Prediction of Reflood Behavior in Ballooned Rods Array of ATHER 5x5 Experiment with Improvement of Modeling Scheme

Young Seok Bang[a*] , Deog Yeon Oh[a], Joosuk Lee[a], Jongrok Kim[b], Sang-Ki Moon[b]
[a]*Korea Institute of Nuclear Safety, 62 Kwahak-ro, Yuseong, Daejeon, Korea*
[b]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong, Daejeon, Korea*
**Corresponding author: k164bys@kins.re.kr*

1. Introduction

Swell and rupture of the cladding of the reactor fuel rods are important part of LOCA analysis, and experimental studies have been conducted on the effect of reflood thermal-hydraulic behavior under the conditions in which the cladding of the fuel rods is deformed [1,2,3]. Most of these experiments simulate deformation of the fuel rods, which cause about 60 percent of the flow blockage. In the event of larger flow path blockages, consequently, further studies have been required, especially for the performances of deformed and non-deformed rods and their interactions.

In 2014, KAERI developed an ATHER experimental facility and conducted reflood experiments in 5x5 rods bundle equipped with deformed rods that simulate a 90% partial flow blockage. [4,5]. In the previous work by the authors [6], preliminary calculations using the MARS-KS code [7] were performed, relying on the information available from the web, without detailed experimental information and data. The study found that reasonable prediction of the thermal behavior of the deformed rods required the simulation of the sleeve heat conductor simulating the deformed part, fouling of the heat transfer area due to contact between the sleeve and the adjacent sleeves, and consideration of the gap between the rod and sleeve.

Recently, the Technology License Agreement between KINS-KAERI on the Use of ATHER Experimental Information and Data came into effect[1], and with the acquisition of detailed experimental information and data, improvements to preliminary calculation models were made. In particular, we find it is important to obtain reliable reflood thermal-hydraulic initial conditions by faithfully implementing experimental sequences for a reasonable validation. In this paper, we discuss the improvement in modeling schemes to obtain the reliable predictions and its results.

2. Experiment

The ATHER 5x5 rod bundle experiment facility is one of the facilities for studying post-LOCA reflood behavior under conditions with partial deformation of rods, and detailed information on this is presented in the literature [4]. In this study, a test, DF22-60080-R47-01, was selected and analyzed among several reflood experiments conducted on this facility. This experiment simulates a typical reflood process in which 80°C of coolant is injected at 2 cm/sec into the core under heater rod power of 47.5 kW and 2 bar at the outlet pressure. The sequence of experiments is presented in the literature [4].

3. Improvements of Modeling Scheme

3.1 Hydrodynamic Modeling Scheme

All calculations in this study used the MARS-KS code version 1.5 [7]. As presented in the literature [4,5], the test section of the ATHER 5x5 rod bundle facility has sleeves that simulates deformation in the 3x3 rods array. (Fig. 1).

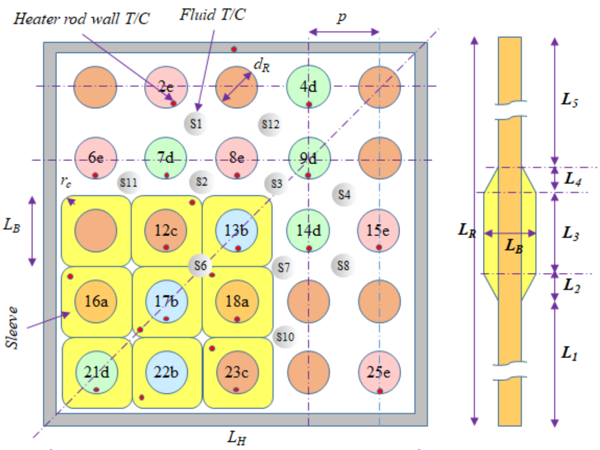

Fig. 1. Sketch of test section of ATHER 5x5 facility

In this study, the following three modeling schemes were applied to model the test section of these configuration:

(1) Single channel model (1-ch): by single pipe component of MARS-KS code
(2) Two channel model (2-ch): Deformed heater rods and non-deformed heater rods are separated into hydraulic channels and the crossflow junctions between channels are connected.
(3) Multid model (multid): by multi-d component adopting three-dimensional momentum equations

[1] The Agreement was signed at May 7, 2021 (Gyujegumjeung-91, May 14, 2021)

Figure 2 shows a sketch of three models. In all models, the test section was described as 29 nodes with non-uniform axial length. The heater rod has the same specifications as the PLUS7 fuel [5]. In addition, each spacer grid built into the fuel assembly was positioned at the junction, reflecting the penetration rate and loss coefficient of the grid based on the design data. Standard modeling options (*vbfe=1100, cahs=1000*) were applied to all volumes and junctions in the test section. For deformed part, fluid volume, flow path area, and hydraulic diameter were reduced based on geometric information, and appropriate loss coefficients were imposed.

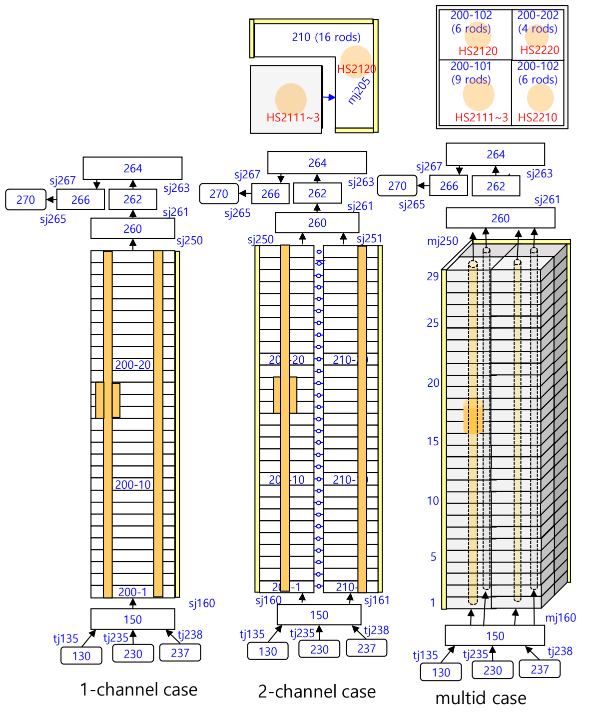

Fig. 2. Nodalization of test section of ATHER 5x5 facility

3.2 Thermal Modeling Scheme

9 deformed rods and 16 non-deformed rods out of the 25 heater rods of the test section were simulated into separate heat structures. In particular, for deformed rods, the section with the sleeves and the upper and lower sections were modeled as separate heat structures. The scheme was consistently applied to multid case. All rods have the same power and an axial power distribution in cosine shape

There is a gap of about 30 μm between the heater rod and the sleeve. In this study, it was assumed that this gap was filled with steam, and the thermal conductivity was set to be k=0.03~0.11W/m-K with respect to temperature from the physical properties of steam.

The sleeve was designated as Inconel 600 with the same material as the cladding. Contact between the sleeves of the deformed rod may interfere with convection heat transfer to the fluid. To simulate this, a fouling factor, 0.4, was imposed on the heat transfer area of the deformed rods. Its actual value was based on the fraction of sleeve surface area contacted with the adjacent sleeves to the total sleeve surface area plus a factor considering the uncertainty in convective heat transfer in a narrow gap between rods and the housing.

The housing surrounding the test section is modeled as a thermal structure. The previous study assumed no heat loss through this housing, however, heat loss was confirmed by the experimental data,. To consider heat loss, an option to impose the heat transfer coefficient function of temperature among the options provided in the MARS-KS code was applied. This eliminates the need to worry about spatial heat loss distribution as higher fluid temperatures give greater heat flux.

3.3 Test-specific Modeling

In the previous study [7], a calculation with steam injection under full power without any heat loss was attempted to get a steady state just before reflood. As a result, the fluid temperatures and the cladding temperatures were overestimated. It was also found that the reflood behavior was significantly affected by this overprediction. Therefore, it was recognized to consider the heat loss. To determine how much the heat loss and how to implement it, it is needed to faithfully implement the process of reaching a steady state and subsequent reflood process of the experiment (Table 1).

Table 1: Sequence of test

Time period	power	Steam supply	Water supply	Ending criteria
~200 s	14.5 kW	0.0147 kg/s	0	T_{clad}<923K
~400 s	7.5 kW	0	--	T_{clad}<973K Inlet plenum fill
~end	47.5kW	0	0.02m/s	

To this end, steam supply, water filling and subsequent reflood water supply to the inlet plenum were modeled separately and were designd to switch-over according to the experimental sequence. Also changes in the power of the heater rod were simulated as the test sequence.

In conjunction with the modeling process of heat loss, the superheating of the injected steam has a significant effect, and no corresponding experimental data has been found. Therefore, the temperature value (497K) that makes the prediction close to the experiment phenomenon was determined by sensitivity analysis.

4. Results and Discussions

4.1 Steady State Initialization

The steady state calculation was performed in such a way as to determine the degree of heat loss required to approach the initial conditions of the experiment by checking the conditions formed. In particular, in this calculation, the time step control option, *tt=16* of the MARS-KS input and the steady state initialization flag of the heat structure were set to 0 to 1000 seconds.

Figure 3 shows the fluid temperatures and housing inner wall temperatures at the various axial locations calculated by the 1-ch model compared with the experiment. The figure compares the cases with and without heat loss (h_w=0, 1, 2 W/m-K). It can be clearly shown that the higher heat transfer coefficient resulted in the closer wall temperatures to experimental data.

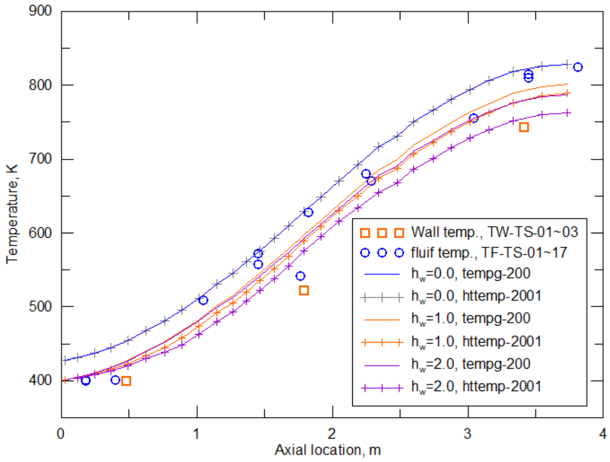

Fig. 3. Comparison of distributions of fluid temperatures and housing inner wall temperatures at steady state condition.

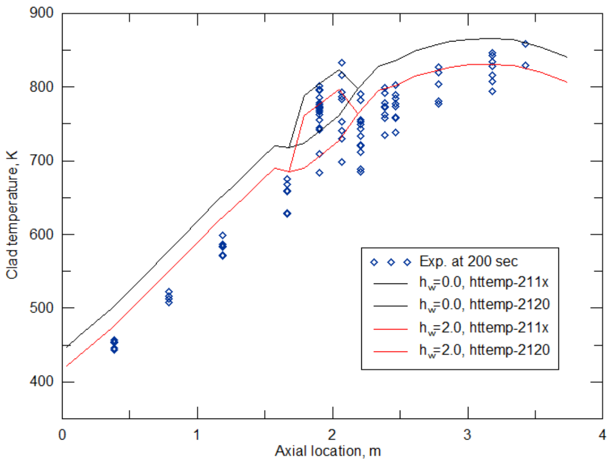

Fig. 4. Comparison of cladding temperatures at steady state condition

This is also confirmed in the comparison of cladding surface temperature at the time of steady state in Figure 4. We can find that considering the heat loss of 2.0 W/m-K is closer to experimental data upstream and downstream than otherwise, and has an improvement effect of up to 50 K in cladding temperature. Furthermore, the difference between the cladding temperature of the deformed rod and that of the non-deformed rod can be said to be the effect of the fouling factor and the sleeve heat conductor applied to the deformed rod. Although not illustrated, this effect is also valid for multid case.

4.2 Reflood Behavior

Using the previously obtained steady state, the transient of the reflood was calculated. The transient calculation was carried out according to the test sequence in Table 1. A special reflood model implemented as an option 40 [8] was applied.

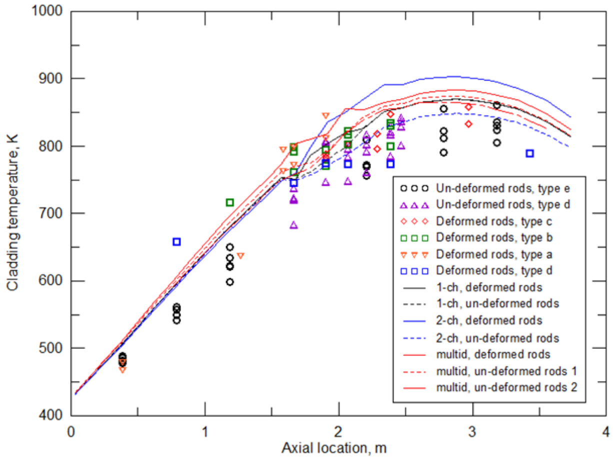

Fig. 5. Comparison of cladding temperatures at the beginning of reflood.

Figure 5 shows a comparison of cladding temperature distributions at 393 seconds just before reflood for three modeling cases. Despite considering heat losses, the predicted cladding temperature is still slightly higher at all the locations. The trend, which the cladding temperatures at the deformed part were locally higher than those at the lower and upper parts in the steady state (Figure 4), became relatively flat as the cladding temperatures at the lower and upper parts increased in a static manner for 200 seconds after the steam injection ended. It was found in both the experiment and the calculations.

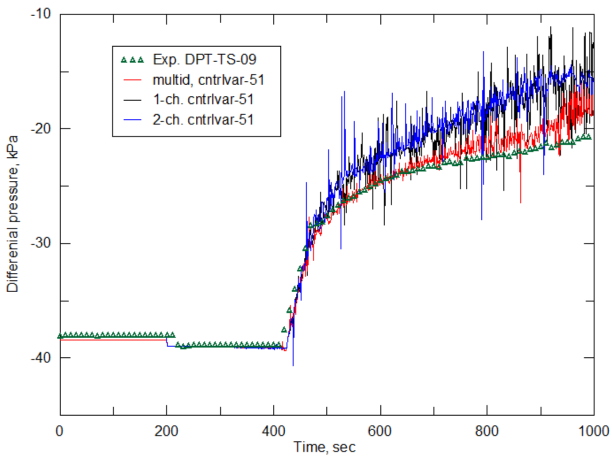

Fig. 6. Comparison of differential pressure over the test section.

Figure 6 shows behaviors of differential pressure over the test section calculated by the three calculations and compared with the experimental data. The results of the calculation and the experimental data are well matched by the initial 500 seconds of transient, however, subsequently the calculation results show that the reflooding as a whole will proceed faster. Calculation using the multid model are relatively closer to experiments than other cases. It can be due that the difference in the interfacial drag model of the rod bundle geometry between the 'multid' component and the 'pipe' component. For a given void fraction, the coefficient f_{ij} of the multid case is greater than that of the pipe case, which appears to slow the progress of the quench front by entraining more water.

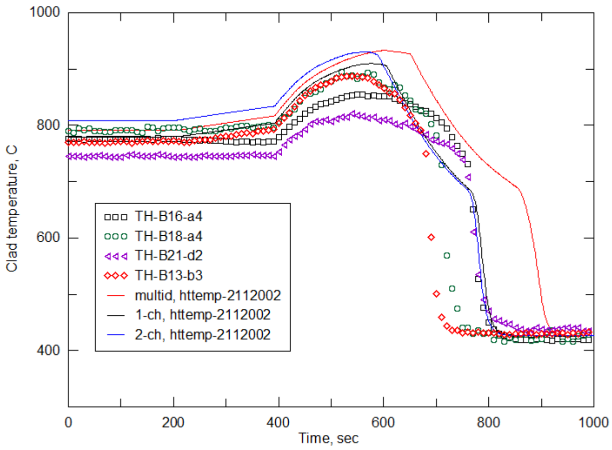

Fig. 7. Comparison of cladding temperatures at the middle elevation of the deformed rods.

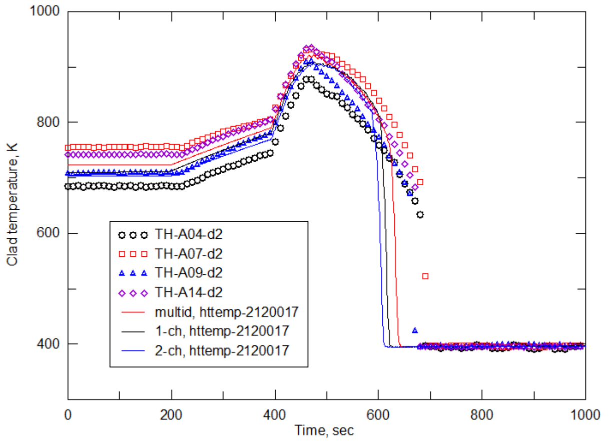

Fig. 8. Comparison of cladding temperatures at the middle elevation of the un-deformed rods.

Figure 7 compares the calculated cladding temperature behavior at the deformed part of the deformed rods with the experimental data. The experimental data show a difference of about 100 K and 100 seconds for maximum temperature and quenching time, respectively, depending on the relative position of the heater rod. The calculation results show similar behavior up to the turnaround point and subsequently different cooling behavior from the experiment. Multid modeling case shows the latest quenching time, which can be due to the difference in interfacial drag model as discussed.

Although not illustrated, in most calculations, cladding temperatures are predicted to be slightly higher than experiment, both at the lower and upper of the deformed part. The quenching is predicted to occur faster than the experiment as it goes to the upper side of the deformed part.

Figure 8 shows the calculated cladding temperature behavior at the middle part of the non-deformed rods. Variations due to the relative positions of the heater rods is also observed to be up to 80 K. The calculation results are agreed with the experiment, but it is predicted that quenching occurs earlier than the experiment.

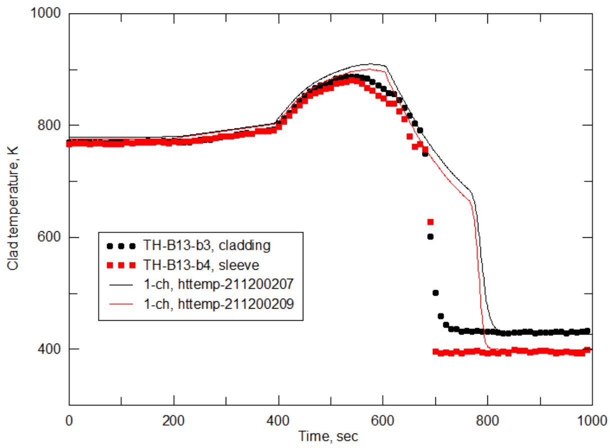

Fig. 9. Comparison of cladding temperature and sleeve surface temperature.

Figure 9 shows a comparison of the calculation results and experimental data for cladding temperature and sleeve surface temperature at the middle part of the deformed rods. This calculation is based on a single channel model. During the reflood process, cladding temperatures tend to be slightly higher than sleeve surface temperatures, especially after quenching, resulting in a difference of more than 20 K due to the recovery of convective heat transfer. This behavior is well matched in experiments and calculations, which demonstrates that the present modeling scheme of steam gap and sleeve are appropriate.

Figure 10 compares the calculated maximum cladding temperatures at all locations with the experiment. In overall, they are well matched with the experimental data and are predicted slightly higher in most locations. Experiment and mutid calculation show that maximum cladding temperatures continue to increase in the region past the sleeve to 2.6 m in axial location, and those of non-deformed rods in this region are higher than those of deformed rods. It seems to be related to the distribution of lateral flow of steam passing through the sleeve and its change over time. This phenomenon is not found in one-dimensional models.

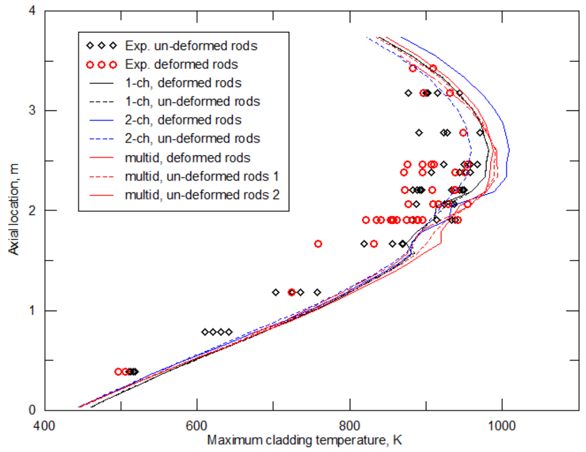

Fig. 10. Comparison of maximum cladding temperatures along the heated length.

Figure 11 compares the calculated quenching time at all locations with the experimental data. At the lower part of the deformed rods, the timing of the quenching is properly predicted. As observed in the experiment, calculations appropriately have shown that the quenching time of the middle part of the deformed rods is later than that of the non-deformed rods. The upper part predicts earlier quenching. This requires further research for improvement. The result of multid modeling tends to be closer to experimental data than in other cases, which can be due to the difference in interfacial drag model as discussed earlier.

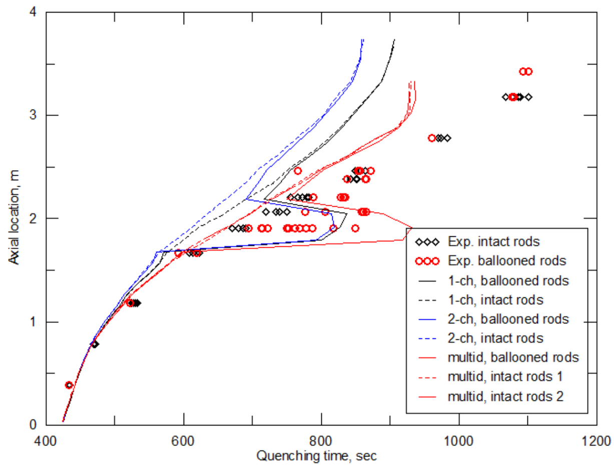

Fig. 11. Comparison of quenching times along the heated length.

5. Conclusions

An experiment simulating a reflood phenomenon in deformed rods array conducted at ATHER 5x5 rod bundle facility was calculated using MARS-KS code The modeling schemes included sleeve thermal conductors simulating deformed rods, fouling of heat transfer area by contact between adjacent sleeves, heat loss through the housing, and faithful simulation of experimental sequence. One-dimensional models with single channel and two-channels and three-dimensional model with multid component were attempted.

The conclusions are as follows:

1) The proposed schemes of sleeve modeling and of considering heat loss have contributed substantially to improve the accuracy of calculations. This allowed us to reasonably predict behavior of the deformed rods and un-deformed rods of the ATHER 5x5 reflood experiment.
2) Differences in cladding temperature and time of quenching between the deformed and non-deformed rods especially at the downstream of the sleeve and their reasons can be understood from the multid calculation results.

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