

Assessment of Reflood Behavior of Fuel Relocated Deformed Rod bundles in AHER 5x5 Rod Bundle Experiment

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1. Introduction

Understanding the swell and rupture phenomena of reactor fuel rods cladding is important as it affects the Peak Cladding Temperature (PCT) during Loss-Of-Coolant Accident (LOCA) [1]. Also, predicting when and where these phenomena will occur is also an important factor in LOCA analysis. Since the 1980s, experimental studies have been continuously conducted to understand the effect of the reflood phenomenon on the fuel cladding when the fuel rod is deformed. In 2014, Korea Atomic Energy Research Institute (KAERI) has developed the Advanced Thermal-Hydraulic Evaluation of Reflood (ATHER) experimental facility and has conducted various reflood test in a 5x5 fuel rod bundle.

Among all the fuel rods, 3x3 fuel rods were in the form of partially deformed rods, simulating the shape of 90% partial flow blockage [2, 3]. In this experiment, the swell was simulated using the sleeve to mimic the deformation of the fuel rod, and the fuel relocation was simulated using the DC power distribution.

2. Methods and Results

2.1 KAERI 5x5 AHER experiment

The AHER experiment facility is developed to study the post-LOCA reflood behavior under the condition of partial deformation of fuel rods. As shown in Figure 1, the test-section consists of 5x5 rod bundles that are electrically heated and 3x3 rod bundles located in the lower left of the figure have sleeves to mimic a deformed rod. The diameter, pitch, and length of the heating rod are 9.5mm, 12.85mm, and 3.81m, respectively. In the case of a uniform power distribution (no fuel relocation), the cosine shape is as shown in Fig. 2(a), and in the case of fuel relocation, as shown in Fig. 2(b). Details of the

experiment are given in the literature [2]. In the experiment, the temperature of the rod surface, sleeve surface, fluid and housing are measured at the points indicated in gray in Figure 1. In this study, the DF22-60080-R47-01 case was selected and analyzed among the experiments performed on this facility.

The experiment is conducted under the conditions of heating power of 47.5kW and outlet pressure of 2 bar, and cooling water at 80 °C is injected into the core at 2cm/sec during the reflood process. A detailed experimental sequence is presented in the literature [2].

The process of the experiment is shown in Table 1 below.

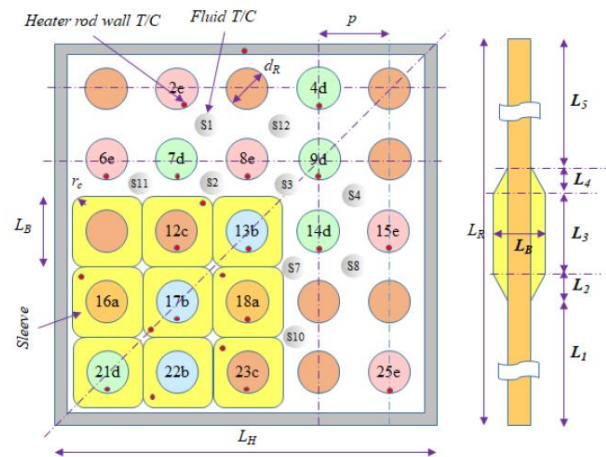


Figure 1 Schematic of test section of AHER 5x5 experiment facility

2.2 MARS-KS Modeling Scheme

All calculations in this study were performed using MARS-KS code version 1.6. Also, the KNF reflood model option was used. A detailed description of the model is given in the literature [5]. In this study, the test section of the AHER experiment was modeled and compared in two modeling types of channel as shown in Figure 3 below.

Table 1 Sequence of the experiment [2]

Time period	Power	Steam supply	Water supply	Ending criteria
~200s	14.5kW	0.0147kg/s	0	$T_{clad} < 923K$
200~400s	7.5kW	0	--	$T_{clad} < 923K$, Filling inlet plenum
400~end	47.5kW	0	0.02m/s	

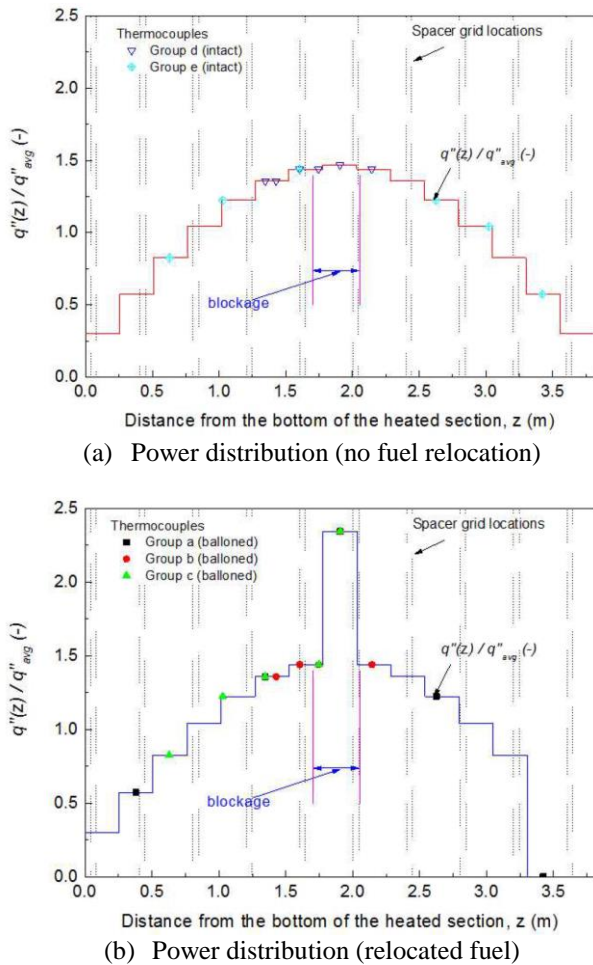


Figure 2 Axial power distribution of rod bundle [2]

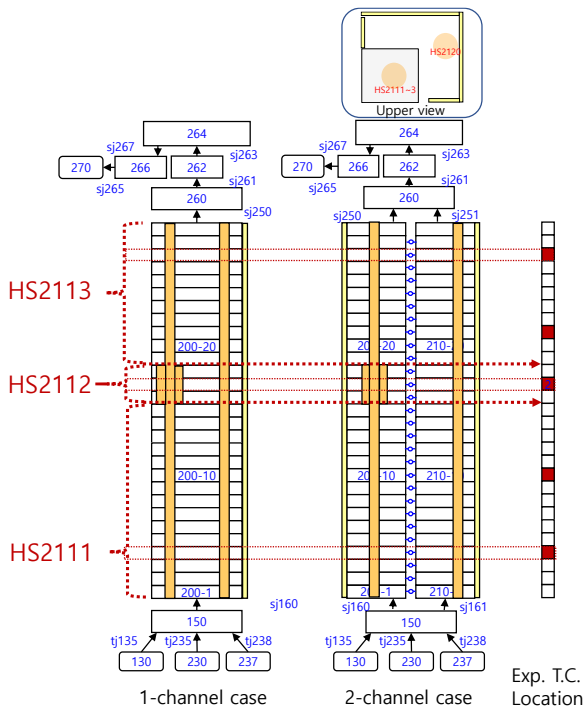


Figure 3 MARS-KS Nodalization of AHER facility

- (1) Single channel model (1-ch): All the rods are in a single channel
- (2) Double channel model (2-ch): Deformed heater rods and normal rods are separated into two channels and each channel are connected by crossflow junctions.

In this study, the difference in fluid behavior between the deformed and non-deformed parts and the effect on the cladding surface temperature of the rods were compared by two different modeling. The test section was nodalized with 29 axial nodes of non-uniform height. In addition, the spacer grid is located at the junction between nodes, and the penetration rate and loss coefficient are based on the design data.

Thermal model of 9 deformed rods and 16 undeformed rods were connected to the channel node by heat structure component. The heat structure of deformed rod is divided into three in the axial direction, and is divided into a deformed part with sleeve (2112), an upper side of the deformed part (2113), and a lower side of the deformed part (2111) as shown in Figure 4. In the experiment, the deformed part is a rectangular column with rounded corners, but in the code, it was modeled as a cylindrical shape as shown in Figure 4 due to the syntax of the MARS-KS code. The radius of this cylinder was set to be the same as the channel area of the experiment considering sleeve. Also, in the experiment, there is a gap of about 30 μm between the heating rod and the sleeve as shown in Figure 4. To simulate this in the calculation, it was assumed that the gap was filled with steam, and the thermal conductivity was assumed to be 0.03~0.11 W/m-K with respect to temperature from the physical properties of steam. The sleeve is made of the same material as the cladding material Inconel 600, and the contact between the sleeve and the deformed rod may interfere with convection heat transfer to the fluid. To simulate this, a fouling factor value of 0.4 was applied, therefore the heat transfer area of the deforming rod was reduced. This value was established by considering the area ratio of the area where the actual sleeve is in contact with the adjacent sleeve and the uncertainty that may exist in the narrow gap between the rod and the housing. In addition, it was confirmed that the amount of heat loss was not negligible from the experimental results. To simulate this, the heat transfer coefficient for heat loss was set.

3. Calculation Results

3.1 Cladding Temperatures

Figure 5 shows the single channel calculation result of the cladding temperature when fuel relocation occurs in the deformed rod compared to the experiment, and Figure 6 shows the double channel calculation result. As a result of the calculation, the overall trend seemed to follow the experiment well, but the maximum temperature of the deformed part was overestimated by

about 50K. In addition, it was confirmed that the calculation results in the entire section predicted cladding temperatures slightly higher than those of the experiment. It can be seen that the cladding temperature at the deformed part is calculated slightly higher from the initial temperature. Although the power distribution in the calculation was exactly matched to the experiment, it was difficult to accurately match the cladding temperature of the entire section. In particular, the HS2112 in Fig. 5 is a calculation result at the local point with the highest power, and shows a rather high cladding temperature value before quenching. Based on these results, it can be judged that the MARS-KS code conservatively predicts the cladding temperature value in a non-uniform power distribution due to fuel relocation.

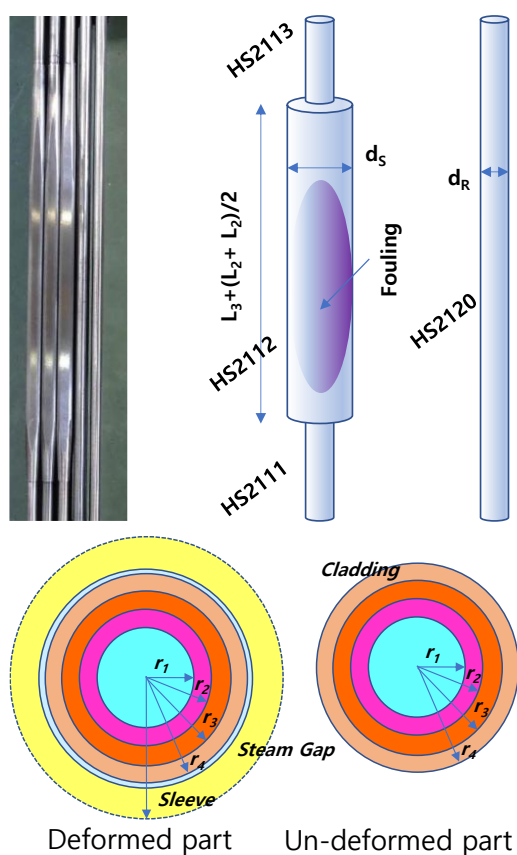


Figure 4 Heat structure modeling of deformed rods and sleeve

3.2 Reflood Water Level

Figure 7 shows the differential pressure, i.e., water level, in the test section. It can be seen that the calculation agreed well with the experiment in the initial stage about 500 seconds. However, after 500 seconds, it can be seen that the calculated result of quenching time rises faster than the experiment. Subsequently, the calculation results show that the reflooding as a whole was proceeded faster. This result is presumed to be a

difference due to the interfacial drag model, which is difficult to consider in one-dimensional modeling, and it has been confirmed that the calculation using the MULTID option is improved [6]. However, further research is needed to accurately analyze the phenomenon.

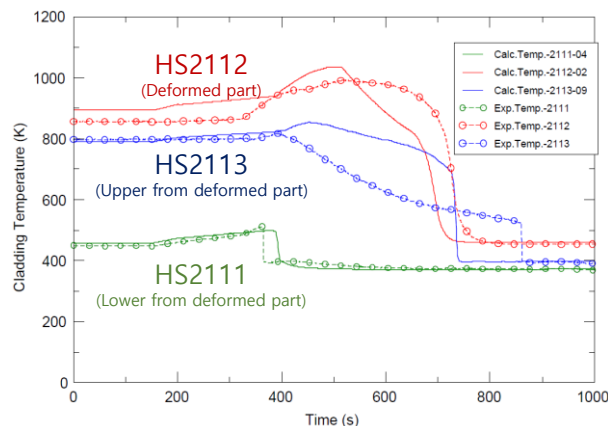


Figure 5 Calculation result of cladding temperature according to the position of the deformed rod: Single channel

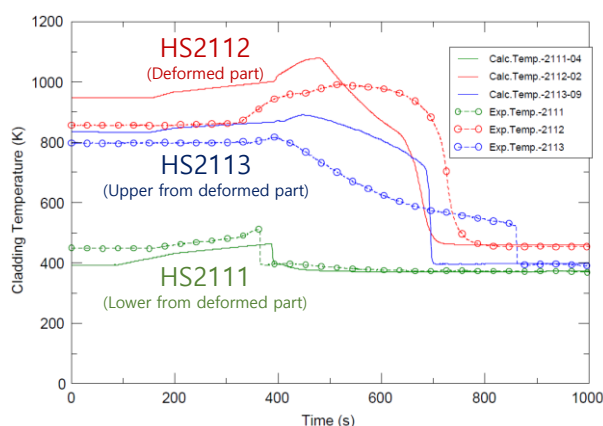


Figure 6 Calculation result of cladding temperature according to the position of the deformed rod: Double channel

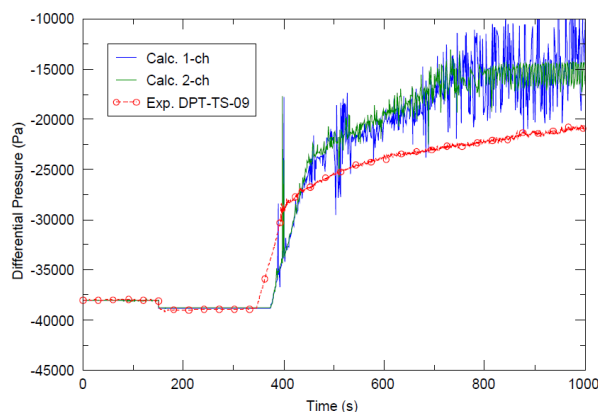


Figure 7 Calculation result of differential pressure

4. Conclusions

In this study, the MARS-KS analysis modeling methodology for the AATHER experiment was presented, and it was confirmed whether the MARS-KS code could adequately predict the cladding temperature and reflood phenomenon in the presence of fuel relocation and fuel rod deformation. As a result of the calculation, the overall trend seemed to follow the experiment well, but the maximum temperature of the deformed part was slightly overestimated. Based on these results, it can be judged that the MARS-KS code conservatively predicts the cladding temperature. For the differential pressure (water level), it can be seen that the calculation agrees well with the experiment in the initial stage about 500 seconds. However, after 500 seconds, the calculation results show that the reflooding as a whole was proceeded faster. Further research is needed to understand the calculation results.

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REFERENCES

- [1] USNRC, Fuel fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident, NUREG-2121, 2012. <https://www.nrc.gov/docs/ML1209/ML12090A018.pdf>
- [2] J. Kim, et al, Experiment Report of Core Cooling Performance for 5x5 Rod Bundle for Simulating Partially Blocked Core, KAERI/TR-5822/2014, Daejeon, Korea, 2014.12.
- [3] J. Kim, et al, Experimental study to assess effects of ballooning and fuel relocation on the coolability of fuel rod bundle, Nuclear Engineering and Design, Vol. 332, pp 1–10, 2018.
- [4] KINS, MARS-KS Code Manual, Volume II: Input Requirements, KINS/RR-1822, Vol. 2, Daejeon, Korea, 2018.7.
- [5] Dong Su Choi, Hee Cheon No, Improvement of RELAP5/MOD3.3 Reflood Model Based on the Assessments against FLECHT-SEASET Tests, Nuclear Engineering and Design, Vol.240, No.4, pp 832-841, April 2010.
- [6] Y.S. Bang et al, Prediction of reflood behavior in a bundle with deformed and un-deformed rods in AATHER 5x5 experiment using MARS-KS code, Nuclear Engineering and Design, Vol.392, 111770, June 2022