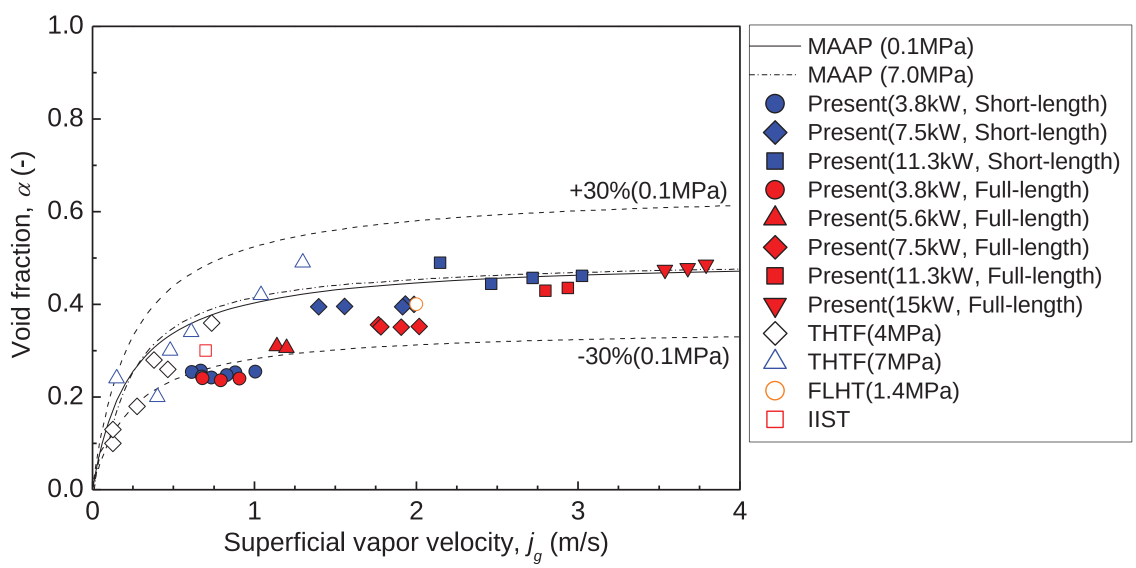


Figure 12. Comparison of void fraction data during boil-off conditions.

the experimental results at velocities over 2 m/s of the superficial vapor velocity. This is related to the boiling two-phase flow behavior and the flow regime under the pool boiling condition. When the bundle thermal power becomes higher, the churn-turbulent flow with a high void fraction is dominant in the entire flow channel. However, when the bundle thermal power becomes lower, the developing flow which changes from a bubble flow to a churn flow is dominant, and the drift velocity is relatively large and the void fraction becomes relatively small. The comparison indicates that the present correlation can predict the void fraction during the boil-off process within approximately ±30%.

4. CONCLUSIONS

A rod bundle boil-off experiment was conducted to clarify the effective cooling level and the void fraction in the rod bundle under atmospheric pressure conditions. The geometry of the test section is a 5×5 rod bundle. The heated rod diameter is 10 mm and the rod pitch is 13 mm. The heated length of the rod bundle is 3.7 m. During the boil-off process, the two-phase mixture level fluctuated as large vapor slugs that covered two or more channels, blew off periodically. Since the two-phase mixture level, based on the rod's surface temperature elevation, was in agreement with the top of a two-phase mixture level fluctuation, the effective cooling level during the boil-off process was equivalent to the top of the two-phase mixture level fluctuation. This result indicates that the rod bundle can be cooled even if a droplet or a liquid film is supplied periodically on the rod's surface. The void fraction obtained by the present experiments were compared to that predicted by the void fraction correlation implemented in the severe accident analysis code MAAP . The result indicates that the present correlation can predict the void fraction during the boil-off process under an atmospheric pressure condition within a tolerance of ±30%. In particular, the predicted value was in agreement with the experimental results for velocities over 2 m/s of the superficial vapor velocity.

NOMENCLATURE

j	: sperficial velocity	[m/s]
t	: time	[s]
Q	: bundle thermal power	[W]
u_d	: decrease rate of collapsed water level	[m/s]
z	: axial position	[m]
Z_m	: two-phase mixture level	[m]
Z_c	: collapsed water level	[m]

Greek letter

α	: void fraction	[-]
ρ	: density	[kg/m^3]

Subscript

g	: vapor
l	: liquid
sat	: saturated condition

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