Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Preliminary study of sensitivity analysis for IFA-650.9 experiment with MERCURY fuel performance code

Hyochan Kim [a*], Changhwan Shin [a], Sung-Uk Lee [a], Donghwa Lee [a]
[a]*LWR Fuel Technology Research Division, KAERI, 111, Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, KOREA*
[*]*Corresponding author: hyochankim@kaeri.re.kr*

***Keywords :** MERCURY, IFA-650.9 Halden experiment, Sensitivity analysis, uncertainty parameters

1. Introduction

Analysis for the behavior of nuclear fuel during accident conditions in a nuclear reactor is being emphasized in terms of nuclear safety criteria and fuel rod degradation. During loss of coolant accident (LOCA), fuel cladding ballooning and burst occur because the temperature of the cladding and the rod internal pressure are raised due to a lack of heat removal by the coolant. [1]. To study fuel behavior during accident conditions, transient fuel performance codes have been developed. The U.S. NRC has developed FRAPTRAN code and FAST code which is merged with FRAPCON code [2, 3]. It has a limitation to simulate multidimensional behaviors such as clad ballooning and burst. To overcome the limitations of the simulation dimension, BISON, which is a U.S.-derived fuel performance code based on the finite element method (FEM), was developed to simulate multidimensional fuel behavior during normal and off-normal conditions [4]. KAERI has developed a multidimensional entire fuel rod analysis module (MERCURY) based on the FEM to simulate multidimensional fuel behavior during accident conditions. [5].

Techniques for evaluating the sensitivity and uncertainty analysis in the results of physical experiments have been applied to the field of computational analysis. In the safety analysis of nuclear reactors, the USNRC has presented a method of uncertainty quantification in the optimal analysis through CSAU (Code Scalability, Applicability, Uncertainty), and the procedure for the entire process of evaluating the uncertainty of the code is presented through EMDAP [6]. Sensitivity analysis in nuclear safety refers to a systematic evaluation of how changes in input parameters or assumptions affect the output of nuclear safety assessments or models. In the context of nuclear safety, sensitivity analysis helps identify which parameters or assumptions have the most significant impact on safety-related outcomes.

In this study, sensitivity analysis(SA) is performed to evaluate the appropriateness of the evaluation model and derive the main factors against figure of merits. As it is necessary to introduce a technique for quantifying such uncertainty in the MERCURY code, the uncertainty parameter was applied as a separate variable for each major factor in the code development phase. A sensitivity analysis of MERCURY prior to uncertainty analysis was performed in terms of the figure of merits (e.g. rod internal pressure, fuel centerline temperature etc.). IFA-650.9, which is one of the IFA-650 series [7], which is the LOCA simulation test of the Halden Research Reactor for in-pile test data was applied

2. MERCURY fuel performance code

Fig. 1 depicts an overview of MERCURY code and models to simulate fuel behaviors. At the beginning of the MERCURY, an input file reading and initial values setting were established for further calculation. In terms of input files, the fuel information file and the mesh information file were separated. The fuel information file included fuel geometry, power history, boundary conditions, and model options. The mesh information included element number, node number, and connectivity. Output files were also separated into fuel performance results and FEM results. To facilitate the review of the FEM results, the FEM results could be read by PARAVIEW [8], while the fuel performance results could be read by a text viewer.

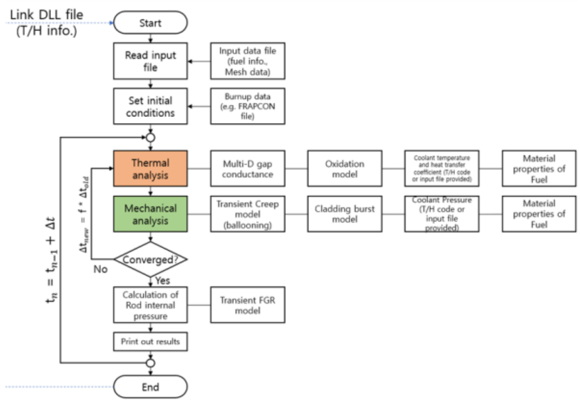

Fig. 1. Flow Chart of MERCURY fuel performance code

The MERCURY incorporated a transient thermal analysis model, a multidimensional gap conductance model, a nonlinear mechanical model, and a transient creep model as thermomechanical models. To reflect the material properties of cladding and pellets regarding burnup, the result of the fuel performance code for steady-state should be stored before calculation begins. The MERCURY can read the result file calculated by

FRAPCON. MERCURY employs an implicit scheme to converge thermal condition and mechanical conditions that are strongly coupled to the gap conductance model. Additionally, MERCURY has the linked module ((Dynamic Link Library(DLL) format) with MARS-KS code which is regulatory safety analysis code in KOREA.

3. IFA-650.9 experiment and modelling

A high burnup (89.9 MWd/kgU) PWR fuel rod was used in the IFA-650.9. The length of the fuel stack was ~ 480 mm and no end pellets were inserted. The rod was filled with a gas mixture of 95 % argon and 5 % helium at 40 bars at room temperature as a refabrication process. The rod plenum volume (free gas volume) was made relatively large in order to maintain stable pressure conditions until cladding burst. The total free gas volume of ~19 cm3 was thus practically all located in the plenum, outside the heated region. Therefore, plenum temperature calculated can be differed from practical plenum temperature which significantly affects rod internal pressure. Unlike typical PWR fuel, the IFA-650.9 cladding consists of duplex cladding, i.e. double-layered cladding. Due to the duplex cladding, even high burned cladding, the amount of hydrogen content and the thickness of oxidation layer are significantly lower than those of typical fuel cladding.

The rod was located in the center of the rig and surrounded by an electrical heater inside the flask. The heater is part of a flow separator, which divides the space into a central channel surrounding the fuel rod, and an outer annulus. The heater is slightly longer than the fuel length, ~518 mm, and it is used for simulating the isothermal boundary conditions, i.e. heat from the adjacent fuel rods during a LOCA. Cladding temperature is influenced by both rod and heater powers.

To build model of IFA-650.9 for MERCURY code, the finite element mesh model is required. As shown in Figure 2, mesh geometry is composed of 2126 nodes and 576 elements for two volumes of the fuel pellet and cladding. In the analysis model, the axial length of the fuel is 480 mm, and the outer diameter and thickness of the cladding are 10.75 mm and 0.725 mm respectively. The gap thickness of specimen for IFA-650.9 is 0.085 mm which was refabricated before the transient test. The displacement in the axial direction was fixed as a boundary condition for the mechanical analysis. For thermal conditions, heat generation as function of time is imposed to pellet and can be transferred through gap. The equivalent heat transfer coefficient and coolant temperature provided from IAEA CRP FUMAC [9] are imposed on the cladding surface. The plenum is not practically modelled. The plenum temperature and plenum void volume are used as input values to calculate the rod internal pressure. The internal pressure of the fuel rod, which is significant factor, is determined by the free volume, the temperature and the composition of the gases in the fuel rod. In the experiment, much of the free volume is outside of the rig to measure rod internal pressure. Therefore, assuming the temperature of the plenum gas from the temperature of the cladding can lead to large errors. In the previous research [10], the comparison of the results of the case where the internal pressure was calculated using the default option of the MERCURY code, which is to add 5.6 K to the cladding surface temperature and the case where the measured internal pressure was applied.

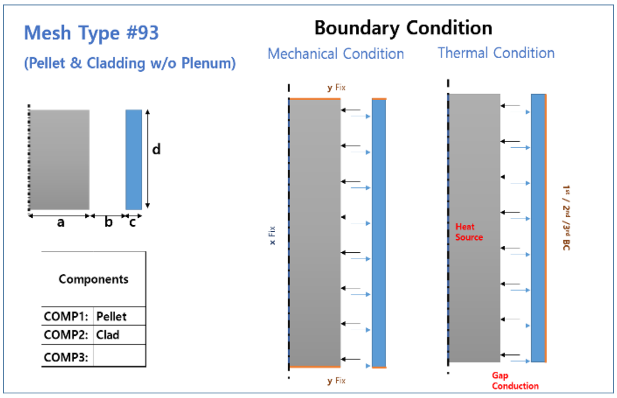

Fig. 2. MERCURY model and boundary conditions

4. Sensitivity analysis result

Figure 3 shows the sequence of steps for sensitivity analysis with MERCURY code. The followings describe each step meaning.

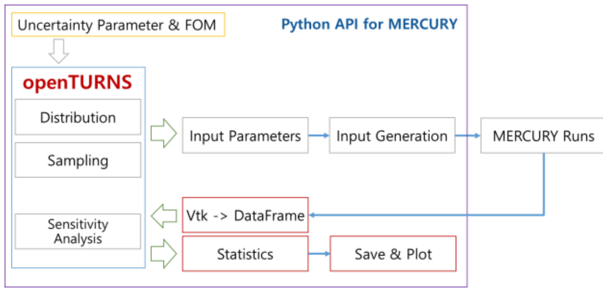

Fig. 3. Procedure of sensitivity analysis with MERCURY

1) Determine the uncertainty parameters and figure of merits (FOMs).

2) Specify the range and distribution of the uncertainty parameters and use the sampling tools in OpenTURNS to produce the desired values.

3) Apply the defined values to create case-specific inputs, such as FRAPCON inputs for normal operation analysis and MERCURY inputs for accident scenario analysis, using the same values for parameters that are applied simultaneously.

4) Calculate FRAPCON and then MERCURY for all cases using the created inputs.

5) Create a data structure to store the calculation results for each case, either by time or by case. In

particular, vtk format generated by MERCURY has been analyzed as function of time.

6) Perform sensitivity analysis using the data produced.

7) Produce charts and sheets to summarize the results.

As MERCURY calculates the results of each element of the FEM, a large amount of results is accumulated for each time step. Therefore, it is necessary to process large amounts of data depending on the scenario. To automate a series of processes with massive data, a Python API was employed.

Figure 4 shows a heatmap of the fuel centerline temperature (TFC). The coolant temperature is one of the main factors for the fuel centerline as the coolant is the main heat sink in this experiment. The thermal properties of the pellet and the gap conductance have a significant effect on fuel centerline temperature. Interestingly, the correlation of these changes from positive to negative during the certain duration of the event. This can be explained as follows; when the blowdown occurs, the stored energy is released to the coolant. Therefore, TFC becomes lower with the higher thermal conductivity and with lower heat capacity and higher gap conductivity. Conversely, as the stored energy disappears, the TFC become higher because the heat comes from the shroud heaters.

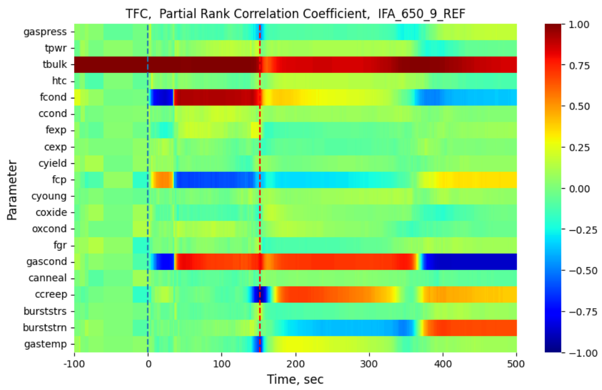

Fig. 4. Heatmap of fuel centerline temperature for IFA-650.9 with MERCURY

5. Conclusions

In this work, preliminary SA of MERCURY for IFA-650.9 were performed to validate the code predictability and feasibility of the code capability. To perform the SA, MERCURY model for IFA650.9 was generated. The calculated thermal hydraulic conditions which are significant for the simulation were imposed. However, multiple coolant temperatures and multiple heat transfer coefficients cannot be considered in the fuel calculation. Instead of multiple variables, equivalent coolant temperature and heat transfer coefficient are applied. For the sensitivity analysis of MERCURY code, procedure was set up. To treat massive results from MERCURY code, Python API package was used. The uncertainty parameters and ranges for fuel rod were defined according to previous works. In the case of fuel centerline temperature among figure of merits, the major parameters are the thermal properties of the pellet and the gap conductance. The trend of the correlation in TFC changes when the heat flux direction is changed. For the future work, the fully coupled T/H and fuel code is required to improve the predictability of fuel behavior as well as T/H behavior.

Acknowledgements

The preparation of this paper was supported by the Ministry of Science and ICT, Republic of Korea (RS-2022-00144002)

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