MARS CODE EVALUATION OF REFLOOD PHENOMENA IN A PARTIALLY-DEFORMED 5X5 ROD BUNDLE

B.J. Kim*, J. Kim, K. Kim, S.K. Moon, C.-H. Song
Korea Atomic Energy Research Institute
Corresponding Address
byoungjae@kaeri.re.kr

ABSTRACT

During a LOCA condition, the cladding temperatures can increase to the extent that the cladding is permanently ballooned. This geometry deformation reduces the flow area in the core, and thus the coolability between coolant and fuel rods deteriorates. Moreover, the temperatures of the fuel rods inside the cladding also may increase such that the rupture of the fuel rods takes place. As a result, the core power (heat flux) increases in the location where the ruptured fuel rods are accumulated. This phenomena is referred to as fuel rod relocation. A literature survey reveals that most of previous studies investigated the effect of flow blockage on reflood phenomena, but without consideration of fuel relocation. Recently, KAERI performed a series of forced reflood tests considering the local power increase by fuel relocation. This paper reports some experimental and computer-code evaluation results for forced reflood tests.

KEYWORDS
Ballooned Fuel, Fuel Relocation, Reflood, MARS Code

1. INTRODUCTION

In the 1980s, various experimental programs were carried out for the coolability of an assembly containing a partial blockage in a group of ballooned fuel rods under accidental LOCA conditions [1-6]. A review on these programs is well documented in [7]. In addition, an important objective of the FLECHT-SEASET program was to develop thermal-hydraulic models that could be used to evaluate the effect of a blockage [6]. By the help of the FLECHT-SEASET program, various two-phase flow models were developed and incorporated into COBRA code. However, most of previous works focused the effect of flow area reduction, disregarding the effect of fuel relocation.

Recently, an experimental program was started in KAERI (Korea Atomic Energy Research Institute) to study the coolability of the partially blocked rod bundle and to develop corresponding two-phase flow models [8-10]. One of important merits in KAERI research activities is the consideration of local power increase by fuel relocation. During a LOCA, the temperatures of the fuel inside the cladding may increase such that the rupture of the fuel rods takes place. As a result, the core power increases in the ballooned region where the fuel fragment slumping from the upper region are accumulated. This phenomena is referred to as the effect of fuel relocation. To our knowledge, only the CODEX-COOL experimentally investigated the effect of fuel relocation [11].

The purpose of this study is to investigate thermal-hydraulic behaviors in the partially blocked 5x5 rod bundle. A series of forced reflood tests were performed with/without consideration of local power increase by fuel relocation. This paper reports computer-code evaluation results. The MARS code was used for this purpose. The reason is that the MARS code includes the COBRA-TF code module.

2. PARTIALLY-BLOCKED 5X5 ROD BUNDLE

2.1. Experimental Geometry and Conditions

Figure 1 depicts a partially blocked 5x5 rod bundle assembly. The pitch of the bundle is 12.85 mm and the total heating length is 3.81 m. The base diameter of the rods is 9.5 mm. For sixteen type-A heater rods, the diameters do not vary along the heating elevation. However, nine type-B heater rods are locally ballooned in the region of vertical elevation x=1.704~2.054 m from the bottom of the heated part. The ballooning of each rod is realized by inserting the rod into a sleeve. The diameter of the deformed rods increases up to 10.5 mm. This geometry configuration yields a flow blockage ratio of 90% in the region of x=1.801~2.004 m. The sheath of the rods and sleeves are made of Inconel 600. Figure 2 shows the axial power profiles of heater rods. In the graph, x is the vertical distance from the bottom of the heated part, and y is the normalized power with regard to the averaged value. One profile is for the typical power shape (blue line). Each heater rod has the same power, that is, radially uniform power. The other profile is the modified power shape considering the effect of fuel relocation. As seen, the local power is intentionally increased in the region where blockages are placed. To match the total power to the typical one, the local power is intentionally decreased to zero for x=0~0.508 m.

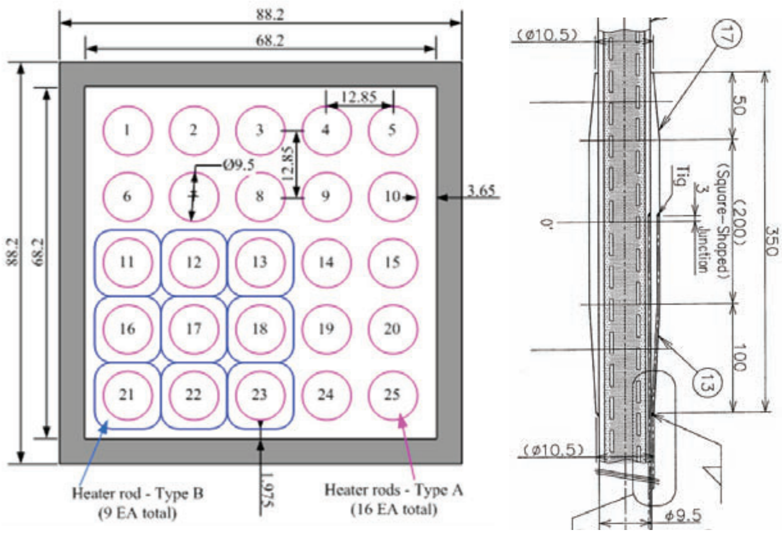

Figure 1. Left: Partially blocked rod bundle, Right: Geometry of the ballooned rod.

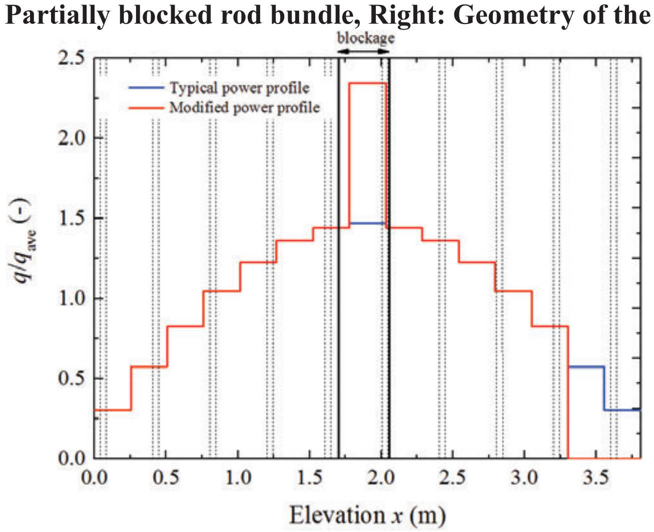

Figure 2. Local power profiles along the elevation

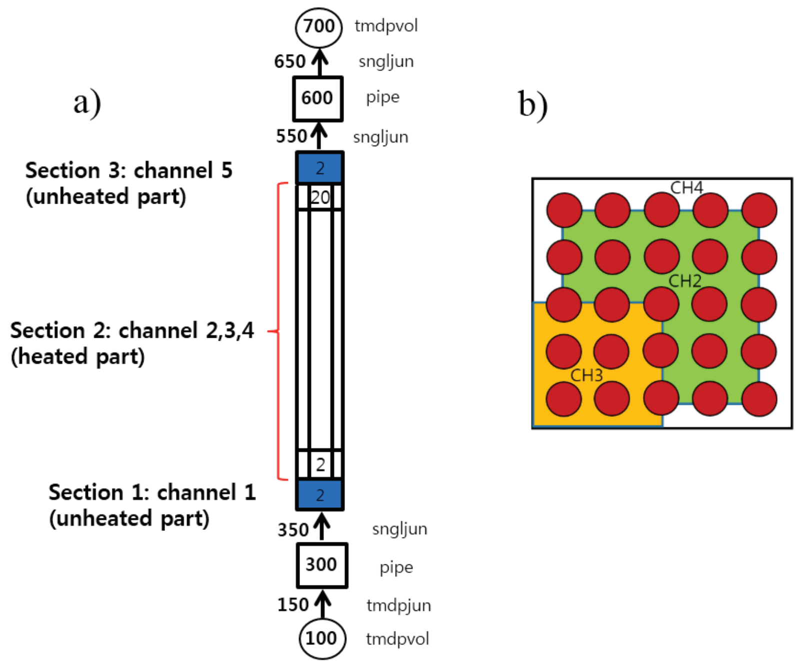

Figure 3. MARS Code Modeling

2.2. MARS Code Modeling

Figure 3a delineates an overall nodding diagram for MARS code simulations. The rod bundle is placed from Section 1 to Section 3, and is modeled utilizing the COBRA-TF module. The other parts are modeled using the RELAP5 module. The rod bundle is comprised of three sections. Sections 1 and 3 are modeled for unheated regions, and Section 2 is designed for the heating region. The number of axial nodes is 19 in the heating region. The power of heaters is radially uniform, but it varies axially according to the power profiles shown in Fig. 2. A coolant is injected at a constant velocity from the bottom. A constant pressure is imposed on the top boundary.

Figure 3b shows a cross-sectional view of the heating region in the bundle. The heating region is divided into three channels which are connected to each other, allowing cross flows. The intact rods (type-A) are placed in channels 2 and 4, and the locally deformed rods (type-B) are placed in channel 3. The axial position of the deformed region corresponds to nodes 8~11 in section 2.

Various experiments were performed depending on the system pressure (p), coolant sub-cooling (ΔT_{sub}), reflood velocity (V_f), total power (P), and maximum initial rod temperature ($T_{w,\max}$). Some experimental data were selected for MARS code evaluation. Tables 1 and 2 list the evaluation conditions. Initially, the rod bundle is empty. When fluid and wall properties reach a steady-state, the coolant path is diverted to the rod bundle to initiate reflood.

Table I. Simulation conditions with the typical power profile

Case	p (bar)	ΔT_{sub} (°C)	V_f (cm/s)	P (kW)	$T_{w,\max}$ (°C)
1	2	90	2	47	600
2	2	50	2	47	600
3	2	90	4	47	600
4	2	50	4	47	600

Table II. Simulation conditions with the modified power profile

Case	p (bar)	ΔT_{sub} (°C)	V_f (cm/s)	P (kW)	$T_{w,\max}$ (°C)
5	2	90	4	47	600
6	2	90	6	47	600

3. RESULTS AND DISCUSSION

Figures 4~7 show the experimental and MARS code results for the typical power profile (cases 1 ~ 4). All of available rod temperatures are plotted in the figures. With reference to Figs. 4a and 4b, the peak temperatures of the type-A group (intact) and the type-B group (locally-deformed) are nearly similar to each other, being close to 700°C. The flow blockage has little effect on the peak temperature. In addition, even final quenching times in Figs. 4a and 4b are nearly the same (600 seconds). However, one can see in Fig. 4b, the wall temperatures of some heater rods are increased on the whole. Moreover, the time period during which the wall temperatures are high is relatively elongated. These experimental trends are well predicted by MARS, as shown in Figs. 4c and 4d. In Fig. 4b, some temperatures do not fall to the saturation temperature of 120°C even though the blockage is completely quenched by water. The reason is that some thermos-couples are sandwiched between the heater rod and a sleeve, and are not exposed to water. Good agreements between predictions and experimental data are also seen in Figs. 5~7 (cases 2, 3, and 4).

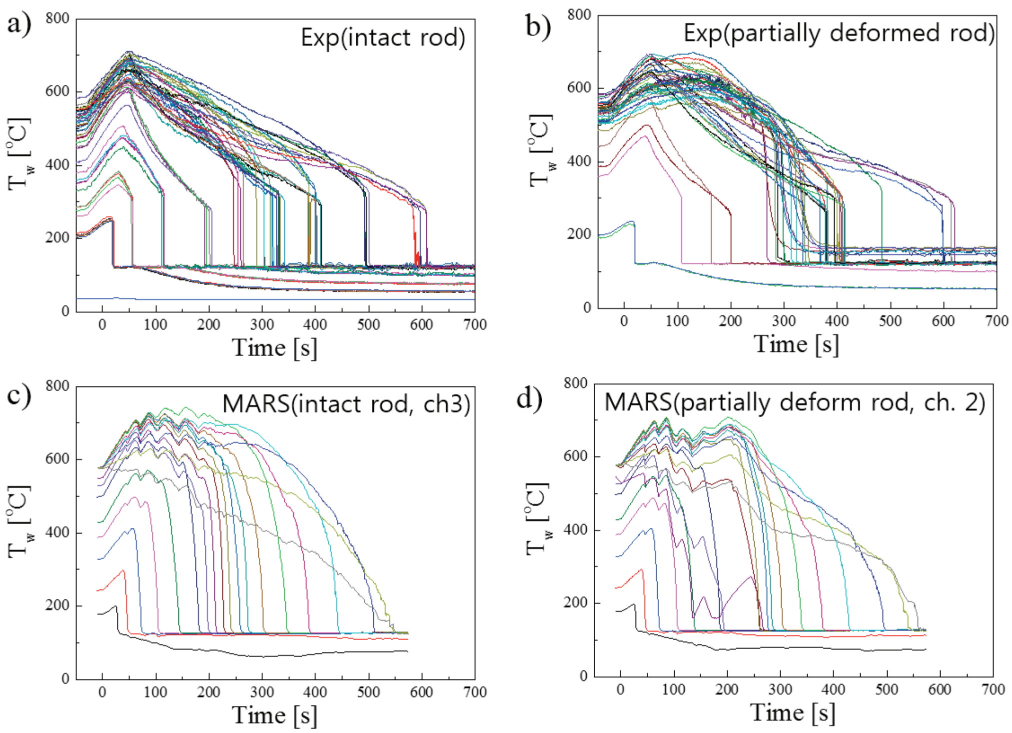

Figure 4. Result for Case 1.

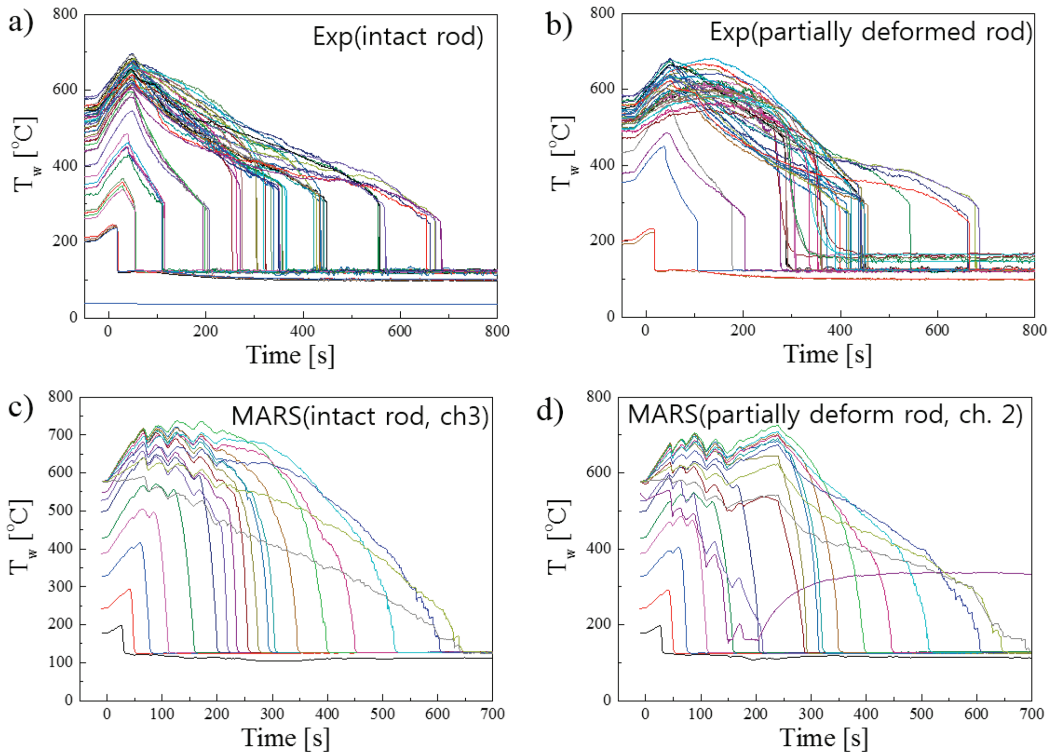

Figure 5. Result for Case 2.

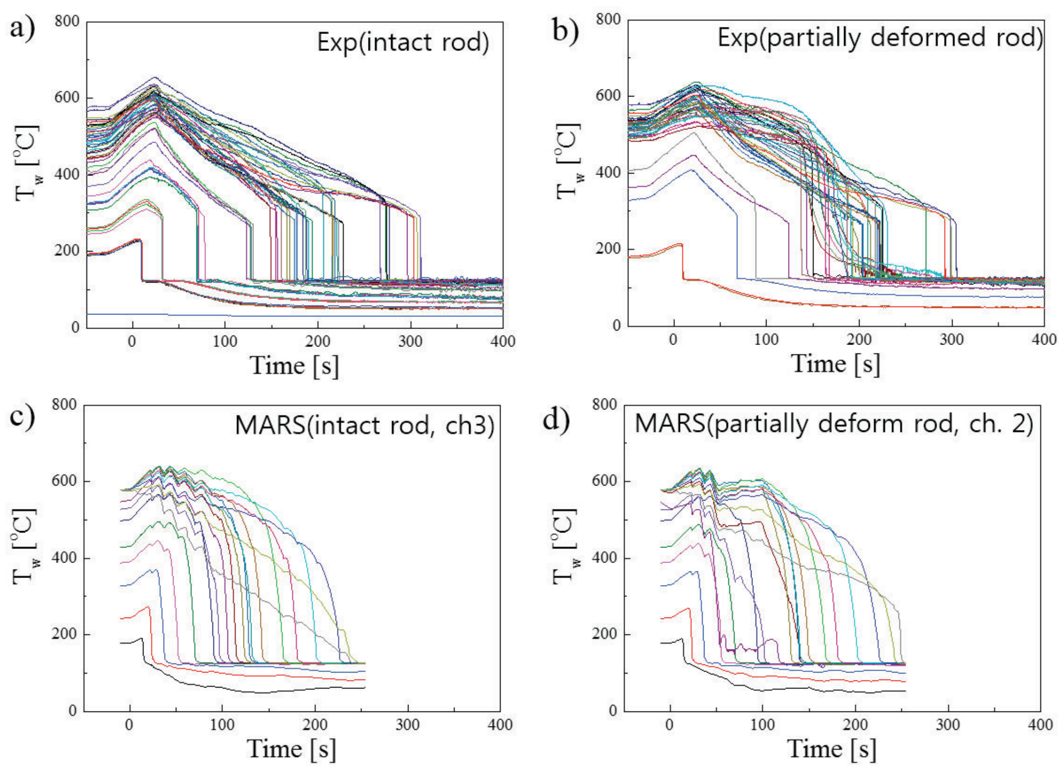

Figure 6. Result for Case 3.

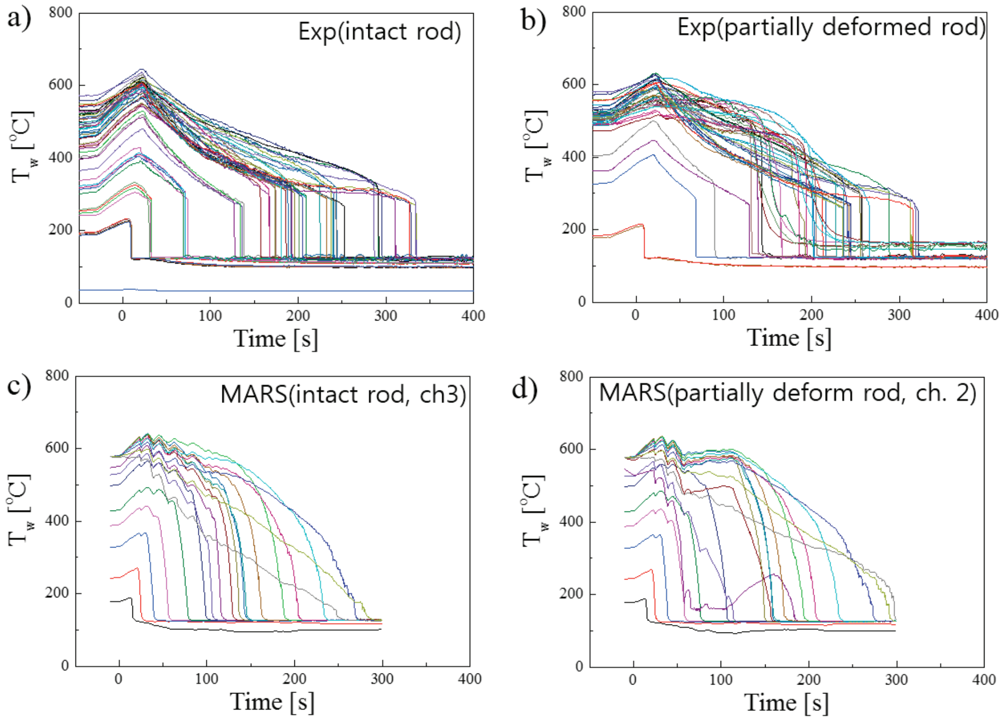

Figure 7. Result for Case 4.

Figure 8 shows the results when the local power increase by fuel relocation is considered (Case 5). With reference to Figs. 8a and 8b, the peak temperature of type-B (local-deformed rods) is higher than that of type-A (intact rods). In addition, the time period during which wall temperatures are high is considerably elongated. Unlike Figs. 4~7, the deformed rods are significantly influenced by the local power increase. Figures 8c and 8d show the MARS code results. The prediction of the peak temperatures is acceptable. However, the overall trends of wall temperatures are not well predicted. Though the local power increase influences considerably the overall trends of wall temperatures (Figs. 8a and 8b), the prediction result from Fig. 8c is not much different from that from Fig. 8d.

Figures 9~11 show detailed comparisons at three different axial positions: $x = 1666$, 1904, 2383 mm. Figure 9 compares the prediction with experiment at the point before the blocked region ($x = 1666$ mm). The MARS predictions are higher than experiment. Figure 10 compares the data at the maximum blocked point ($x = 1904$ mm). One can see that the peak temperature of deformed rods (type-B) from Fig. 10 is similar to that from Fig. 8b. This means that the peak temperature takes place among the deformed rods with increased local power. Figure 10 shows clearly that while the intact rod temperatures are reasonably predicted, the deformed rod temperatures are not well predicted.

Figure 12 shows the results for Case 6. The overall trends of wall temperatures are similar to case 5 (Fig. 8). The prediction of the peak temperature is acceptable. However, the overall trends of wall temperatures are not well predicted by MARS. According to experimental data, the peak temperature of type-B (local-deformed rods) is higher than that of type-A (intact rods), and the time period during which the wall temperatures are high is considerably elongated. However, the prediction shown in Fig. 12c is not much different from that shown in Fig. 12d.

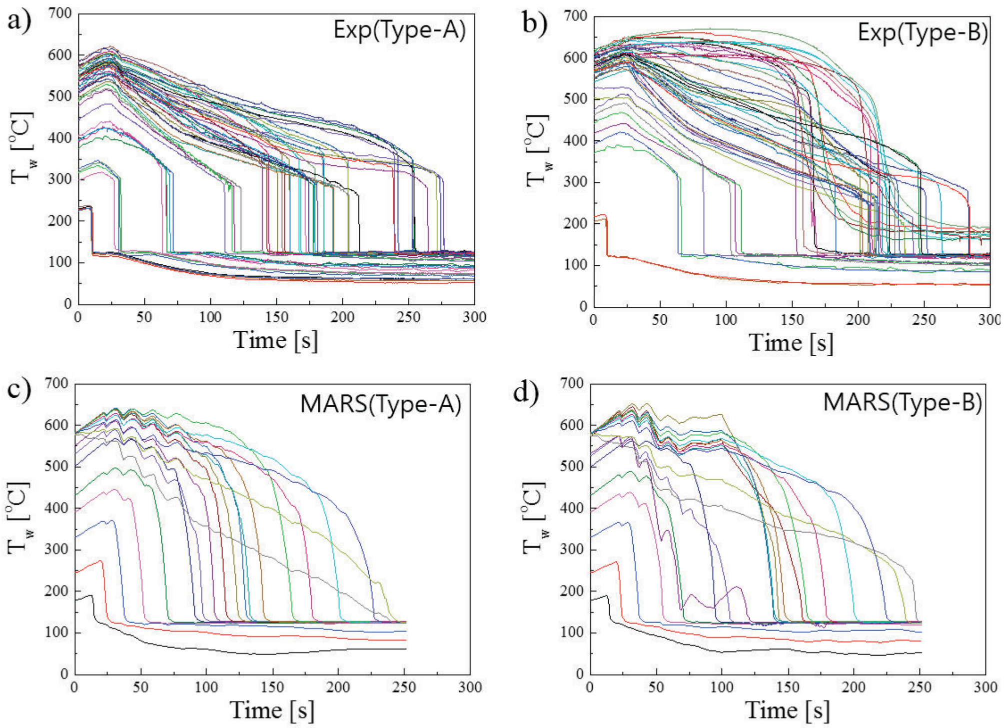

Figure 8. Result for Case 5.

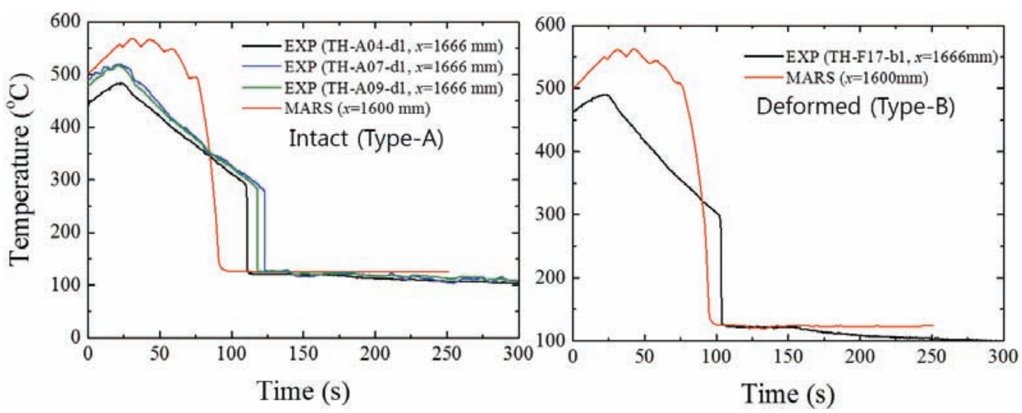

Figure 9. Comparison of MARS with experiment (Case 5) at $x = 1666$ mm

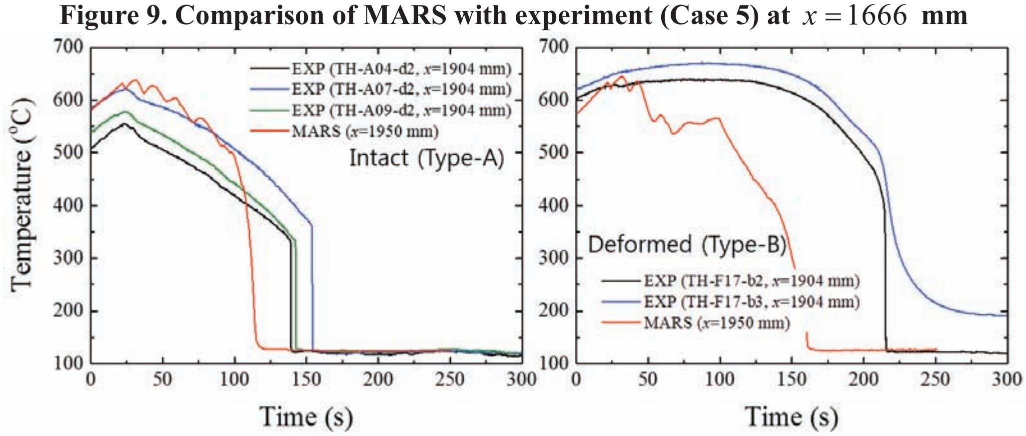

Figure 10. Comparison of MARS with experiment (Case 5) at $x = 1904$ mm

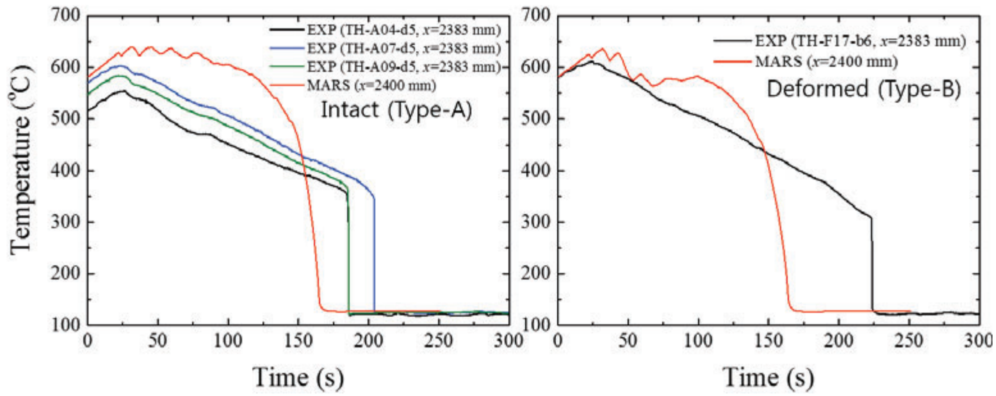

Figure 11. Comparison of MARS with experiment (Case 5) at $x = 2383$ mm

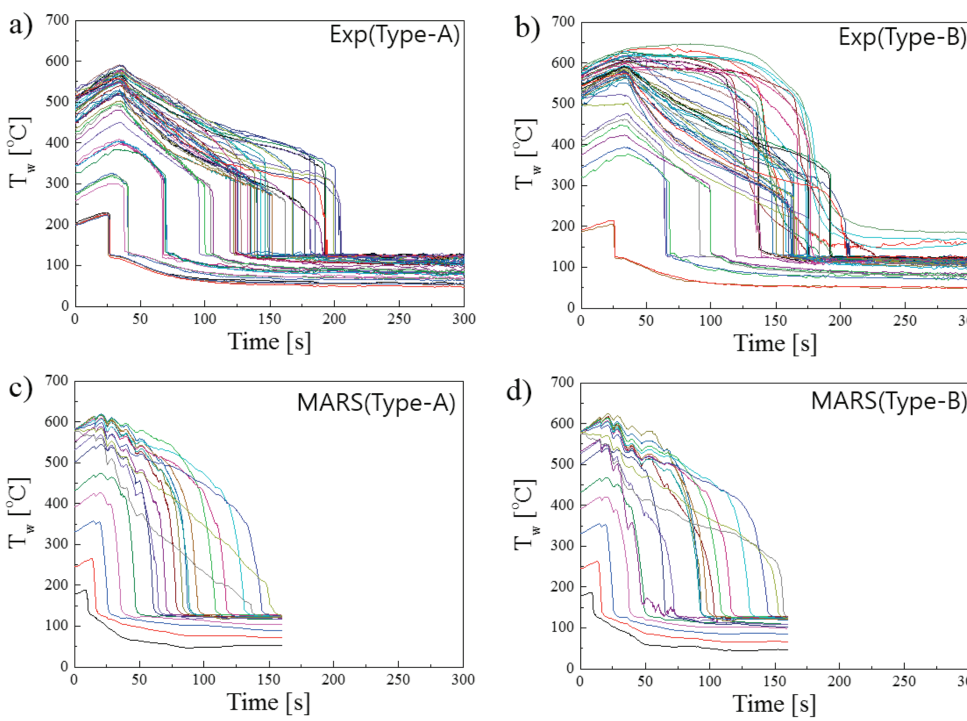

Figure 12. Result for Case 6.

4. CONCLUSIONS

We have presented the experimental data and computer-code evaluation results for forced reflood tests in a partially blocked rod bundle. When the local power increase by fuel relocation was not considered, the blockage had little effect on the peak temperature. The wall temperatures of deformed rods were slightly increased, and the time period for high temperature was somewhat elongated. These behaviors were well predicted by MARS code. However, when the effect of fuel relocation was taken into consideration, the peak temperature was notably increased, and the time period during which wall temperatures are high was considerably elongated. The prediction of the peak temperature was acceptable, but the overall trends of wall temperatures were not well predicted by MARS. This study is a first step toward development of two-phase flow models considering the effect of fuel relocation. We will improve the blockage models including the effect of the fuel relocation.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (no. 2012M2A8A4026028).

REFERENCES

1. P. Ihle and K. Rust, *FEBA looding Experiments With Blocked Array*: *Evaluation Report*, KfK 3657 (1984).
2. P. Ihle and K. Rust, *SEFLEX Fuel Rod Simulator Effects in Follding Experiments. Part 1: Evaluation Report*, KfK 4024 (1986).
3. C.A. Cooper, K.G. Pearson, and D. Jowitt, *The THETIS 80% Blocked Cluster Experiment. Part 3: Forced Reflood Experiments*, AEEW-R1765 (1984).
4. P. Dore and K.G. Pearson, B, *ACHILLES Ballooned Cluster Experiments*, AEA-TRS-1060/AEEW-R2590 (1991).
5. L.E. Hochreiter, *FLECHT-SEASET Program Final Report*, NUREG/CR-4167; EPRI NP-4112; WCAP-10926 1985.
6. C.Y. Paik et al., *Analysis of FLECHT-SEASET 163-Rod Blocked Bundle Data Using COBRA-TF*, NUREG/CR-4166; EPRI NP-4111; WCAP-10375 (1985).
7. C. Grandjean, *A State-of-the-art Review of Past Programs Devoted to Fuel Behavior Under LOCA conditions: Part 2 Impact of Clad Swelling Upon Assembly Cooling*, SEMCA-2006-183, IRSN (2006).
8. S.-K. Moon, J.R. Kim, S. Cho, J.K. Park, Y.J. Youn, and H.S. Choi, *Construction Report of 5x5 Rod Bundle Reflood Test Facility for Simulating Partially Blocked Core*, KAERI/TR-5274/2013 (2013).
9. K. Kim, B.J. Kim, Y.J. Youn, H.S. Choi, S.-K. Moon, and C.-H. Song, “Effect of Flow Blockage on the Coolability During Reflood in a 2x2 Rod Bundle,” *Science and Technology of Nuclear Installations*, **2014**, Article ID 247862 (2014).
10. K.S. Hamdan, D.-E. Kim, and S.-K. Moon, “Droplet Behavior Impacting on a Hot Surface Above the Leidenfrost Temperature,” *Annals of Nuclear Energy* **80**, pp.338-347 (2015).
11. I. Nagy, A. Vimi, Z. Hozer, and P. Windberg, “Coolability of Ballooned VVER Type Bundles with Pellet Relocation,” AEKI-FL-2010-401-02/01 (2010).