Development of heat transfer model of oxide layer and deformation restriction model in MERCURY code

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1. Introduction

In nuclear reactors such as Light Water Reactors (LWR), fuel rods consist of a pellet and a cladding tube. It is the cladding that actually prevents the leakage of radioactive material, and also serves to transfer the heat generated by the pellet to the external coolant. In an accident scenario such as a loss of coolant accident (LOCA), it is important to contain the radioactive material and prevent it from progressing to a serious accident. In order to understand various phenomena under LOCA, many studies have been conducted using fuel performance codes over several decades. In recent years, there has been a growing interest in developing higher fidelity analysis tools with multidimensional, multi-physics, and multiscale capabilities. The nuclear fuel performance code with finite element (FE) method is being developed with high fidelity analysis, out of the existing correlation equation or conventional FDM.

MERCURY is a finite element-based nuclear fuel analysis code that has been under development at KAERI since 2017[1]. In this paper, new models that take into account thermal barrier by outer oxide layer and deformation restriction due to neighbor fuel rod are developed to describe the practical behavior of irradiated nuclear fuel in the reactor. To evaluate the developed models, MERCURY incorporating new models simulates fuel behavior during accident conditions.

2. Developed models of MERCURY for fuel rod calculation

During normal operation condition, an oxide layer that corrosion induces is generated on the outside of the cladding, and this oxide layer acts as a thermal resistance. In the view of fuel assembly that a lots of fuel rods are assembled, the deformation of cladding is limited due to the nearby fuel rod when ballooning occurs. In order to take into account these phenomena in MERCURY code, new models for calculating heat transfer through outer oxide layer and a deformation restriction model were developed.

2.1. Thermal model for outer oxide layer.

The temperature of the cladding might rise more than the surface temperature because the heat transfer to the outside was restricted by the oxide layer, which was generated during the steady-state operating condition and accident condition. The rising temperature of cladding is a major point to analyze the deformation in the event of the LOCA. Under the assumption that the oxide layer did not act as a load bearing for the cladding and only affects heat transfer, a model was developed to perform the analysis considering the oxide layer in the thermal analysis process as shown in Figure 1. Through this model, heat transfer analysis was performed efficiently considering the oxide layer in the FEM code.

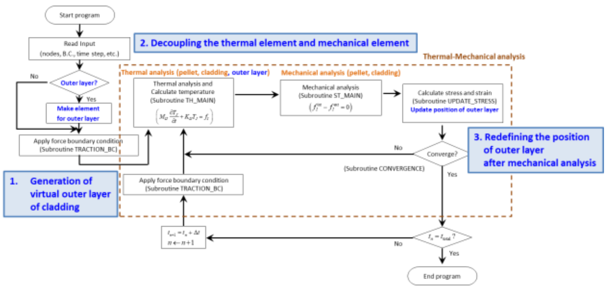


Fig. 1 The flow chart of MERCURY code considering the outer oxide layer.

2.2. Deformation restriction model.

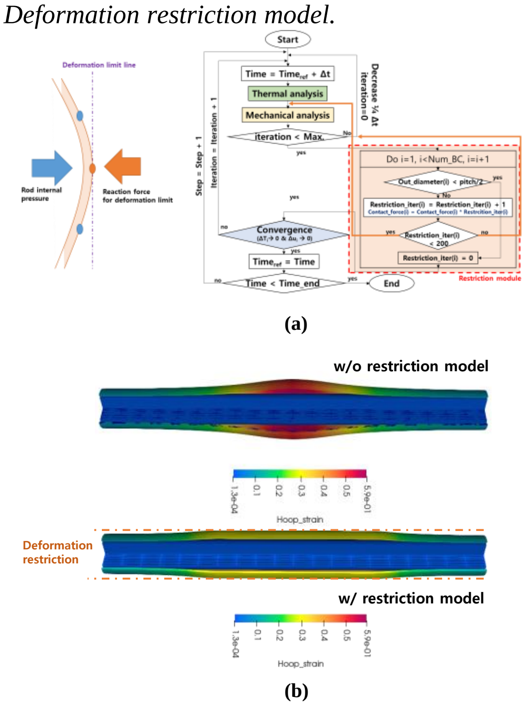


Fig. 2 The deformation restriction model for MERCURY code. ; (a) Algorithm of restriction model and (b) Analysis results according to the model application.

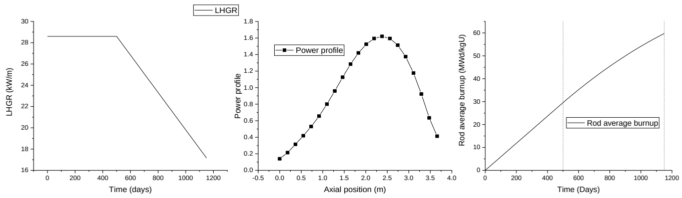
Since the fuel rod is composed of a bundle of rods, the deformation of rod is limited by the surrounding fuel rods. In order to describe this behavior, a model was developed in a way that limits the deformation by applying a virtual force in the opposite direction when the amount of deformation was exceeded as shown in Figure 2. Because the current MERCURY code evaluates a single fuel rod, it does not reflect the various contact conditions that occur in the fuel assembly. It only considers the pitch between the fuel rods to limit the deformation.

3. Evaluation of new model with accident condition

The entire fuel rod analysis was performed with conservative input conditions using the updated MERCURY code. To simulate fuel behavior for accident condition, FAMILY code calculates boundary conditions and loading conditions for MERCURY.

3.1. Steady-state fuel analysis

Because MERCURY is transient fuel analysis code under accident condition, fuel performance information during steady-state calculated by FRAPCON4.0P1 is required.[2] A FRAPCON input deck was made assuming a conservative heat generation condition as shown in Figure 3. The simulation was performed up to 60 MWd/kgU fuel burnup, and the amount of deformation and irradiated results through FRAPCON analysis were used as initial conditions of MERCURY and FAMILY.



(a) (b) (c)

Fig. 3 FRAPCON input data and analysis result ;
(a) Linear power, (b) Axial power profile,
and (c) Average burn-up

3.2. Generation of boundary conditions by FAMILY code

To calculate fuel behavior for accident condition, MERCURY needs boundary conditions and loading conditions. Boundary conditions are cladding surface temperature for each elevation along time. Loading conditions are coolant pressure, power and rod internal pressure along time. To obtain practical conditions for evaluation, calculation result of FAMILY code was employed. KINS has been developing a fully integrated computer code between fuel performance and system TH code, named as FAMILY(FRAPTRAN And MARS-KS Integrated for Safety AnaLYsis), can evaluate the TH behaviors and their uncertainties completely [3]. To take into account fuel burnup effects, initial conditions are set with FRAPCON output files. In addition, option in input file for MARS-KS is activated. Accident scenario for reactor was chosen. Figure 4(a) shows LHGRs as function of burnup. Figure 4(b) and (c) represent axial power shape and rod internal pressure along time, respectively. Figure 4(d), (c) and (f) shows cladding surface temperature of each axial node along time. Since initial conditions of FAMILY input files consider burnup effects of fuel, surface temperature profiles are distinguished.

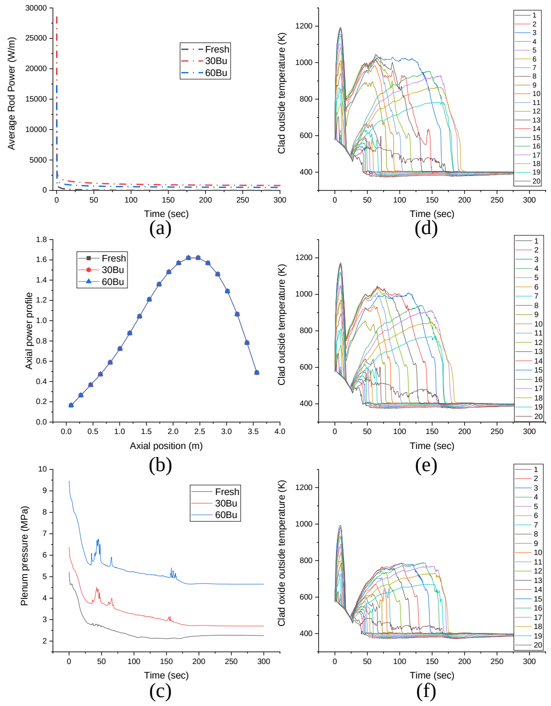


Fig. 4 MARS-KS/FRAPTRAN analysis results ; (a) Linear power, (b) Axial power profile, (c) Rod internal pressure, and Cladding outer temperatures (d) Fresh, (e) 30MWd/kgU, (f) 60 30MWd/kgU

3.3. Simulation result

Figure 5 shows the axial temperature distribution and deformation shape as a result of MERCURY analysis. In the case of 60MWd/kgU burnup, as the cladding boundary temperature condition is formed as low as 1000K or less, the amount of deformation is small even at a relatively high internal pressure. In terms of deformation, the simulation results for fresh and 30 MWd/kgU were used for comparative analysis. In case of 30 MWd/kgU burnup, the outer temperature of the zircaloy layer was expressed higher than the given cladding boundary temperature (Oxide outer temperature) due to the oxide layer effect. In all analysis, the cladding deformation was smaller than the bundle pitch limit, so the deformation restriction model was not activated. It is demonstrated that thermal barrier effect is simulated due to outer oxide for all cases.

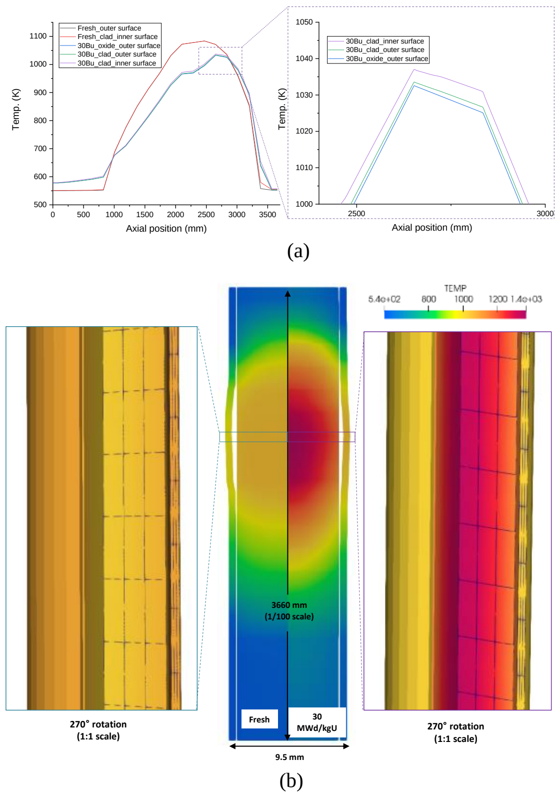


Fig. 5 MERCURY results ; (a) Temperature distribution according to axial direction and (b) Temperature contours of fuel rod (Axial 1/100 scale for visualization)

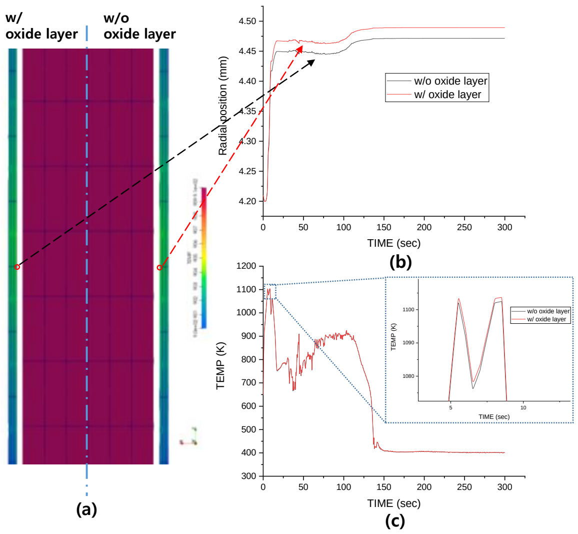


Fig. 5 MERCURY results in case of 30MWd/kgU ;
(a) Temperature distribution (100 sec), (b) Radial position of inner cladding surface and (c) Temperature of inner cladding surface

As shown in Figure 6, it can be seen that the internal temperature is different due to the oxide layer barrier under the same analysis conditions. Since temperature affects the deformation of the cladding, the amount of deformation increases as the cladding temperature is increased by the oxide layer.

4. Conclusions

The heat transfer model for outer oxide layer and deformation restriction model were developed in order to describe the actual nuclear fuel behavior. The developed model was evaluated through simulation of accident condition. FAMILY code provides boundary conditions and loading conditions for MERCURY. In the entire fuel rod analysis, the temperature calculation by the oxide layer was expressed, but the deformation limitation due to the bundle pitch was not shown due to the input condition that did not induce large deformation.

For the future work, MERCURY simulates practical fuel behavior incorporating practical fuel models in the reactor with various accident scenarios.

ACKNOWLEDGEMENTS

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