EEFECT OF A BLOCKAGE LENGTH ON THE COOLABILITY DURING REFLOOD IN A 2X2 ROD BUNDLE WITH A 90% PARTAILLY BLOCKED REGION

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ABSTRACT

If fuel rods are ballooned or rearranged during the reflood phase of a large break loss-of-coolant accident (LBLOCA) in a pressurized-water reactor (PWR), the transient heat transfer behavior is entirely different with those of the intact fuel rods owing to the blocked region in the core region. The coolability at the blocked region is determined by the combined effect of a complex two-phase heat transfer with various thermal hydraulic conditions. In addition, the blockage characteristics, such as the blockage ratio, length, shape, and configurations, are also significant factors affecting the coolability. In the present study, several reflood experiments were carried out to understand the effect of the blockage upon two-phase heat transfer phenomena by varying the reflooding rates, especially on the effect of the blockage length. The 2x2 electrically-heated rod bundle were used and a ballooning shape of the rods was simulated using blockage simulators, which have the same blockage ratio but different blockage lengths. The transient temperature profile was measured and the quenching time and heat transfer coefficient were calculated to evaluate the influence of the blockage region on the coolability. The droplet behaviors were also investigated by measuring the velocity and size of droplets near the blockage region. The coolability at the downstream region of the blockage was significantly enhanced, owing to the reduced flow area of the sub-channel, intensification of turbulence, and the entrained droplets on the blockage region.

KEYWORDS
Blockage length, Coolability, Reflood Test, Rod bundle, LBLOCA

1. INTRODUCTION

The local overheating during a LBLOCA in a PWR may induce the ballooning of the cladding of the fuel rods. The ballooned fuel rods cause a restriction of cooling water passages in the subchannel, and thus the transient heat transfer behavior during a reflood phase is entirely different with the intact fuel rods owing to the blocked region. Therefore, the coolability for the ballooned fuel rods has been an important issue since the 1980s. Many large experimental programs have been carried out to investigate the influence of the blocked region on the coolability. The main experimental programs can be summarized as the FEBA [1], SEFLEX [2], THETIS [3, 4], ACHILLES [5], CEGB [6], and FLECHT-SEASET programs [7]. More detailed reviews of the programs were given by Grandjean [8]. In addition, JAERI conducted forced reflood tests with a 60% blockage ratio using the Slab Core Test Facility (SCTF) for modeling and verification of the safety code [9]. Previous studies conducted forced or gravity reflood tests for various test conditions to examine the heat trasnfer behavior at the blockage region and to determine an upper limit of the blockage

*Thermal Hydraulics Safety Research Division coolability with respect to the blockage geometry and configurations. They concluded that the coolability at the blockage region greatly depends on the blockage characteristics (blockage ratio, maximum blockage length, blockage shape, and blockage configuration) and the coolant conditions (flow rate, system pressure, and inlet temperature). However, the effect of fuel relocation in the process of the ballooning of the fuel rods was not considered in their study.

Recently, an experimental program was launched by the Korea Atomic Energy Research Institute (KAERI) in 2011 to understand the related physical phenomena and evaluate the coolability of the ballooned fuel rods considering the fuel relocation. The experimental program consists of two large group tests. The first group test is intended to understand the heat transfer phenomena and examine the effect of the blockage characteristics on the coolability in a modeled 2x2 subchannel. The second experiment, after the first group test, will be performed in a more elaborate 5x5 facility considering the blockage region and fuel relocation.

More specifically, the main objective of this study, which is the first group test, is to identify the effect of the blockage characteristic on the coolability. Two kinds of experiments have been performed for a single-phase steam flow tests and reflood tests. The single-phase steam flow test, which was intended to investigate the influence of the blockage length on the convective heat transfer, was conducted before using a 2x2 test facility by these authors [10]. The axial temperature behavior was measured with various stream flow rates, and the local Nusselt numbers were analyzed to systematically examine the convective heat transfer. The presence of the blockage region resulted in improved cooling due to the enhancement convective heat transfer because the steam velocity was increased in proportion to the reduced flow passage. However, the results do not consider the effect of coolant by-pass at the blockage region, which may induce a different flow distribution, owing to the inherent geometrical restriction of the 2x2 test facility.

In this study, the reflood test results will be described to understand the transient heat transfer behavior and investigate the effect of the blockage region on the coolability in a 2x2 rod bundle test facility. As a parametric study, the maximum blockage length and reflood rates were chosen as the main parameters since the long blockage length significantly affect the coolability in the low reflood rate. Therefore, two different types of blockage simulators, which have different maximum blockage lengths, were designed to simulate the ballooned shape of the fuel rods. The reflood tests were performed at different reflood rates between 2.0 and 3.5cm/s. Thermocouples were directly mounted on the outer surface of the blockage simulator along the elevation to understand the local quenching phenomena in the blockage region. All transient temperature profiles of the heater rod and blockage simulator were simultaneously measured, and the heat transfer coefficients and quench time were calculated and compared with each other to evaluate the overall coolability at the blockage region. In addition, the velocities and sizes of the droplets near the blockage region were measured to scrutinize the droplet effect on the quench phenomena.

2. EXPERIMENTAL TEST FACILITY

2.1. Main Test Section and Instrumentation

The experiments were performed in a 2x2 rod bundle test facility in which the fuel rods were simulated by electrical heaters made of Nichrome. The heaters were embedded in BN+MgO insulators and enclosed in a 1.65mm Inconel 600 cladding layer. The total heated length of the heater rods was 1800mm, and uniform electrical power in both the axial and radial directions was supplied to the heater rods. The heater rods were 20mm in diameter and arranged in a square array with a 27mm pitch, as shown in Fig.1. This geometry is about twice as large as the subchannel of a conventional PWR reactor. Four spacer grids without mixing vanes were assembled to the test section with a 580mm interval to support the heater rods. A quartz measurement window was installed at the center region of the test section to measure the droplets using a high-speed camera. The droplet images were analyzed using commercial software (VisiSize) from Oxford Laser Ltd to extract the droplet size and velocity [11]. The VisiSize software has 3.2% uncertainty for a 0.1mm droplet diameter and 0.03% uncertainty for 2mm [12]. The subcooled water from the coolant storage tank is injected into the bottom of the test section for the reflood phase.

To measure the temperature on the heater rods, each rod was instrumented with 10 thermocouples (TCs), which were mounted directly on the outer surface of the Inconel cladding. The axial locations and radial locations of all TCs are shown in Figs. 2 and 3. The steam flow rate, steam inlet temperature, and steam inlet pressure were measured by a vortex flow meter, a K-type thermocouple, and a pressure transmitter, respectively. The uncertainties of the measurement instruments are 1.00% of the span, ±1.1℃, and 0.065%, respectively.

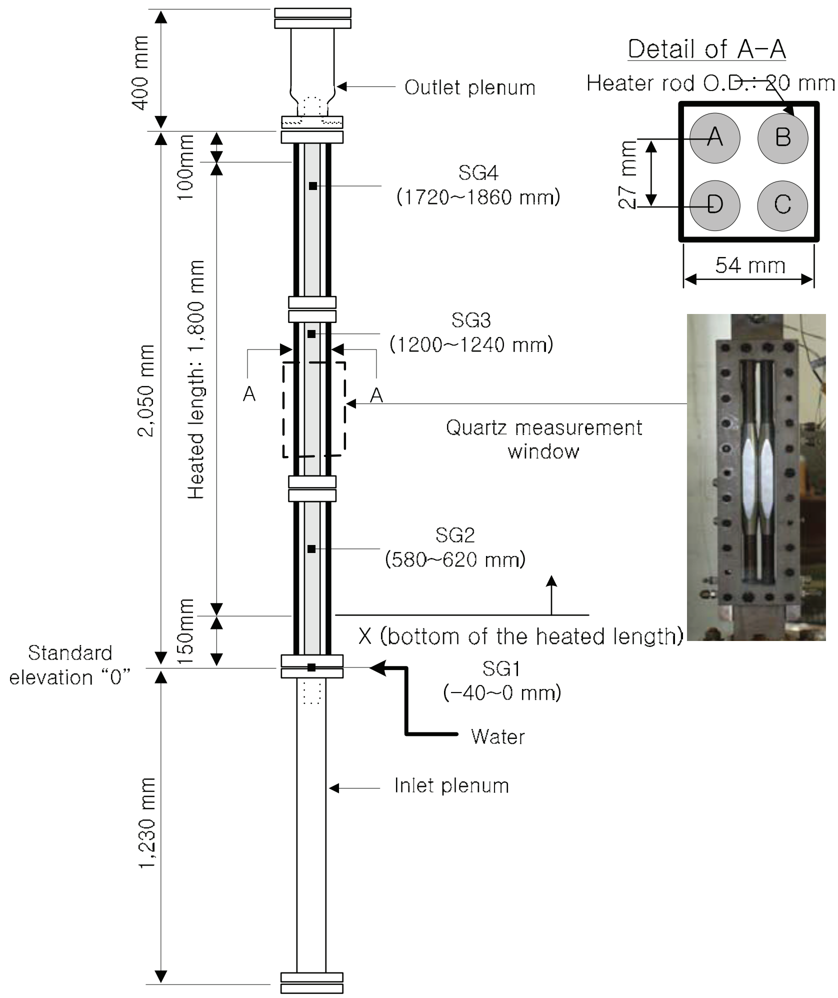

Figure 1. Schematic Diagram of the 2x2 Test Facility.

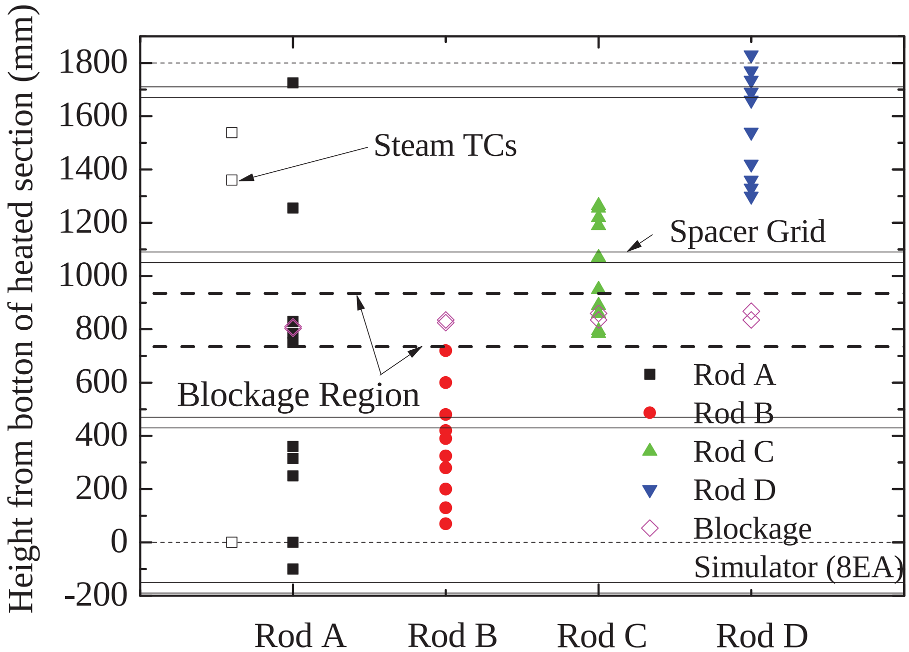

Figure 2. Axial TC Locations of the Main Test Section.

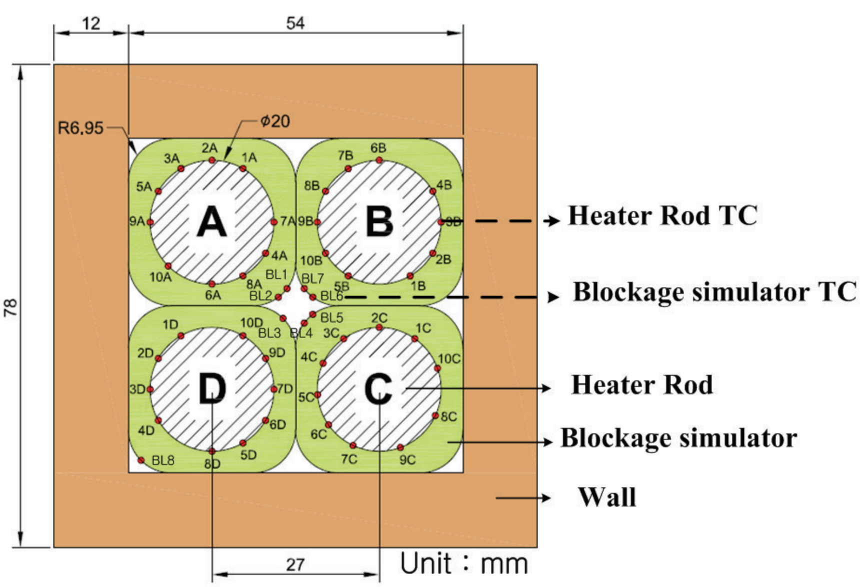

Figure 3. Radial TC Locations of the Main Test Section.

2.2. Blockage Simulator Design

In this study, two blockage simulators that have a different blockage length, were used to understand the effect of the blockage length on the coolability. The ballooning shape of the each fuel rod was simulated by superimposing the blockage simulators onto the heater rods. A schematic diagram is shown in Fig. 4. The tapered hollow sleeves were used to simulate the shape of the ballooning. The blockage simulators were made of Inconel 600, which is the same material as the heater rod cladding. The total length of the blockage simulator was 200mm, among which 80mm or 160mm was the maximum blockage length and 60mm or 20mm was the inlet/outlet taper lengths, respectively. The maximum blockage ratio in the blocked region was maintained at 90%. The inner diameter of the blockage simulator was manufactured according to the outer diameter of the heater rod, and attached to the heater rods using two grub screws per blockage simulator. It should be noted that the blockage simulators were installed on the same elevation without considering the bypass flow region between the adjacent fuel rods, owing to the inherent geometrical restriction of the 2x2 test facility. The blockage simulators are placed between 735mm and 935mm from the bottom of the heated length to minimize the effect of the 2nd and 3rd spacer grids. The previous experimental programs [8] have not provided any temperature profiles along the elevation in the blockage region. However, in this study, eight additional TCs were embedded on the outer surface of the blockage simulator along the axial direction to monitor the transient temperature profiles directly, as shown in Figs. 2 and 3.

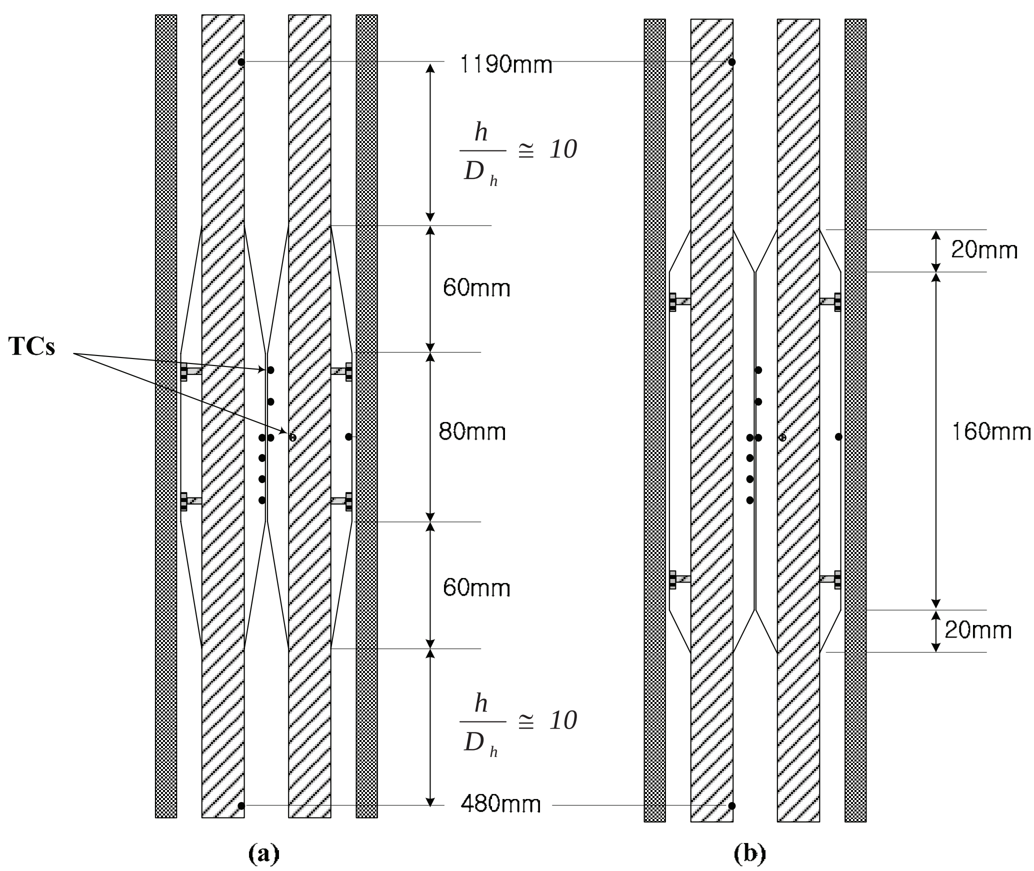

Figure 4. Schematic Diagram and Instrumentation of Blockage Simulator.

3. EXPERIMENTAL RESULTS

Reflood tests were carried out for the non-blockage, 90% short blockage, and 90% long blockage conditions with various reflood velocities ranging from 2.0 to 3.5 cm/s. The inlet subcooling temperature, and power were maintained at about 50℃, and 1.5kW/m, respectively. The system pressure was about 0.101 MPa since the outlet of the test section was exposed to the atmosphere. The main test conditions of all reflood tests are summarized in Table I.

Table I. Main Test Conditions of Reflood Tests

Vr (cm/s)	Test section	*Vr* (cm/s)	P_{sys} (kPa)	ΔT_{sub} (℃)
2.0	Non-blockage	2.03	101.4	46.1
	90% short blockage	2.04	101.3	53.1
	90% long blockage	2.06	101.8	49.6
2.5	Non-blockage	2.49	101.5	47.4
	90% short blockage	2.56	101.3	50.6
	90% long blockage	2.54	101.8	49.2
3.5	Non-blockage	3.47	101.5	49.8
	90% short blockage	3.43	101.3	51.0
	90% long blockage	3.45	101.6	48.7

Transient temperature profiles were measured along the elevation of heater rods, and the droplet velocity and size were also measured near the blockage region. The heat transfer coefficients and quenching time at bare heater rods were calculated from the measured temperature using the Finite Volume Method (FVM). Figures 5 and 6 show the quenching times along the axial direction of the heater rods, and the heat transfer coefficients at the downstream (1190mm) region, respectively. Regardless of the relfood rates, great differences in the quenching time at the upstream of blockage region were not found, except for 2.0cm/s, as shown in Fig. 5. When the reflood rate was 2.0cm/s, the quenching times of short and long blockage tests were similar, but the rewetting of the non-blockage tests occurred earlier than the blockage tests. In the upstream region, the steam flow generated from the quench front was suddenly blocked due to the large hydraulic resistance of the blockage region. This means the stream flow velocity decreases, and thus the convective heat transfer is also decreased. When the reflood rates were high, no great differences were found, which might be associated with the large amount of stream flow enhancing the convective heat transfer.

On the contrary, in the case of the blockage tests, the cooling and rewetting always occurred earlier at the downstream region compared with those of the non-blockage tests as shown in Figs. 5 and 6. The discrepancy of the quenching time between the long blockage and short blockage increased with a decrease the reflood rates since the advance of the quench front is much slower for low reflood rates. In the case of blockage tests, the coolability at the downsteam region was greatly enhanced compared with those of non-blockage tests. This tendency can be explained with an enhancement of the convective heat transfer, intensification of the turbulence intensities, and the effect of droplets.

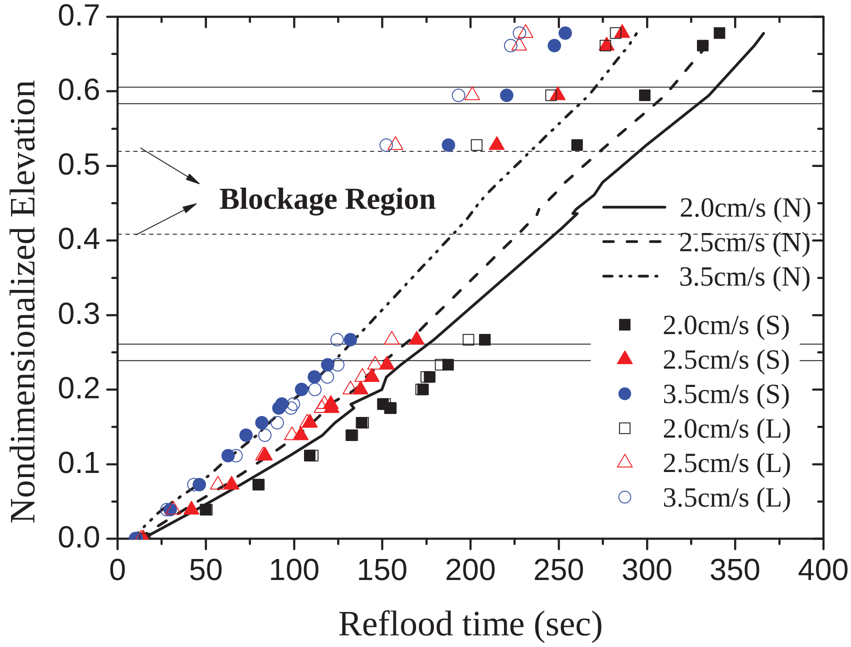

Figure 5. Comparison of Quenching Time along the Elevation.
(N: non-blockage, S: short blockage, L: long blockage)

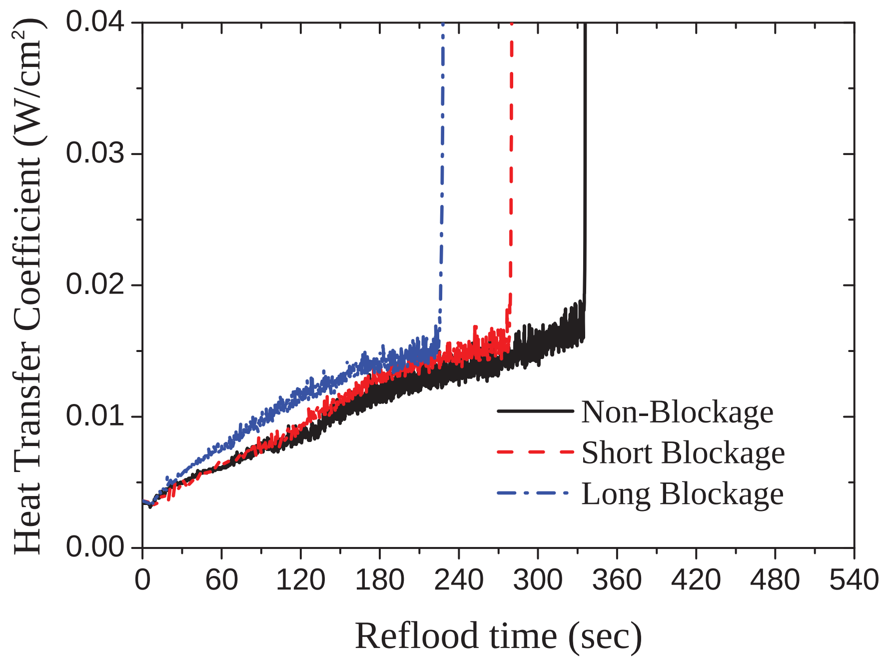

Figure 6. Comparison of Heat Transfer Coefficients at the Downstream Region for 2.5cm/s.

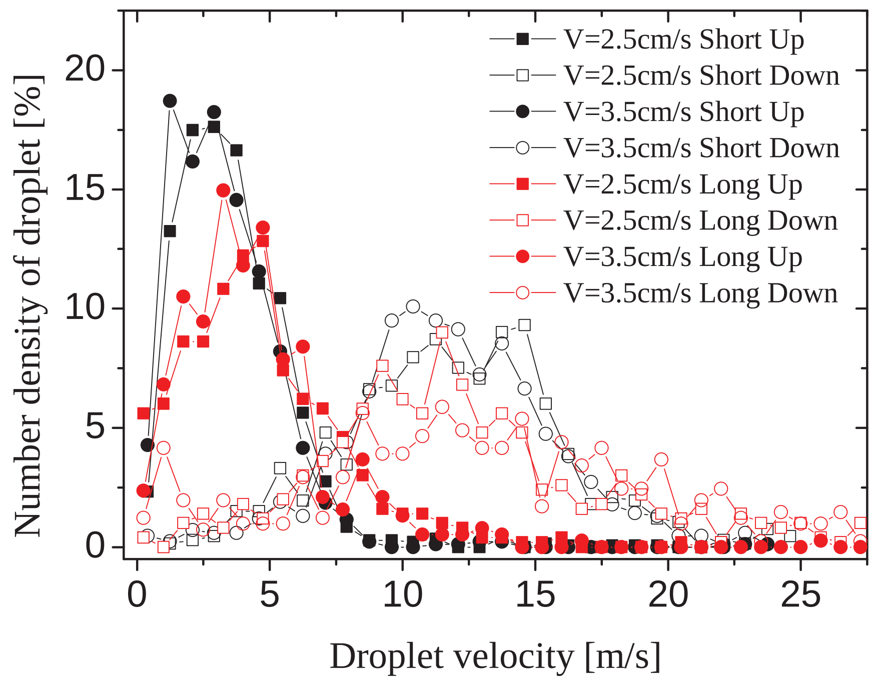

Figure 7. Comparison of Droplet Velocities near the Blockage Region.

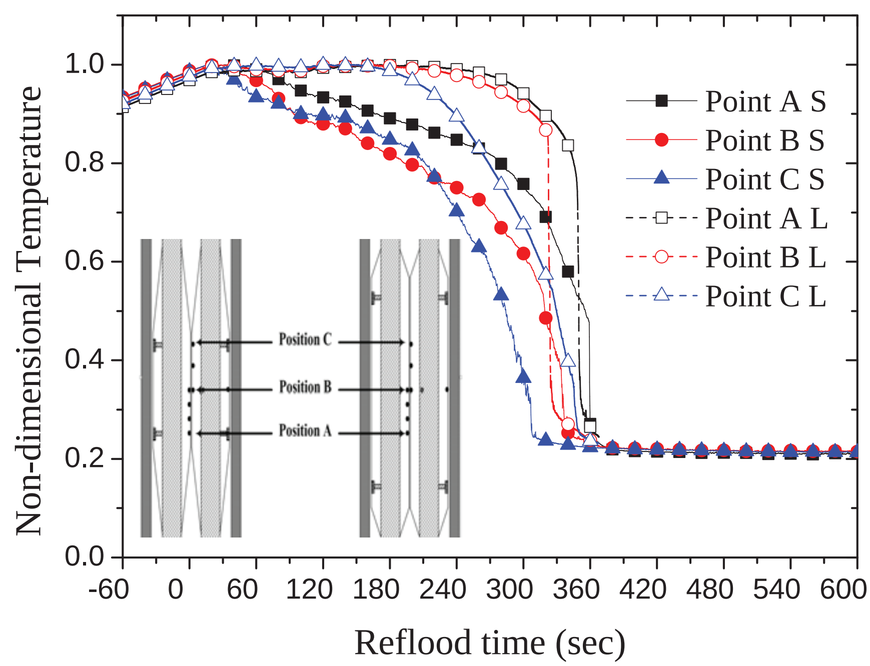

Figure 8. Temperature Profiles along the Blockage Internal Region.

(a) **(b)**

Figure 9. Examples of Droplet images near the Blockage Region for 90% short blockage. (a: upstream, b: downstream)

Table II. Averaged Droplet Velocity and Size near the Blockage Region

Vr (cm/s)	Test Section	Upstream Velocity (m/s)	Upstream Sauter mean (μm)	Downstream Velocity (m/s)	Downstream Sauter mean (μm)
2.5	Short	3.6	1007	12.0	427
	Long	3.2	734	8.3	631
3.5	Short	3.3	1121	11.7	637
	Long	3.1	756	8.9	727

The droplet size and velocity were measured in the upstream and downstream regions of the blockage. Unfortunately, the measurement of the droplets or liquid slugs based on image processing was possible only in the very early stage of the reflood phase. The correlations between the droplet velocity and number density are shown in Fig. 7, and the average values of the droplet velocity and Sauter mean diameter are summarized in Table II.

As shown in Fig. 8, the droplet velocities are considerably increased in the downstream region. In the single-phase steam flow tests [10], steam velocities were increased in proportion to the reduced flow area in the blockage region. This is a favorable effect in terms of the coolability. The increased steam velocity becomes more turbulent, and accelerated the liquid droplet having a high inertia in the blockage region. When the blockage length is short, the droplet velocity is getting higher, since the pressure loss of the steam flow is relatively small compared with the long blockage. Therefore, the liquid droplet velocity between the short and long blockage is different owing to the steam velocity augmentation.

The maximum blockage length also significantly affects the coolability in the blockage region. To understand the quenching phenomena in the internal region of the blockage, the transient temperature profiles on the outer surface of the blockage simulator were measured along the blockage elevation, as shown in Fig. 8. The main finding is the rewetting phenomena in the blockage internal region. As shown in Fig. 8, it is observed that the cooling occurred earlier in the downstream region. It is anticipated that the flow separation occurs at the edge of the tapered length, and thus the probability of impacting of a liquid droplet on the surface in the downstream region is increased owing to the secondary stream flow. In the case of the long maximum blockage length, the diffuser length is short, and thus the secondary steam flow becomes strong compared with the short blockage.

When the liquid droplets generated from the quench front are accelerated by the steam flow, they can collide with the surface of the blockage simulator. However, according to the droplet measurement in the upstream region, most of the droplets colliding with the rod/blockage surface bounced back and slid into the blockage region owing to the high surface temperatures. In the internal region of the blockage region, the liquid droplets may collide strongly and frequently with the surfaces of the blockage owing to the reduced flow passage with a high blockage ratio, which results in droplet breakup due to hydro-dynamic instability. In the case of the short blockage, the droplets were fragmented into smaller ones, as shown in Table II and Fig. 9. The smaller shattered droplets evaporated easily providing an additional steam source, and also increased the convective heat transfer coefficient. In the case of the long blockage, the temperature in the center region of the blockage was maintained constantly for a while and drastically decreased, as shown in Fig. 8. The sudden changes of the temperature are closely related to the rewetting phenomena of liquid droplets in the internal region of the blockage. If the rewetting occurs in the blockage region, the liquid droplets can be entrained from the liquid film on the wall of blockage passing through the long blockage region. On the contrary, in the case of the short blockage, the liquid droplets fragmented into small ones could more easily follow the streamlines in the flow generated by the blockage geometry. This scenario can be supported by a comparison of the droplet break-up ratio with the COBRA-TF model [13], as shown in Fig. 10. The COBRA-TF droplet break up model is expressed as a function of the impact Weber number as follows [13]:

$$\frac{D_o}{D_i} = exp\left[-\frac{(We_D-30)}{124}\right], \tag{1}$$

where, D_0 , D_i , and We_d are the initial droplet size, breakup droplet size, and Weber number, respectively. This model states that the liquid droplets can more easily beak-up when the projected area of the portion of the blockage appearing at in a flat plate and velocity component normal to the plate are increase since the droplet spreads out into liquid thin sheet. As shown in Fig. 10, the results for the short blockage tests are more close the COBRA-TF Model than those for the long blockage tests, and thus it can be explained as there being no significant differences in the droplet size between the upstream and downstream regions in the case of a long blockage (Table II) and the small droplets can more easily follow the streamlines in the flow generated by the blockage geometry, unlike in the case of the short blockage tests.

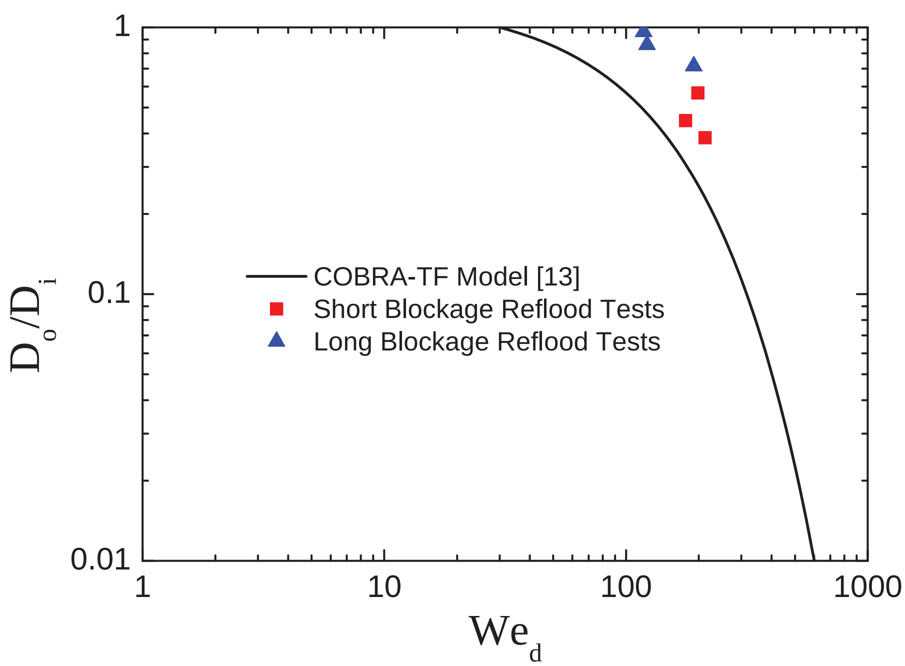

Figure 10. Comparison of We Number of reflood tests

4. CONCLUSIONS

In this study, several reflood tests were carried out to understand the transient heat transfer behavior using a 2x2 rod bundle test facility. The non-blockage, short and long blockage simulators were tested for various refold rates to investigate the effect of the blockage length on the coolability. All transient temperature profiles of the heater rods and blockage simulators were directly measured along the elevation, and the heat transfer coefficients and quench time were calculated to evaluate the overall coolability. In addition, the velocities and sizes of the droplets near the blockage region were measured to scrutinize the droplet effect on the quench phenomena.

The results show that the coolability in the blockage region depends highly on the combined effect of the fluid flow and droplet behavior. Regardless of the blockage length, the coolability in the downstream of the blockage region is significantly enhanced since the turbulence intensities are increased owing to the sudden change of the flow passage area and the rewetting of the droplet in the downstream region. The differences of coolability between the short and long blockage were analyzed from the measured temperature profiles in the blockage region and the results of the droplet measurement. In the case of the long blockage, quenching at the downstream region always occurred earlier regardless of the reflood rates owing to the significant intensification of the turbulence flow and rewetting of the droplets. As a conclusion, the convective heat transfer enhancement owing to the turbulent flow and the cooling effect by liquid droplets are the main factors for the coolability improvement in the downstream of the blockage region. The main findings that have been obtained in this study are only true when the blockage configuration does not considering the effect of the coolant by-pass, which may induce a different flow distribution and heat transfer behavior. Therefore, additional tests are required to verify the coolability in a large test facility, i.e., a 5x5 rod bundle test facility, as future work.

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