Evaluation of the effect of flow channel deformation with ballooning of fuel rods during LBLOCA of APR1400

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1. Introduction

In general, the thermal hydraulic system codes have conventionally represented the fuel rods by extending the heat structure model. For modeling the fuel rods, the following items are conventionally considered; metal-water reaction, gap conductance, rod pressure. However, when considering the fuel rods exposed to extreme conditions such as core inventory loss accompanied by loss of coolant accident (LOCA), swelling and burst of fuel rods and its resulting effects are also required to be considered. As depicted in Fig. 1, in such extreme conditions, the deformed fuel rods could degrade the cooling performance imposing additional flow resistance with flow blockage [1]. However, such details are not generally considered in the system codes. For example, in MARS-KS [2], although it includes the models for the deformation and rupture of fuel cladding, the deformed geometries of fuel rods as well as the corresponding flow blockage effects are not applied to the results of code simulation.

Meanwhile, Korea Institute of Nuclear Safety has developed an improved safety analysis code, namely FAMILY, by integrating the fuel performance code, FRAPTRAN, into MARS-KS [3]. The computational framework of FAMILY is based on MARS-KS, and it utilizes FRAPTRAN as an independent fuel analysis module. Thus, FAMILY represents the fuel behavior based on the coupled fuel analysis results from FRAPTRAN. In addition, it applies those detailed fuel analysis results including the deformed fuel rod geometries to the thermal-hydraulic analysis. Therefore, using FAMILY, the above-mentioned effects of flow channel deformation could be considered.

In this study, the effects of flow channel deformation have been evaluated using FAMILY with LBLOCA analysis for APR1400. Since FAMILY is only capable of single rod coupling with FRAPTRAN, the equivalent channel deformation with respect to thermo-mechanical behavior of single hot pin has been modeled by enhancing the deformation rate equivalent to the fuel bundle scale where the hot pin of interest is located.

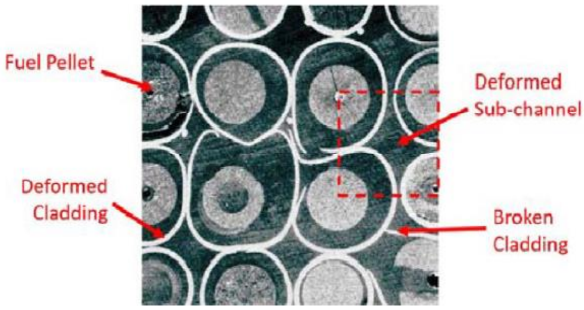


Fig. 1. Rod bundle cross-section after PHEBUS LOCA experiment [1]

2. Thermal-hydraulic volume change model

Since MARS-KS, a computational body of FAMILY, consists of field equation based on the constant control volume scheme, an alternative field equation model with deformable control volume, namely thermal-hydraulic volume change model, has been developed in FAMILY. The model reconstitutes the thermal-hydraulic field equation of FAMILY based on the porous media approach as follows [4]:

- Mass

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

- Momentum

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

- Energy

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

where, the subscripts w and σ denote wall surface and fluid interface, respectively. The variable ε is called porosity, which is defined as the ratio of the fluid volume to the entire control volume including solid structure as depicted in Fig. 2. By implementing the rate change of porosity, i.e. changing of the fluid volume, the model can represent the flow channel deformation with time. However, since MARS-KS constitutes the control volume only with the fluid, the porosity by itself cannot be applied as it is treated as a constant ($\varepsilon = 1$) in the control volume scheme of MARS-KS. Thus, in thermal-hydraulic volume change model, the porosity has different definition as follows:

$$\varepsilon = \frac{V_{f,0}+\Delta V}{V_{f,0}} = 1 + \frac{\Delta V}{V_{f,0}} = 1 + \frac{V_{s,0}-V_s}{V_{f,0}} \qquad (4)$$

where, $V_{f,0}$ denotes the initial fluid volume. $V_{s,0}$ and V_s denote initial and deformed solid volumes, respectively. Based on the above definition, implementing the rate change of solid volume, the expected flow channel deformation can be implemented. In the simulation of FAMILY, the rate change of solid volume corresponds to the rate deformation of fuel cladding calculated by FRAPTRAN.

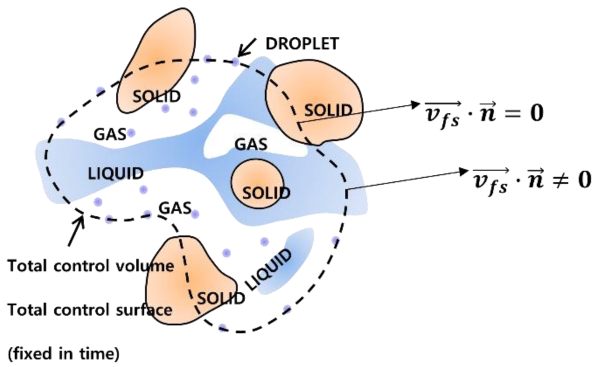
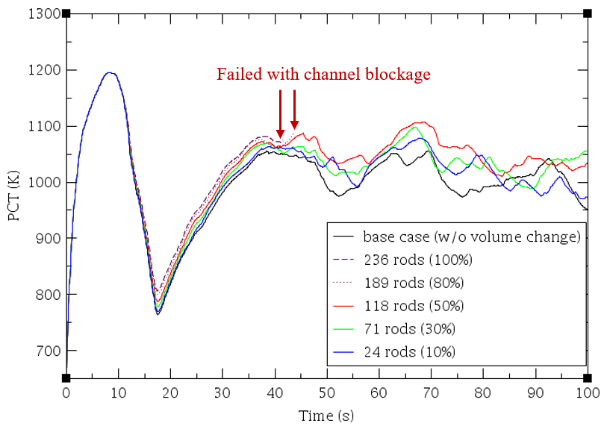


Fig. 2. Porous media control volume scheme

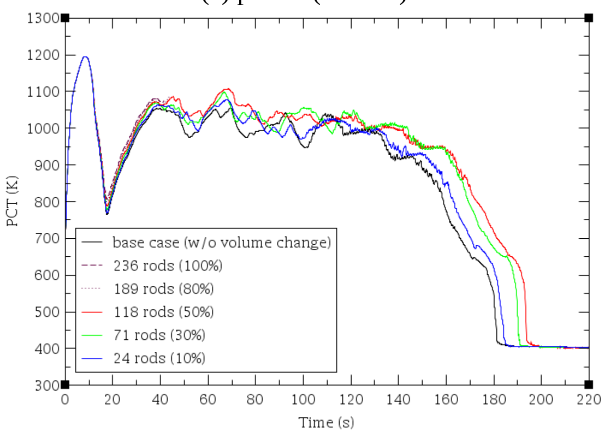
3. LBLOCA analysis

Since FRAPTRAN is only capable of single rod analysis, the flow channel deformation is implemented corresponding to a single rod deformation. However, as the hot pin of interest is conventionally modeled within the assembly-scale hot channel, the deformation of single hot pin cannot have a great significance to make the expected effects with flow channel deformation. Thus, in this study, the deformation of hot channel has been implemented enhancing the channel deformation rate equivalent to rod bundle scale, by multiplying the number of fuel rods to the results of single rod deformation from FRAPTRAN. For example, multiplying 236 is equivalent to the deformation of the entire fuel rods in the hot channel.

Assuming the channel deformation resulted from the equivalent number of fuel rods from 10% to 100% in the hot channel, its sensitivity on peak cladding temperature (PCT) of hot pin has been evaluated for LBLOCA scenario at APR1400 plant. Fig 3. shows the results of sensitivity analysis on PCT behavior of hot pin during LBLOCA. The results clearly reveal that the cooling performance was degraded with respect to the flow channel deformation as all the cases with deformation predicted higher heat up during reflood and corresponding delayed quenching behavior compared to the base case, which was simulated without the volume change model. In addition, it was revealed that the amount of heat up and the resulting quenching time increased proportional to the number of deformed fuel rods. As listed in Table I, except the cases for 100% and 80%, the case of 50% revealed the highest reflood PCT. For the cases of 100% and 80%, the simulation failed with channel blockage at the early stage of reflood period as depicted in Fig. 4. Therefore, further heat up calculation featured in the middle of reflood period could not be reflected.



(a) period (0~100s)



(b) period (0~220s)

Fig. 3. Sensitivity results – effect of channel deformation on PCT behavior of hot pin

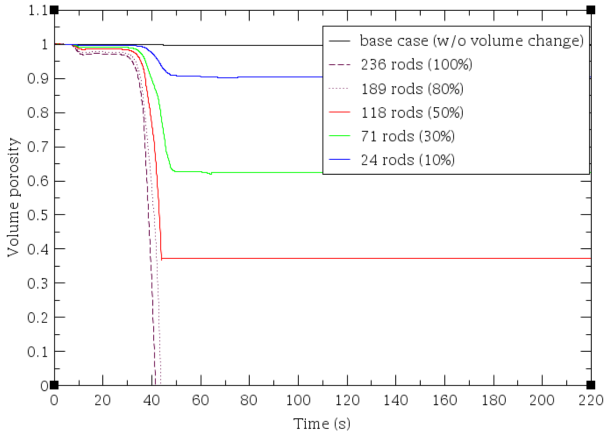


Fig. 4. Sensitivity results – rate change of volume porosity

Table I: Reflood PCT comparison

Cases	Reflood PCT (K)
Base case	1055.28
236 rods (100%)	1081.67
189 rods (80%)	1087.28
118 rods (50%)	1107.24
71 rods (30%)	1098.59
24 rods (10%)	1078.51

4. Conclusion

The consideration of flow channel deformation revealed great significance on the PCT behavior during LBLOCA, showing that the cooling performance was degraded with respect to the flow channel deformation, and therefore, higher heat up and corresponding delayed quenching behavior were predicted during the reflood. However, those results were obtained by simply scaling up the deformation results of single rod to have equivalent bundle-scale deformation. Therefore, as a future work, more realistic evaluation will be conducted by implementing the subchannel-scale subsection within the hot channel, which includes the hot pin and its surroundings, in order to evaluate the effects of flow channel deformation, realistically.

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