Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Evaluation of effects for subchannel-scale rod deformation during LBLOCA

Yunseok Lee [a] and Taewan Kim [a*]
[a] *Department of Safety Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea*
[*] *Corresponding author: taewan.kim@inu.ac.kr*

Keywords : MARS-KS, rod bundle, flow blockage, fuel deformation

1. Introduction

This study aims at evaluating the effects for deformation of multiple fuel rods during LBLOCA. For this, LBLOCA analysis has been performed on APR1400 plant, modifying the modeling scheme for hot pin from the averaged hot assembly to the subchannel-scale subsection including the fuel rods surrounding the hot pin. The effect of flow restriction has been evaluated, using MARS-KS [1], improved to consider the rod deformation and resulting flow channel deformation. The code improvement was made by applying thermal-hydraulic volume change model and a new rod deformation model for modeling clad deformation based on the thermal creep behavior at high-temperature condition.

2. Methods and Results

2.1 Fuel rod Model

MARS-KS calculates the rod deformation for changes of gap conductance in fuel rod. For this, the code calculates strains for thermal expansion, elastic and plastic deformation, respectively. The strains for thermal expansion and elastic deformation are calculated applying property tables obtained from MATPRO [2]. For the plastic strain, the code utilizes the burst strain and temperature data from NUREG-0630 [3]. As described in the Fig.1, the plastic strain of fuel clad is calculated assuming the rod pressure as a function of coolant temperature, neglecting the dynamic changes of rod gap volume. As afore mentioned, the current deformation model of MARS-KS calculates the fuel and clad deformation to consider the gap conductance change. That is, the deformed geometries are neglected for heat balance calculation of fuel rods. Therefore, it is not feasible to implement the hydraulic response due to thermo-mechanical behavior of fuel rod using the current deformation model of MARS-KS.

For this, a new fuel deformation model has been developed in this study. As depicted in Fig 2, similar to the current model of MARS-KS, the new model calculates strains for thermal expansion and elastic deformation using MATPRO. However, the plastic strain is calculated based on Norton thermal creep model, using the effective strain [4]. The burst of fuel clad is determined using both burst hoop strain and clad temperature from NUREG-0630. In contrast to the current fuel model of MARS-KS, the rod gap pressure is calculated, changing gap volume and using gap averaged temperature, not the coolant temperature. In addition, the new model applies the deformed geometries for the heat balance calculation of fuel rods

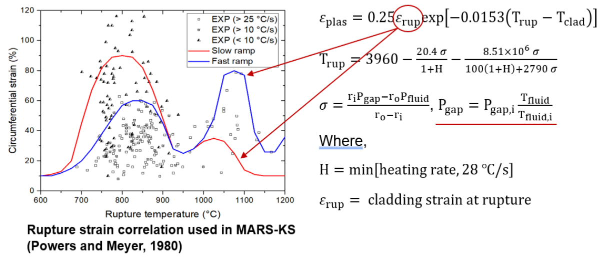

Fig. 1. Fuel clad deformation model in MARS-KS

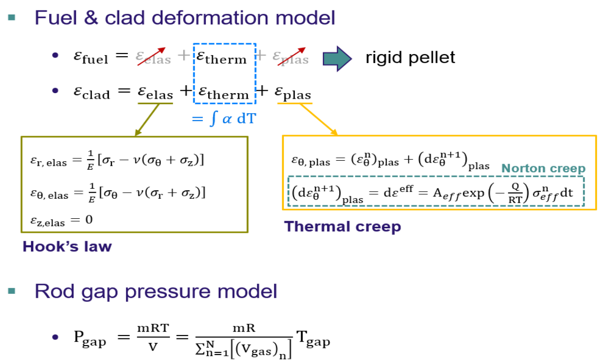

Fig. 2. New fuel clad deformation model

2.2 Thermal-hydraulic volume change Model

Since MARS-KS consists of field equations, assuming a constant fluid volume, the code cannot implement the flow channel deformation, despite calculating deformed geometries. For this, the field equation model has been improved, based on the concept of porous media, to consider deformable control volume [5]:

$$\frac{\partial}{\partial t}(\varepsilon \alpha_k \rho_k) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon \alpha_k \rho_k v_k A) = \varepsilon \Gamma_k \qquad (1)$$

$$\frac{\partial}{\partial t}(\varepsilon\alpha_k\rho_k v_k)+\frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_k\rho_k A v_k v_k) = -\varepsilon\alpha_k\frac{\partial P}{\partial x}+\varepsilon\alpha_k\rho_k g + \varepsilon\Gamma_k(v_{kI})-\varepsilon f_{wk}-\varepsilon f_{\sigma k} \quad (2)$$

$$\frac{\partial}{\partial t}(\varepsilon\alpha_k\rho_k u_k)+\frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_k\rho_k A u_k v_k) = -P\left[\frac{\partial}{\partial t}(\varepsilon\alpha_k) + \frac{L}{V}\frac{\partial}{\partial x}(\varepsilon\alpha_k v_k A)\right]+\varepsilon\Gamma_k h_k + \varepsilon Q_{wk}+\varepsilon Q_{\sigma k} \quad (3)$$

where, the subscript 'k' indicates an arbitrary fluid phase (vapor or liquid), and subscripts 'wk' and 'σk' indicate wall surface and fluid interface, respectively.

The variable, 'ε', indicates porosity, defined as the ratio of available fluid volume to the entire control volume including solid structure. Therefore, the change of porosity represents the change of fluid volume, i.e. channel deformation. The change of porosity is defined by the change of clad radius as follows:

$$\varepsilon = 1-\frac{dV}{V_o} = 1-\frac{\pi L}{V_o}\left(r_{clad}-r_{clad,o}\right) \quad (4)$$

where, V_o is the control volume at initial state, and $r_{clad,o}$ is as-fabricated clad radius. L is the channel length.

2.3 Results of LBLOCA analysis for APR1400

As depicted in Fig. 3, in total, five-identical subchannels were additionally modeled for simulating the multi-rod behavior during LBLOCA. The hot pin was located at the center, and four additional fuel rods were modeled into the surrounding subchannels. Since the hot assembly included 236 fuel rods, the flow area of each subchannel was modeled equivalent to having 1/236 of hot assembly.

In Fig. 4, the results of peak cladding temperature (PCT) for both lumped (conventional) and subchannel models (modified) were compared, using both original and new fuel models. As depicted in the figure, it was revealed that the PCT of hot pin in the subchannel featured higher heat up compared to the lumped model. As listed in Table I, the subchannel model revealed higher power-to-flow ratio, and thus, it led to having more conservative results than the lumped model. Meanwhile, the results of the new fuel model revealed lower heat up compared to the original model. As depicted in Fig. 5, the new model resulted in decrease of clad heat up, as it calculated the expansion of fuel clad while the original model featured negligible deformation.

In Fig. 6, the results were compared when applying the thermal-hydraulic volume change model. As depicted in the figure, the PCT changed to increase, as the flow channel deformed to be reduced. As depicted in Fig. 7 and Fig. 8, approximately 14% reduction in flow area occurred within the hot subchannel, and, due to increase of hydraulic resistance, reflood quench was delayed for hot pin. As listed in Table II, this resulted 36K increase in PCT of hot pin during reflood.

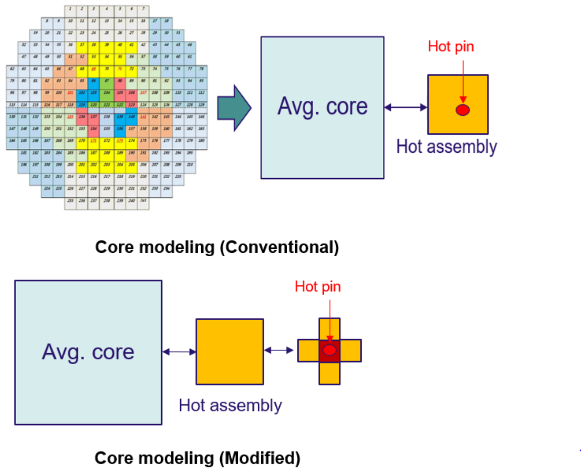

Fig. 3. Reactor core model for multi-rod simulation

Table I: Subchannel flows at plant steady-state conditions

Channel	Rod averaged power (kW)	Inlet velocity (m/s)	Mass flow rate (kg/s)	Power-to-flow ratio (kJ/kg)
Hot assembly (including hot pin)	96.047	6.776	85.535	265.002
Subchannel (hot pin)	108.956	6.776	0.632	300.613
Subchannel (west)	107.336	6.776	0.632	296.143
Subchannel (east)	107.002	6.776	0.632	295.223
Subchannel (north)	107.382	6.776	0.632	296.272
Subchannel (south)	106.909	6.776	0.632	294.967

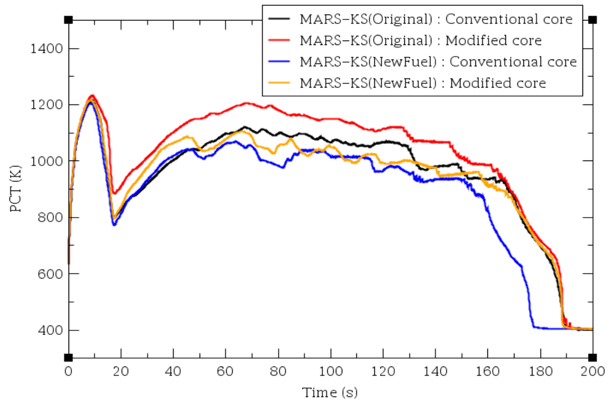

Fig. 4. PCT - lumped and subchannel core models

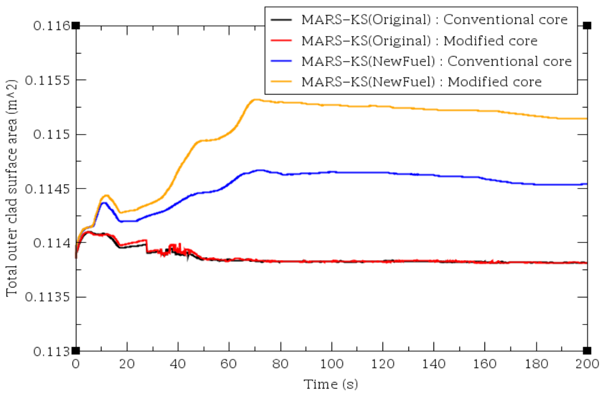

Fig. 5. Clad surface area - lumped and subchannel core models

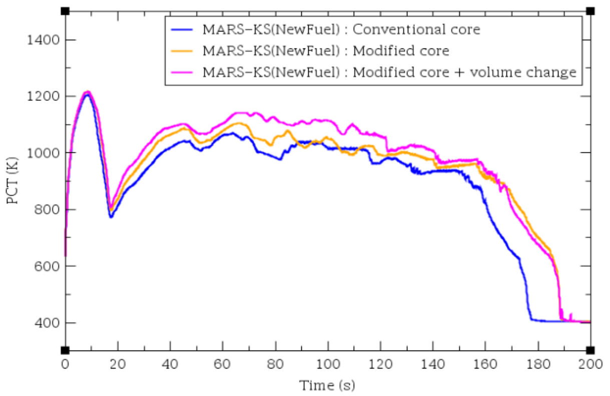

Fig. 6. PCT – with and without volume change model

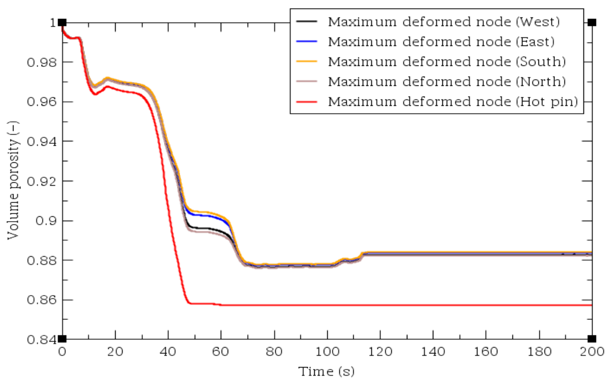

Fig. 7. Maximum volume change in subchannels

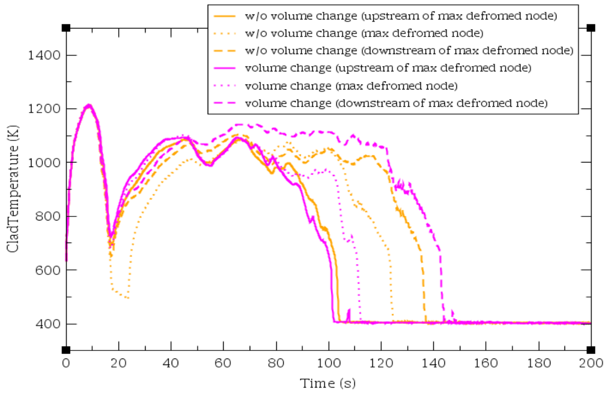

Fig. 8. Clad temperature distribution near the deformed node

Table II: Effect of channel deformation for PCT

Parameter	w/o volume change	w/ volume change
Blowdown PCT (K)	1215.147	1215.653
Reflood PCT (K)	1105.782	1142.283

3. Conclusions

In this study, the effect of multi-rod deformation for LBLOCA has been evaluated on APR1400 plant. Modeling additional subchannel-scale subsection, the multi-rod simulation was conducted. The results revealed that approximately 14% reduction in flow area occurred within the subchannel, and this resulted in delayed reflood quench. As a result, PCT of hot pin increased 36K during reflood. This result clearly indicates that the increase in hydraulic resistance with flow channel reduction was dominant during accident, rather than increasing cooling performance with the reduced flow area. As future work, further evaluation will be performed including the high burnup conditions, expected to evaluate remarkable blockage effect.

REFERENCES

[1] Korea Institute of Nuclear Safety, MARS-KS code manual, VolumeI: Theory manual, KINS/RR-1822 Vol.1, 2018.
[2] D. L. Hagrman, G. A. Reyman, and R. E. Manson, MATPRO-Version 11 (Revision 1): A Handbook of Materials Properties for Use in the Analysis of Light water Reactor Fuel Rod Behavior, NUREG/CR-0497, 1980.
[3] D. A. Powers and R. O. Meyer, Cladding Swelling and Rupture Models for LOCA Analysis, NUREG-0630, 1980.
[4] H.E. Rosinger, A Model to Predict the Failure of Zircaloy-4 Fuel Sheathing during Postulated LOCA conditions, Journal of Nuclear Materials (120), p. 41-54, 1984.
[5] Neil E. Todreas and Mujid S. Kazimi, Analysis of interacting channels by the porous media approach, Nuclear Systems II- Elements of Thermal Hydraulic Design (pp.171-208), 1990.