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Research Article

Effect of Flow Blockage on the Coolability during Reflood in a 2 × 2 Rod Bundle

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During the reflood phase of a large-break loss-of-coolant accident (LBLOCA) in a pressurized-water reactor (PWR), the fuel rods can be ballooned or rearranged owing to an increase in the temperature and internal pressure of the fuel rods. In this study, an experimental study was performed to understand the thermal behavior and effect of the ballooned region on the coolability using a 2 × 2 rod bundle test facility. The electrically heated rod bundle was used and the ballooning shape of the rods was simulated by superimposing hollow sleeves, which have a 90% blockage ratio. Forced reflood tests were performed to examine the transient two-phase heat transfer behavior for different reflood rates and rod powers. The droplet behaviors were also investigated by measuring the velocity and size of droplets near the blockage region. The results showed that the heat transfer was enhanced in the downstream of the blockage region, owing to the reduced flow area of the subchannel, intensification of turbulence, and deposition of the droplet.

1. Introduction

The effect of the ballooned fuel rods on the coolability has been an important issue since the 1980s. The ballooned fuel rods cause a flow blockage of subchannel and flow redistribution near the blockage region. As a result, the transient heat transfer behavior of the ballooned fuel rods is entirely different from the normal ones. Therefore, many experimental studies have been conducted over the past several decades. 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 safety code [9]. The previous studies conducted forced or gravity reflood tests for various test conditions to examine the thermal behavior of the blockage region and to determine an upper limit of the blockage 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 to examine the effect of the blockage characteristics on the coolability in a modeled 2×2 subchannel. The second experiment, after the first group test, will be performed in a more elaborate 5 × 5 facility considering the blockage and fuel relocation.

As mentioned earlier, more specifically, the main objective of the first group tests is to identify the effect of the blockage ratio and length on the heat transfer behavior. Therefore, four different types of blockage simulators (blockage ratio: 62% or 90%, maximum blockage length: 80 mm or 160 mm) are designed to simulate the ballooned shape of the fuel rods. Single-phase steam flow and forced reflood tests were

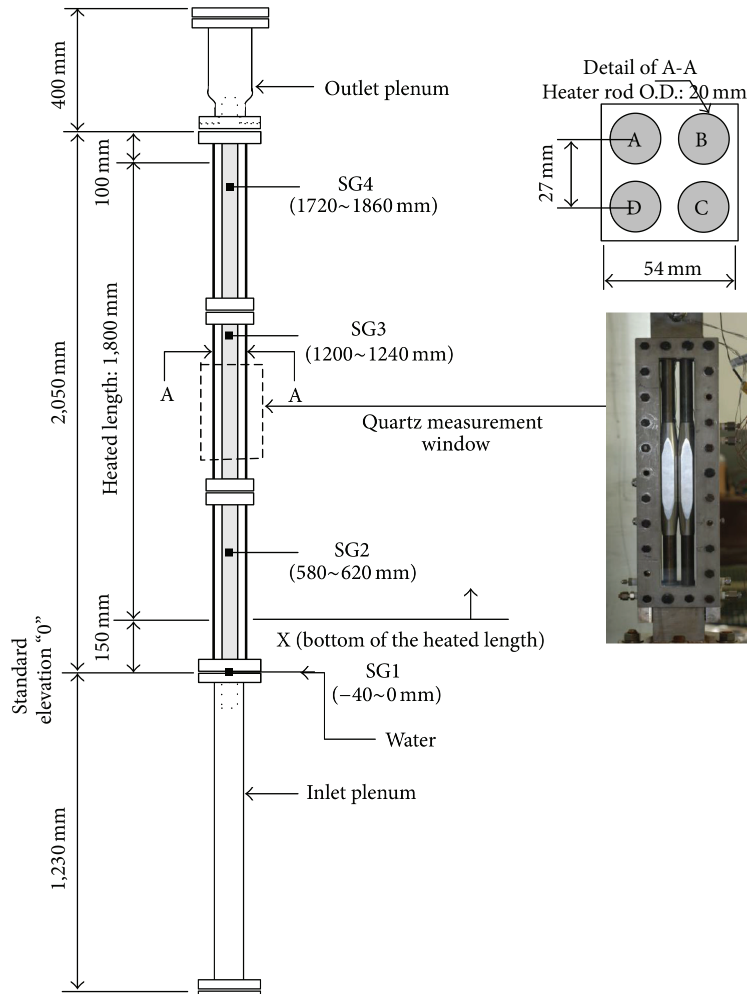


Figure 1: Schematic diagram of the test section in the 2 × 2 test facility.

performed and the results were compared with the reference test (nonblockage) results. However, in the present study, forced reflood test results for the blockage simulator with a 90% blockage ratio and short maximum blockage length will be presented. The remaining tests for other blockage simulators will be conducted later. A single-phase steam flow test, which was intended to investigate the influence of the blockage on the convective heat transfer, was already conducted by the authors of [10]. The reflood rate was chosen as the main parameter for the forced reflood tests since it can significantly affect the coolability, especially for low reflood rates. Therefore, the forced reflood tests were performed at different reflood rates, between 1.0 and 3.5 cm/s. In addition, the tests were also carried out for two different rod powers, 1.0 kW/m and 1.5 kW/m. The axial temperature profiles of the heater rods were measured, and the local heat transfer coefficients were calculated. Moreover, the velocity and size of the droplets at the upstream and downstream regions of the blockage simulator were measured to investigate quantitatively the droplet behavior which plays a significant role in the coolability. The results were carefully discussed based on the temperature profiles of the heater rods and the droplet behavior.

2. Experimental Test Facility

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

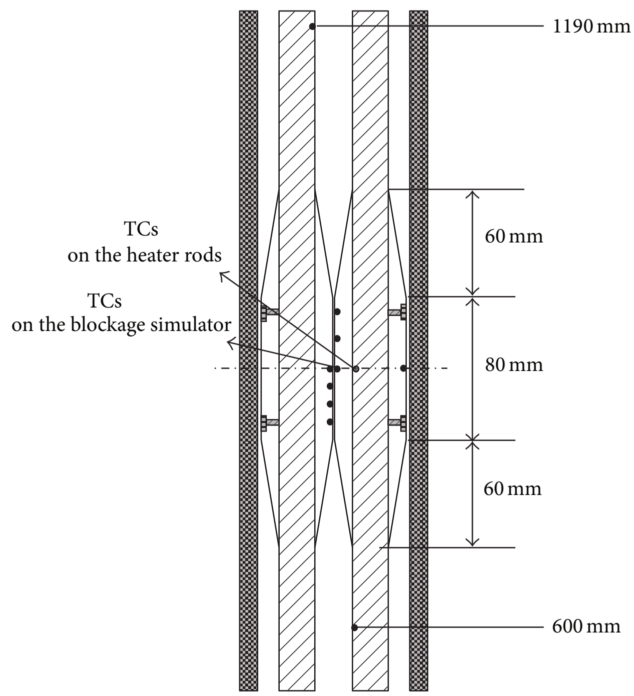


FIGURE 2: Schematic diagram and instrumentation of the 90% blockage simulator.

The ballooning of the fuel rods was simulated by superimposing the blockage simulators onto the heater rods. The blockage simulators were made of Inconel 600, which is the same material as the heater rod cladding. A schematic diagram is shown in Figure 2. The tapered hollow sleeves were used to simulate the shape of the ballooning. The total length of the blockage simulator is 200 mm, among which 80 mm is the maximum blockage length and 60 mm is the inlet/outlet taper lengths. The maximum blockage ratio in the center region is 90%. The inner diameter of the blockage simulator is the same as the outer diameter of the heater rod. The blockage simulators were fixed on the heater rods using grub screws. It should be noted that the blockage simulators have no bypass flow region, owing to the inherent geometrical restriction of the 2 × 2 test facility. The blockage simulators were placed between 735 mm and 935 mm from the bottom of the heated length. In this region, it is thought that the effect of the second and third spacer grids (SG2 and SG3) is diminished.

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. Previous experimental programs [7] 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 Figures 2 and 4. The axial locations and radial locations of all TCs are shown in Figures 3 and 4. 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 span, ±1.1°C, and 0.065%, respectively.

TABLE 1: Main test conditions of the non-blockage tests.

V_r (cm/s)/Test conditions	V_r (cm/s)	P_{sys} (kPa)	ΔT_{sub} (°C)	Q (kW/m)
1.0	1.03	101.5	61.0	1.00
	1.03	101.5	47.8	1.50
1.5	1.55	101.4	50.3	1.00
	1.53	101.4	49.2	1.49
2.0	2.06	101.4	48.4	0.99
	2.03	101.4	46.1	1.50
2.5	2.55	101.4	47.5	1.01
	2.49	101.5	47.4	1.51
3.5	3.43	101.4	46.7	0.97
	3.47	101.5	49.8	1.50

3. Test Results

For a parametric study, forced reflood tests were performed for various reflood velocities between 1.0 and 3.5 cm/s. In addition, two different rod powers were also considered: 1.0 kW/m and 1.5 kW/m. The main test parameters for the nonblockage and blockage tests are summarized in Tables 1 and 2, respectively. The temperature profiles of the heater rods and blockage simulator were measured simultaneously along the elevation, and the droplet measurements were also performed for three blockage tests as shown in Table 3.

The transient temperature profiles for different reflood rates and rod powers are compared with the nonblockage test results in Figures 5 and 6. The hollow and solid symbols represent the temperatures of the nonblocked and blocked test results, respectively. Figure 5 shows the temperature

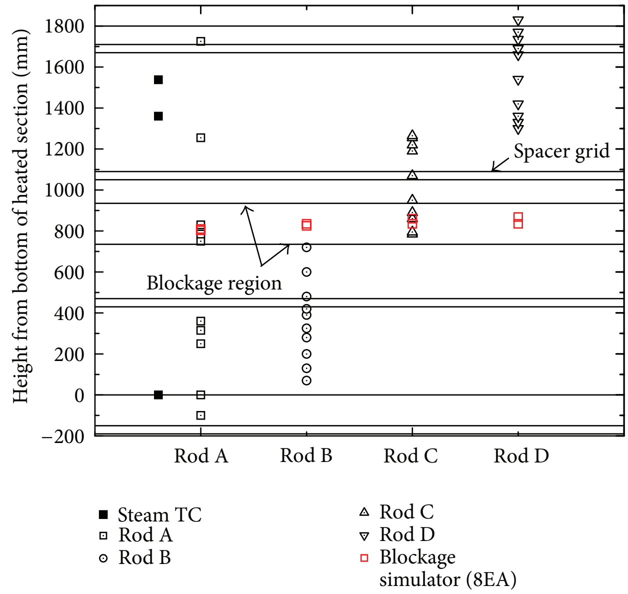


Figure 3: Axial TC locations of the test section.

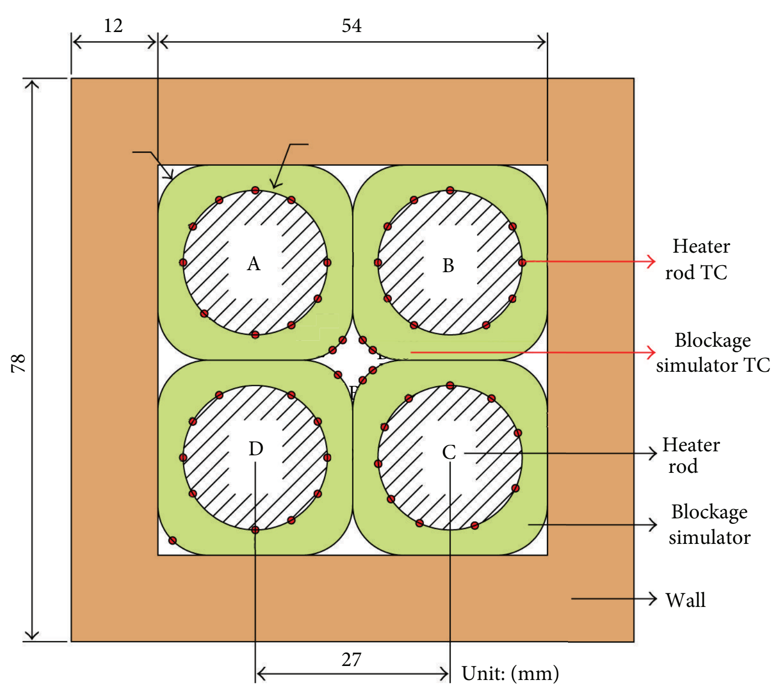


Figure 4: Radial TC locations of the test section.

profiles at the upstream region. When the rod power is low, there are almost no differences for all reflood rates. This may be attributed to the small amount of steam and droplets generated in the low rod power. However, when the rod power is high and the reflood rates are lower than 2.5 cm/s, the coolability of the blockage test is reduced in proportion to the reflood rate. Thus, the coolability is important at the low reflood rate, and this tendency is consistent with the previous experiments [8]. To the contrary, the coolability of the blockage tests is significantly enhanced in the downstream region, as shown in Figure 6. The tendency of the temperature profiles at the upstream and downstream regions can be explained with the results of the droplet measurement. For three reflood rates ($V_r = 1.0$, 2.5, and 3.5 cm/s), the droplet size and velocity were measured at the upstream and downstream regions in the early stage of the reflood phase. The correlations between the droplet velocity and number of droplets are shown in Figure 7. In addition, Table 3 shows the averaged values of the velocity and Sauter mean diameter of the droplets. Compared to the upstream, the downstream shows a narrow distribution of the droplet size, though not shown here, but the droplet velocities are in a wide range, as

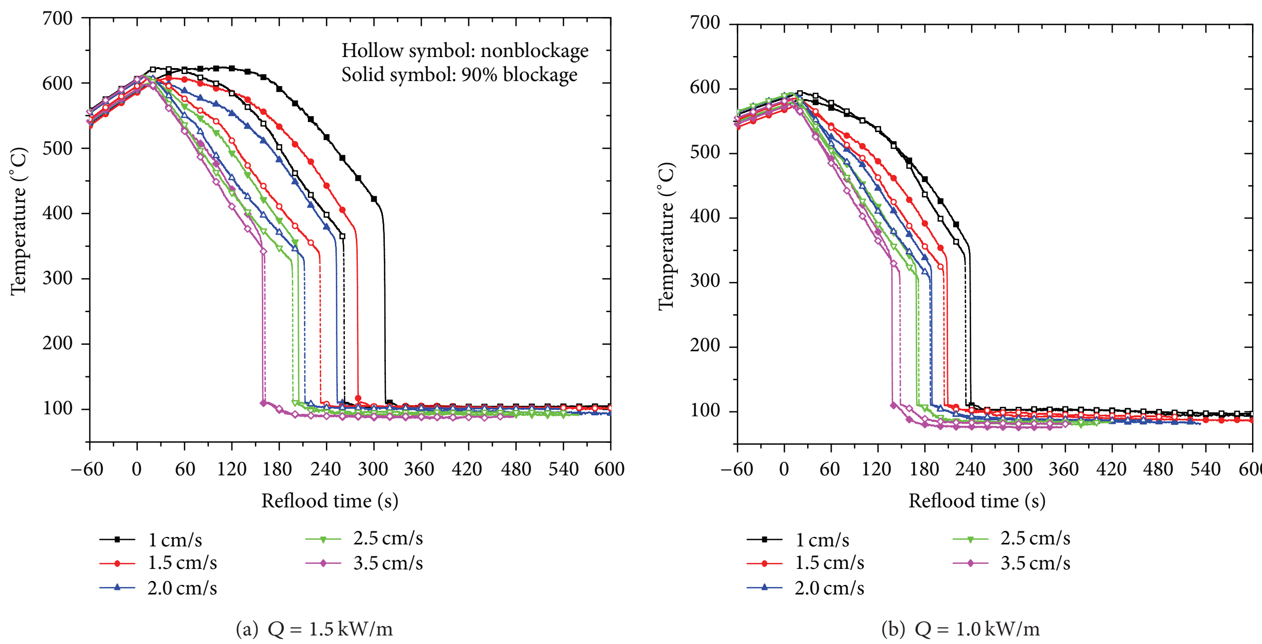


FIGURE 5: Comparison of the temperature profiles at the upstream region (600 mm).

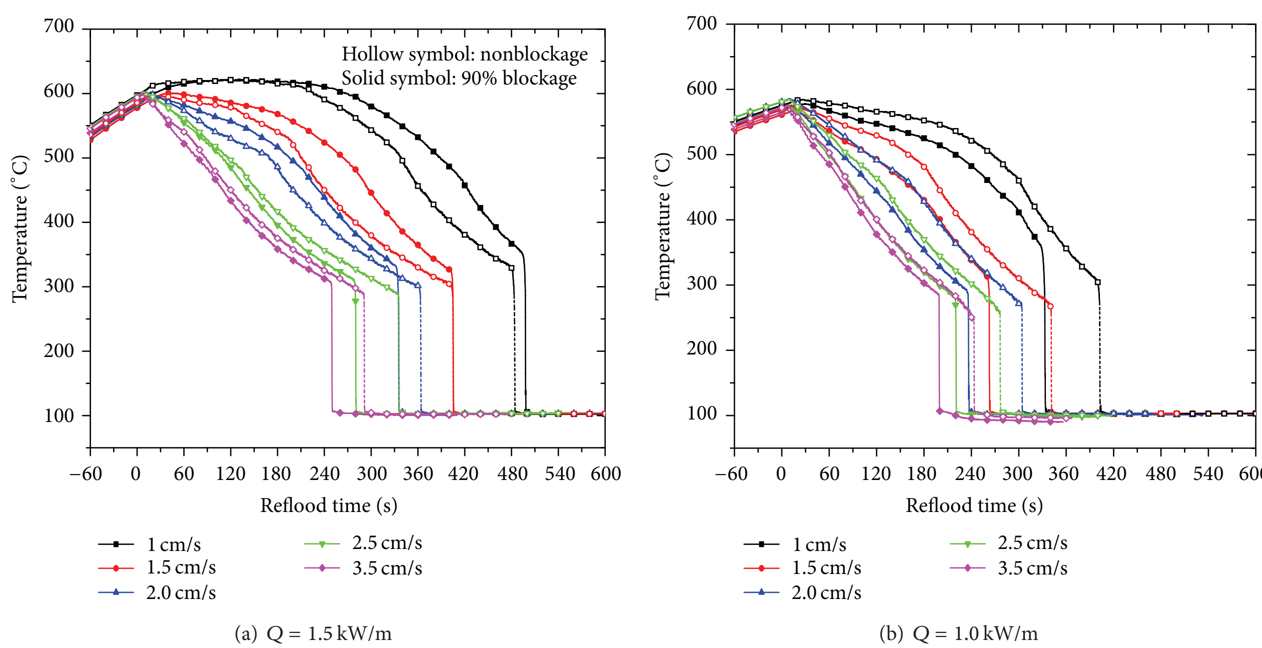


FIGURE 6: Comparison of the temperature profiles at the downstream region (1190 mm).

shown in Figure 7. This means that the turbulence intensities of the steam flow are highly increased in the downstream. It was also noted that the droplet velocity at the downstream is faster than that of the upstream region, as shown in Table 3, since the inertia of the droplet is high enough that the droplets do not follow the reduced steam velocity faithfully in the downstream region. Figure 8 shows droplet images taken at nearly the same time in the early reflood phase when the reflood rate and rod power are 2.5 cm/s and 1.5 kW/m. In the ballooned region, the steam flow is accelerated and becomes more turbulent, which results in droplet breakup due to hydrodynamic instability. We can see in Figure 7 that the droplet size is smaller in the downstream region. The secondary steam flows in the downstream cause the liquid droplets to collide strongly and frequently with the surfaces of the blockage or heater rods. As a result, the convective heat transfer and rewetting of the droplets on the heat rods in the downstream become more enhanced than the droplet impact

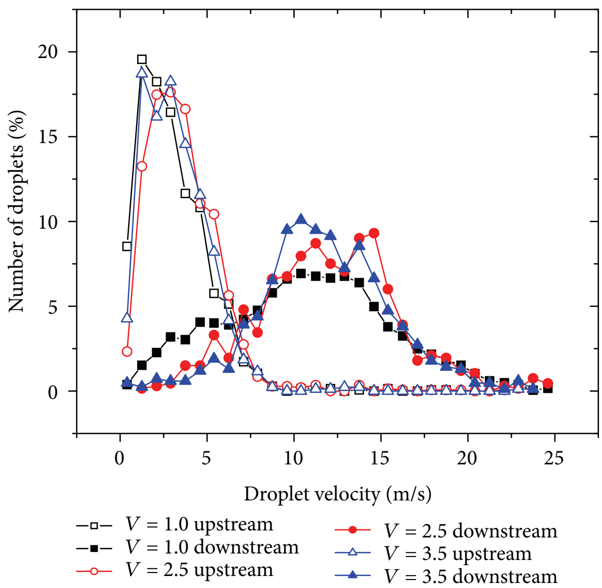


Figure 7: Velocity distributions of droplets for various reflood rates when Q = 1.5 kW/m.

Table 2: Main test conditions of the blockage tests.

V_r (cm/s)/Test conditions	V_r (cm/s)	P_{sys} (kPa)	ΔT_{sub} (°C)	Q (kW/m)
1.0	1.03	101.5	57.0	1.00
	1.04	101.3	52.0	1.50
1.5	1.55	101.3	52.1	1.01
	1.53	101.4	52.7	1.50
2.0	2.06	101.4	51.0	1.01
	2.04	101.3	53.1	1.51
2.5	2.56	101.4	50.2	1.00
	2.56	101.3	50.6	1.50
3.5	3.43	101.4	54.3	1.01
	3.43	101.3	51.0	1.51

Table 3: Averages of the droplet velocity and size near the blockage region.

V_r (cm/s)	Upstream (720 mm)		Downstream (950 mm)	
	Velocity (m/s)	Sauter mean (μm)	Velocity (m/s)	Sauter mean (μm)
1.0	3.0	1204.5	10.7	538.4
2.5	3.6	1006.9	12.0	427.4
3.5	3.3	1120.8	11.7	636.8

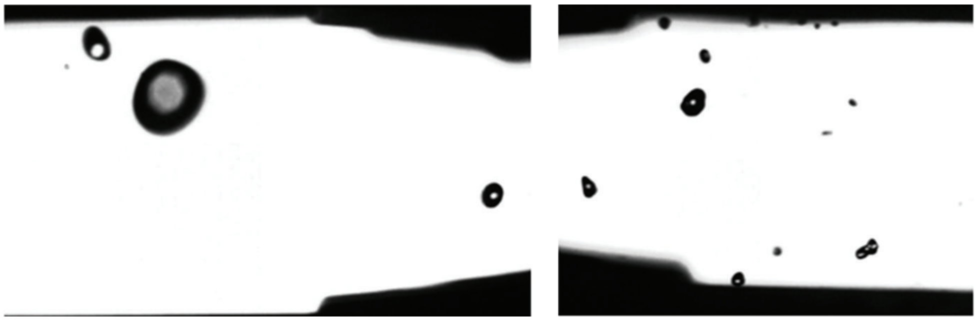
heat transfer in the upstream. This means that the droplets behind the blockage simulator play a significant role in the coolability enhancement.

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 elevation. The main finding is the rewetting phenomena in the internal region for various reflood rates. As shown in Figure 9, it is obvious that the cooling occurred earlier in the downstream region for all reflood rates. However, it is interesting to note that the temperature profiles of the center region show large fluctuations when the reflood rates are higher than 2.5 cm/s. When increasing the reflood rates, the droplet velocity is more accelerated and the size of the droplets at the downstream region becomes small as shown in Table 3. This means that most of the droplets fragment into smaller ones by passing through the blockage region. Therefore, the drastically decreased temperature at 830 mm may be explained by the droplet breakup and rewetting phenomena in the blockage region.

Figure 10 shows the heat transfer coefficients calculated at the outer surface of the heater rods. The heat transfer coefficients in the downstream are always higher than those in the upstream. For each experimental case, the quenching time, at which $\partial T^2/\partial t^2$ is the most negative value, is given in Table 4. The quenching time in the downstream is generally earlier than that in the upstream. It should be noted that the subchannel size of the present facility is twice as large as that of a typical PWR, and thus the applied power may not be sufficient for a large quantity of droplets. The number of droplets is not enormous, and thus in the case of 1.0 kW/m a strong turbulent stream flow would be a dominant cooling factor because the blockage ratio is 90%. The number of droplets increases with the power. Therefore, for 1.5 kW/m, although the number of droplets may not be enormous, most droplets affect the upstream cooling. Steam flow speed tends to increase with the reflood rate. For the 1.5 kW/m power and low reflood rate, the droplets evaporate, if any, while they pass through the blockage. As a result, not many droplets could appear in the downstream. However, as the reflood rate increases further, a large quantity of droplets is generated and the steam velocity increases, thus many droplets can appear in the downstream. In this case, the downstream is cooled, not only by the turbulent flow but also by the droplets, leading to the early quenching of the downstream.

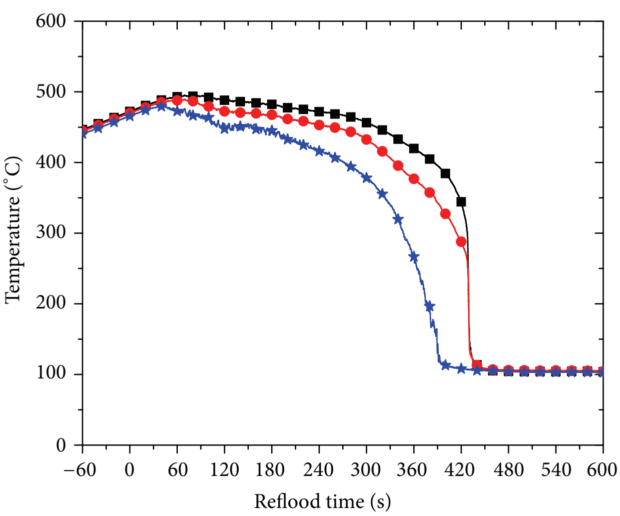
4. Conclusions

In this study, forced reflood tests were carried out for different reflood rates and rod power to understand the heat transfer behavior. The nonblockage and blockage tests were performed to investigate the effect of the ballooned fuel rod on the coolability in a 2 × 2 rod bundle test facility. The ballooned shape of the fuel rods was simulated using the blockage simulator with a 90% blockage ratio. 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 to evaluate the overall coolability of the blockage region. In addition, the velocities and sizes of the droplets near the blockage region were also measured to scrutinize the droplet effect on the quench phenomena. The results show that the coolability in the blockage region highly depends on the combined

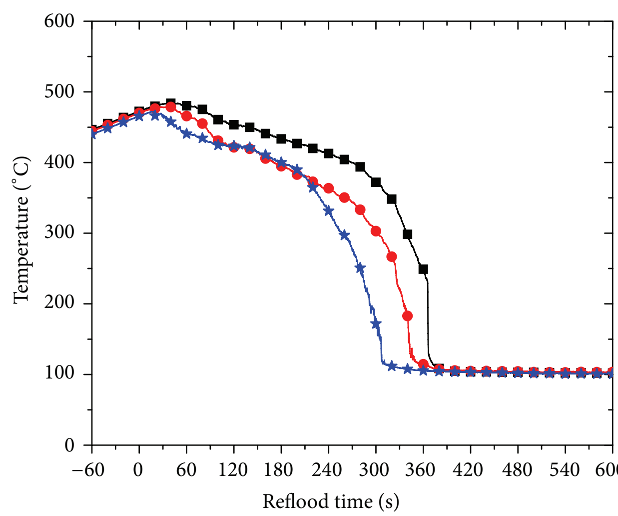


(a) Upstream region (b) Downstream region

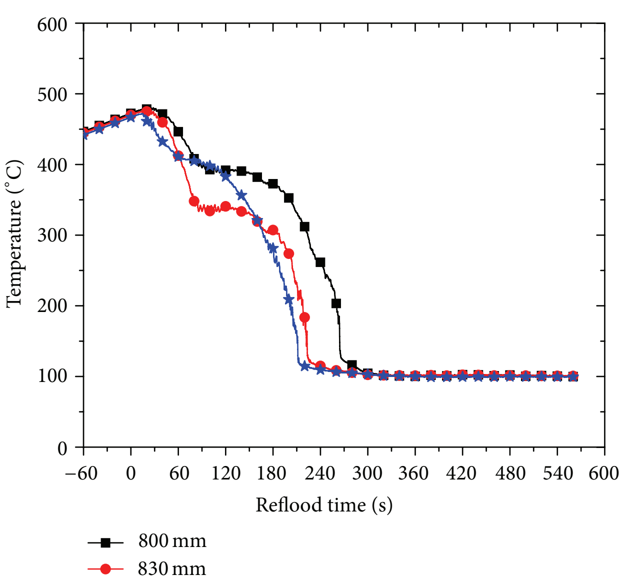
Figure 8: Droplet images near the blockage region.



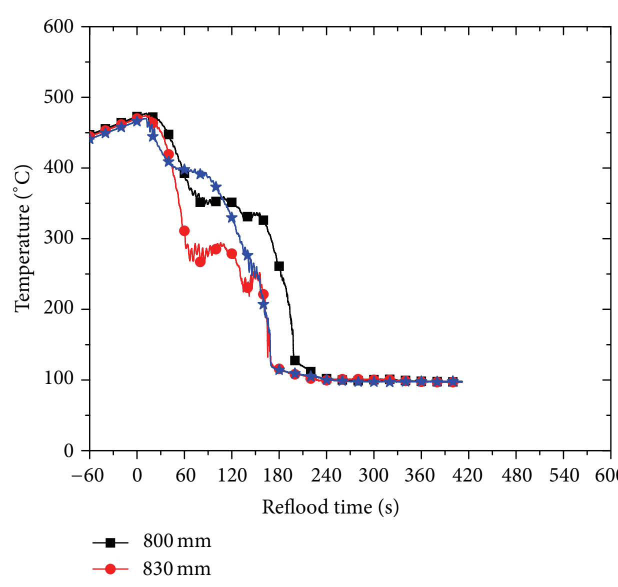
(a) $V_r = 1.5$ cm/s



(b) $V_r = 2.0$ cm/s

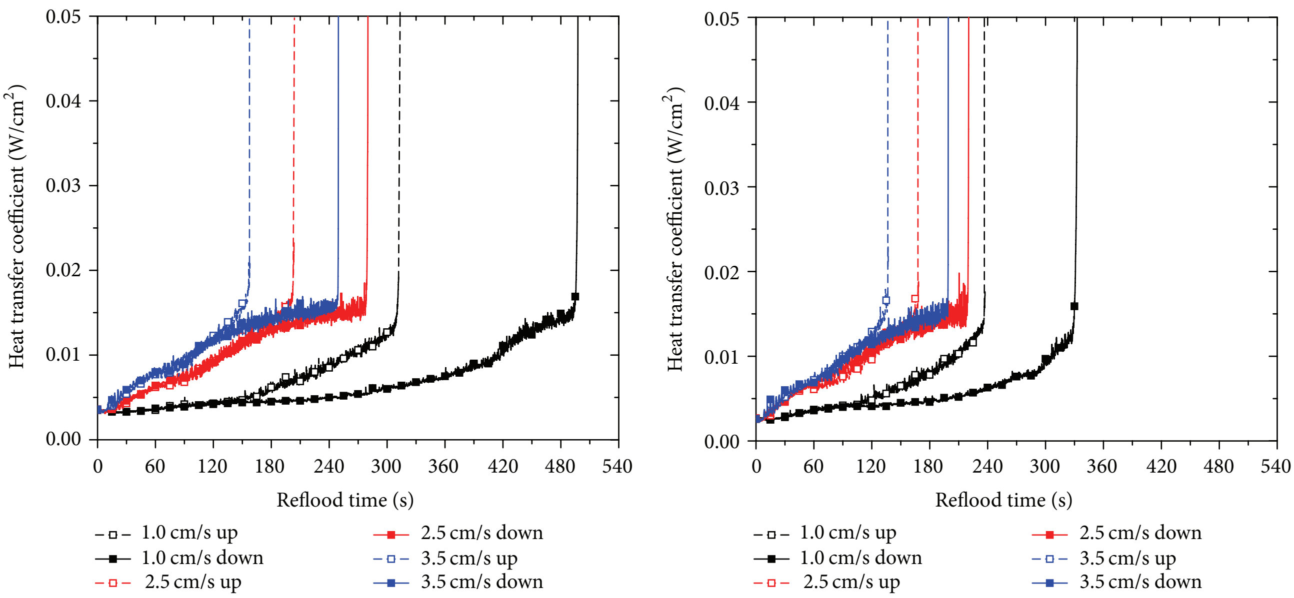


(c) $V_r = 2.5$ cm/s



(d) $V_r = 3.5$ cm/s

Figure 9: Temperature profiles in the blockage internal region for $Q = 1.5$ kW/m.



(a) Q = 1.5 kW/m

(b) Q = 1.0 kW/m

FIGURE 10: Comparison of the heat transfer coefficients distributions.

TABLE 4: Quench time at the upstream and downstream region of blockage.

V_r (cm/s)	Test	Upstream (600 mm)		Downstream (1190 mm)	
		1.0 kW/m	1.5 kW/m	1.0 kW/m	1.5 kW/m
1.0	Non-blockage	231.6	261.5	401.9	483.4
	90% blockage	237.7	313.4	332.7	497.0
1.5	Non-blockage	203.9	231.4	340.5	404.4
	90% blockage	208.3	278.7	262.2	404.6
2.0	Non-blockage	186.3	211.6	303.5	363.1
	90% blockage	188.3	252.2	235.7	334.7
2.5	Non-blockage	171.5	196.5	276.2	335.4
	90% blockage	168.6	203.7	219.9	279.5
3.5	Non-blockage	147.7	161.3	243.0	290.7
	90% blockage	137.5	158.3	198.8	249.2

effect of the fluid flow distribution and droplet behavior. 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 on the heater rod in the downstream region. In the internal region of the blockage, the droplets were accelerated owing to the reduction of the flow area and fragmented into smaller ones while passing through the blockage region. 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 valid for the blockage configurations without a coolant bypass. For this reason, additional tests are scheduled to be performed in a 5 × 5 rod bundle test facility with a coolant bypass.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] P. Ihle and K. Rust, "FEBA-flooding experiments with blocked arrays-influence of blockage shape," in *Proceedings of the ANS-Transactions European Nuclear Conference*, vol. 31, p. 398, 400, May 1979.

[2] P. Ihle and K. Rust, "SEFLEX-fuel rod simulator effects in flooding experiments. Part 1: evaluation report," KfK 4024, 1986.

[3] K. G. Pearson, C. A. Cooper, D. Jowitt, and J. H. Kinneir, "Reflooding experiments on a 49-rod cluster containing a long 90% blockage," AEEW ER 1591, 1983.

[4] K. G. Pearson, C. A. Cooper, and D. Jowitt, "The THETIS 80% blocked cluster experiment. Part 4: gravity reflood experiments," AEEW ER 1766, 1984.

[5] M. K. Denham, D. Jowitt, and K. G. Pearson, "ACHILLES unballooned cluster experiments. Part 1: description of the ACHILLES Rig, test section and experimental procedures," AEEW R 2336, 1989.

[6] S. A. Fairbairn and B. D. G. Piggott, "Flow and heat transfer in PWR rod bundles in the presence of flow blockage due to clad ballooning experimental data," Report. Part 2 CEGB-TPRD/B/0511/N84, 1984.

[7] L. E. Hochreiter, "FLECHT-SEASET Program," Final Report NUREG/CR-4167, EPRI NP-4112, WCAP-10926, 1985.

[8] C. Grandjean, "Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions: main findings from a review of past experimental programmes," *Nuclear Engineering and Design*, vol. 237, no. 15–17, pp. 1872–1886, 2007.

[9] Y. Sudo and M. Osakabe, "Effects of partial blockage on core heat transfer in forced-feed reflood tests," *Journal of Nuclear Science and Technology*, vol. 20, no. 4, pp. 322–332, 1983.

[10] K. Kim, B. J. Kim, Y. J. Youn, H. S. Choi, and S. K. Moon, "Convective heat transfer of a blocked region in ballooned 2×2 rod bundle under a single-phase flow," in *Proceedings of the 6th Korea-China Workshop on Nuclear Reactor Thermal-Hydraulics (WORTH-6 '13)*, Busan, Republic of Korea, 2013.

[11] *VisiSize Software Operation Manual for VisiSize 5*, Oxford Lasers Imaging Division, 2010.

[12] D. R. Todd, *Characterization of the VisiSizer Particle/Droplet Sizing System [M.S. thesis]*, State University, 1999.