Application of MARS-FRAPTRAN Integrated Code to LBLOCA Analysis and Understanding of Fuel Rod Behavior

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1. Introduction

In preparation for the revision of the acceptance criteria for Emergency Core Cooling System (ECCS) performance, studies have been extensively conducted [1]. Since the basic direction of the revision is to impose new criteria on the limits of the cladding temperature, the cladding oxidation, etc. considering the fuel burnup [2], it is necessary to systematically consider the distribution of the fuel rod burnup in the reactor core that may be expected in the cycle operation of the actual nuclear power plants. And it is especially important to predict the fuel behavior under given burnup condition in detail. In this respect, Korea Institute of Nuclear Safety (KINS) has been developing an integrated code [3] that integrates the existing system thermal-hydraulic code, MARS-KS [4], and the US Nuclear Regulatory Commission (NRC) code for analyzing the behavior of fuel rods, FRAPTRAN [5].

To apply this MARS-FRAPTRAN integrated code to the Large Break Loss-of-Coolant Accident (LBLOCA) analysis of nuclear power plants, code validation using experimental data shall be carried out. Although each code has an accuracy appropriate for each purpose of use, the code integrating the two codes must be sufficiently validated as a new code. Validation of the integrated code is currently being conducted [6].

Apart from the code validation, a preliminary application of the integrated code to LBLOCA calculation of the actual plants can be helpful to improve the code robustness, provided that the problems that may arise at the actual LBLOCA calculation can be understood. Furthermore, preliminary calculations can contribute to supplementing and securing reliability of inputs for the integrated code. In the present study, the MARS-FRAPTRAN integrated code developed up to date is applied to the LBLOCA calculation of the APR1400 plant and its result compared to the results of MARS standalone code analysis. The present paper is also aimed to understand the reasons for the differences between two codes.

2. Code and Modeling

2.1 Code

In the present study, MARS_FRAPV191129sig was used, which was an integrated code of MARS-KS 1.4 and FRAPTRAN-2.0. The code can describe the thermal and mechanical behavior of pellet, gap, and cladding according to the burnup level, and has the capability to consider the thermal effect of crud and oxide layer. In the integrated code, the FRAPTRAN is embedded in the MARS-KS code, which is not the external coupling method.

2.2 Modeling

The calculation of the integrated code requires inputs of the MARS (both steady state and transient state) and FRAPTRAN. Initial fuel rod status which was varied according to the level of burnup can be obtained from FRAPCON analysis result. In the present study, the MARS input for the LBLOCA analysis of APR1400 is used, which was developed through a previous study [7]. In this input, the reactor core was modeled as two average and two hot hydraulic channels, and 32 fuel rods, including the average and the hot rods are allocated in those channels. Selection of the fuel rods is based on the fifth cycle design data. Details are described in Fig. 1.

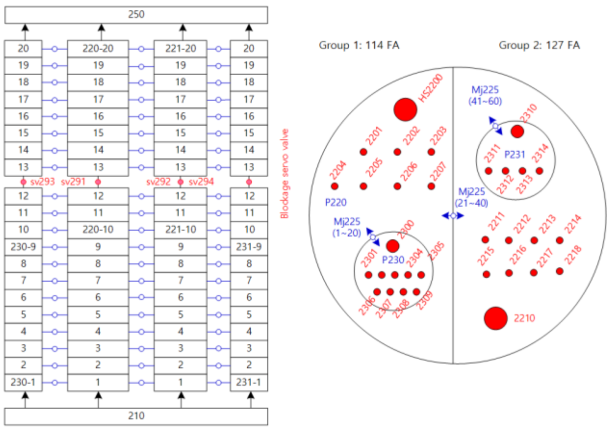

Fig. 1. Hydraulic channels and fuel rods

In this input, a dynamic model is implemented to determine the blockage of the core flow path by summing the magnitude of deformation of the fuel rods up. The deformation of the fuel rods is calculated by the swell and rupture model of the code and the number of fuel rods is taken into account. The calculated blockage is converted to the opening areas of the virtual valves in the core to dynamically adjust the area of the flow path.

However, calculating the channel flow area requires a multi-rods computing capability, and the current integrated code can calculate the behavior only for a single rod, so this could not be implemented at the current level.

For the execution of the integrated code, the data of the geometry and material properties of the fuel rods in the corresponding burnup conditions is needed. This information was provided by the analysis results of the FRAPCON code [8] for the PLUS7 fuel.

Inputs for the FRAPTRAN include a protocols of inputs/outputs, nodalization, geometric design data, rod power, boundary conditions, and uncertainty parameters. In the FRAPTRAN, fuel rod was discretized axially 20 nodes consistent to the MARS input, and divided into 25 meshes in radial direction. Basic deformation model, the gap pressure and conductance model, and the metal-water reaction model of the FRAPTRAN code are used. As a boundary condition, the rod power over time is come from the results of the MARS. The radial burnup and power distribution within pellet is come from the FRAPCON. The cladding temperature was determined from the iterative calculation with the coolant temperature and heat transfer coefficients of MARS. Fig.2 shows an overall calculation process.

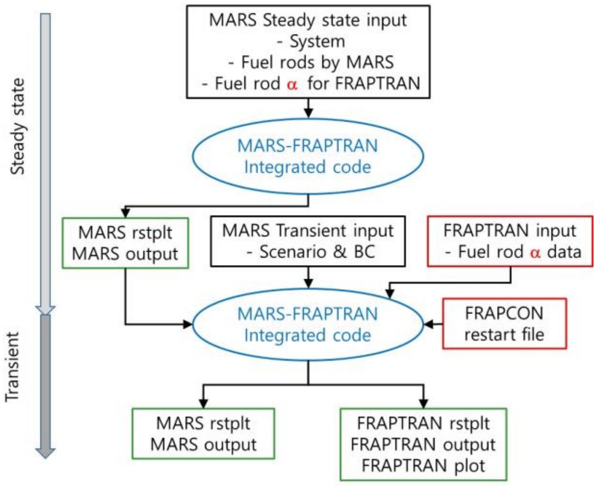

Fig. 2. Overall process for MARS-FRAPTRAN calculation

Meanwhile, the initial conditions of fuel rod before transient, such as the rod internal pressure and gap width used in the MARS standalone calculation, may differ from the results of the FRAPCON. Therefore, in order to apply the same initial conditions, MARS standalone calculation was re-conducted by reflecting the initial conditions from the FRAPCON result.

3. Result and Discussion

Calculations were performed on APR1400 LBLOCA using the codes and inputs described earlier. As described in the previous section, the calculation was performed and compared with the results of the MARS standalone.

Fig. 3 shows a comparison of cladding temperature evolution at the hottest spot of the hot rod between two codes. The average burnup of the rod was at 30 MWD/kg-U. As shown in the figure, the integrated code indicated a lower cladding temperature in both the blowdown and reflood periods than the MARS standalone. The difference in Peak Cladding Temperature (PCT) was about 88 K. This can also be found in the comparison of the fuel centerline temperature at this point (Fig. 4).

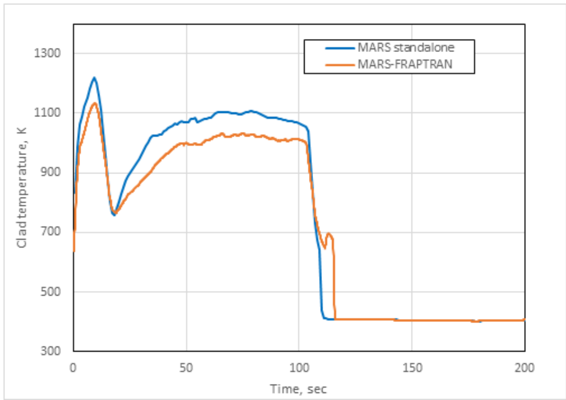

Fig. 3. Comparison of cladding temperatures

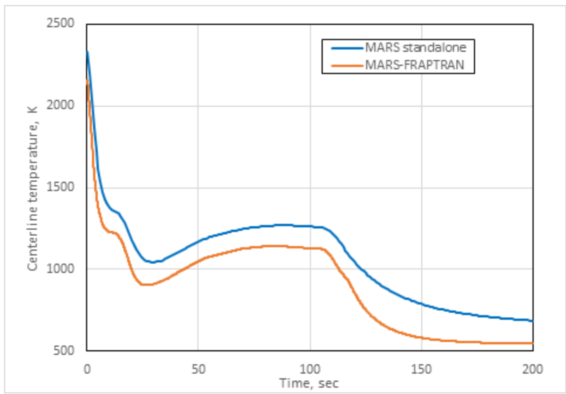

Fig. 4. Comparison of fuel centerline temperatures

Fig.5 shows a comparison of the collapsed water level of the hot channel. As shown in the figure, there is no difference in water level behavior between two calculations. It means that the reason for the cladding temperature difference must be due to the difference of model to predict the distribution of stored energy within the fuel rods between two codes.

There are many differences of models between the MARS code and the FRAPTRAN code, especially focusing on predicting the energy distribution in a pellet, such as pellet thermal conductivity and radial power profile, gap conductance, and cladding swell and rupture, etc.

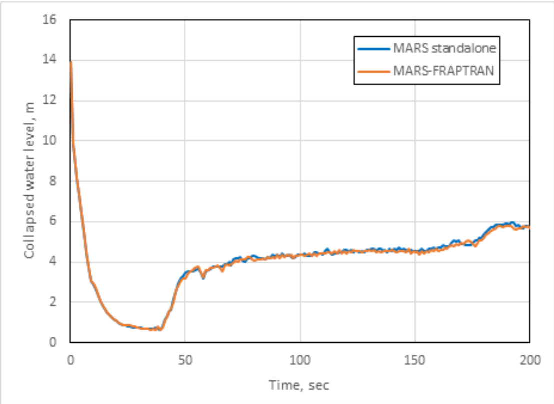

Fig. 5. Comparison of collapsed water level of hot channel

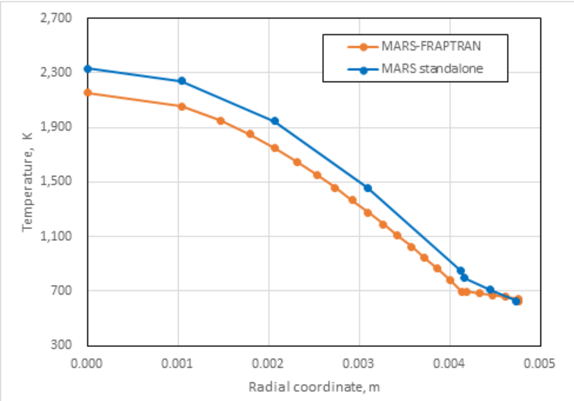

Fig. 6. Comparison of temperature distribution within the fuel at the beginning of transient

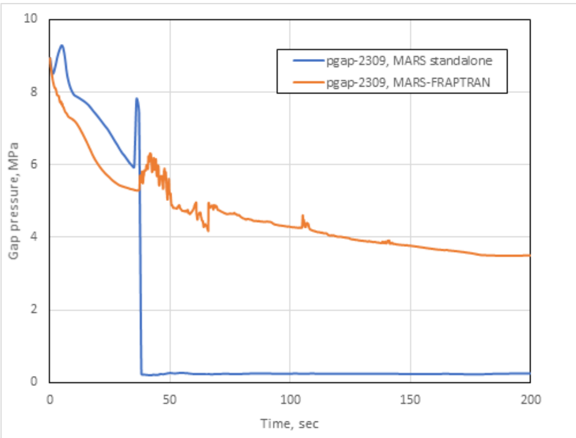

Fig. 7. Comparison of gap pressure

Fig. 6 shows a comparison of the radial temperature distribution in the fuel rod at the beginning of the transient between two cases. As shown in the figure, the fuel centerline temperature from the MARS standalone calculation was about 100 K higher than that from the integrated code calculation. This seems to be related to the prediction of temperature gradient in cladding and gap. The MARS standalone calculation showed higher cladding inner surface temperature than that of the integrated code. This indicates that the modeling used in the current MARS standalone calculation is more conservative than those of the integrated code, i.e. effective thermal conductivity of cladding considering the effects of oxidation layer, and the thermal conductance of gap. And the integrated code calculation considers the varying power and burnup level within a pellet. As high power and high burnup is attained near the periphery of the pellet, this may result in higher heat conduction from the pellet to coolant in a steady state.

Fig. 7 shows a comparison of the gap pressure calculated by two codes. As shown in the figure, the gap pressure from the MARS standalone was higher than the result of the integrated code for about 40 seconds. In addition, the MARS standalone results in a temporal pressure increase at the beginning, and a rapid decrease due to the rupture of the cladding at around 40 seconds. However, rupture was not predicted in the integrated code.

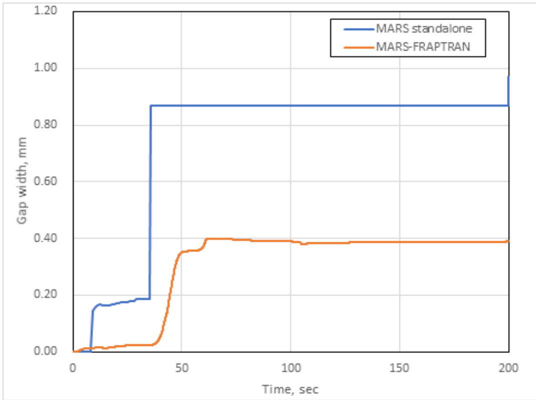

Fig. 8. Comparison of gap width

Fig. 8 shows a comparison of the gap width calculated by two codes. In MARS standalone calculation, the gap width was initially unchanged and then suddenly increased from 6 to 7 seconds. In the integrated code, the gap width increased slowly from the beginning, and then significantly increased when the ECCS water reached the core and the system pressure decreased. Thus, the initial gap pressure increase in the aforementioned MARS standalone calculation may be attributed to the gap width prediction, which is likely to be related to the cladding deformation model. Due to the difference of performance, the deformation of the cladding is deduced to have reached the rupture strain earlier than the integrated code.

4. Conclusions

1) Based on the analysis results so far, all FRAPTRAN models of the integrated code are shown to have

been programmed and used for calculations in accordance with the development purpose.

2) The behavior of the fuel rods predicted by the application of the integrated FRAPTRAN and MARS code is significantly different from the MARS-KS standalone code, especially in predicting the rupture of cladding. This difference appears to be due to the model and modeling methods between the two codes.
3) Based on the comparative study, conservative factors applied to the MARS standalone calculations, such as effective cladding thermal conductivity considering oxide layer, were identified. However, these differences do not have a significant effect on the behavior of the system's thermal-hydraulics. This may be because the FRAPTRAN model has been applied only to the single rod.
4) Comparative analysis also showed that the MARS-FRAPTRAN integrated code is more realistic than the existing MARS-KS code in view of cladding deformation. This requires further study of phenomena not well understood in MARS standalone calculations.

Acknowledgements

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