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Axisymmetric Finite Element Analysis Code for Predicting Cladding Large Deformation at High Temperature and Its Validation

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1. Introduction

During the loss of coolant accident (LOCA), the cladding temperature increases due to the loss of the cooling water and the cladding is pressurized by internal gas. As a consequence, it undergoes large deformation due to the high temperature creep and finally bursts (ballooning and burst). Hence, it is necessary to analyze the cladding large deformation for the safety analysis and design of emergency core cooling system. To analyze the deformation of the cladding, several thermal-mechanical fuel analysis codes were developed. FRAPTRAN [1] is one of the widely used fuel analysis code and calculates the cladding deformation according to the thermal-hydraulic condition and burnup histories. However, the FRAPTRAN uses one dimensional assumption along the cladding's axial position. This assumption could lead to less accurate solution for the large deformation because 1-D assumption with several nodes might be difficult to predict the characteristics such as ballooned shape. In order to overcome this issue, in this study, an axisymmetric analysis code based on coupled thermal-mechanical finite element method (FEM) was developed to fully analyze the large deformation, and to reflect core characteristics of the nuclear fuel which are gap heat transfer and creep deformation. As a code validation, an out-of-pile test was used to investigate the cladding large deformation at high temperature and the simulation was compared with the test results.

2. Methods and Results

2.1 FE code structure

The developed code was based on the coupled thermal-mechanical finite element method. Firstly the code calculates the temperature of structures. Next, the displacement, strain, and stress are calculated. For the strain field, it was assumed that the total strain is additively decomposed into elastic and creep (inelastic) part, which is given in equation (1).

$$\varepsilon = \varepsilon^{\mathrm{el}} + \varepsilon^{\mathrm{cr}} \tag{1}$$

After the strain and the stress are obtained, continues to the next time step and perform the same procedure.

2.2 Gap Heat Transfer Model

Because the cladding temperature increases due to the heat transfer through the gap between the pellet and the cladding, it is necessary to model the gap heat transfer through gap conductance model. The present study used Ross and Stoute model [2], which is given in equation (2), as the gap conductance model.

$$h_{\mathrm{gap}} = k_{\mathrm{gas,He}} / \left(\Delta x + g + \Delta R\right) \tag{2}$$

where $k_{\mathrm{gas,He}}$, Δx, g, and ΔR are the gas conductivity of the internal helium gas, distance between the pellet and the cladding surface, temperature jump distance, and surface roughness of the pellet and the cladding, respectively. In the present study, zero of the temperature jump distance was assumed and the surface roughness was neglected. The helium gas conductivity, given in equation (3), was used by referring TRAFR code which was introduced in Yadav et al [3].

$$\begin{aligned} k_{\mathrm{gas,He}} &= 0.0476 + 0.362\times10^{-3}T - 0.618\times10^{-7}T^2 \\ &\quad +0.718\times10^{-11}T^3 \ \left[\mathrm{W/m\cdot K}\right] \ (T \text{ in Kelvin}) \end{aligned} \tag{3}$$

2.3 Creep Model

In order to simulate the large deformation (ballooning) of the cladding due to the creep, the following power law-Arrhenius equation was implemented in the developed FE code.

$$\dot{\varepsilon}^{\mathrm{cr}} = A\exp\left(-Q / RT\right)\bar{\sigma}^n \tag{4}$$

In equation (4), $\bar{\sigma}$ is an effective stress, R is the gas constant ($R = 8.314\ \mathrm{J/mol\cdot K}$). Coefficients A , Q , and n were taken from the Rosinger [4] with the assumption of isotropic material.

2.4. Experimental procedure

In order to validate the developed code, an out-of-pile test equipment introduced in Yadav et al. [3] was used. The objective of this equipment is to observe the large deformation of the cladding at high temperature by increasing the cladding temperature for a given internal pressure. The main parts of this equipment are an internal heater, pellets (which have annular section and are in contact with the heater), and a Zircaloy-4 cladding. The remaining parts are molybdenum rods for insulation in axial direction of the heater, other pellets which are in contact with the molybdenum rods. In the present study, the cladding was pressurized up to 5 MPa and initial temperature was set to 573.15K

2.5. Simulation of the experiment and its result

For the code validation, a simulation of the out-of-pile test which was previously described was performed. Because the experimental result showed that most of the cladding deformation occurred near the heating zone and rapidly decreased as far away from the heating zone, only the region near the heating zone was modeled. For the Zircaloy-4 properties, material properties in MATPRO [5] were used with assuming fresh material. In addition, the main focus of the present study was to predict the cladding large deformation according to the temperature and it was difficult to obtain the exact value of the heat generation of the heater. Hence, in numerical model, the heater and the pellet were unified as one pellet and the heat generation value was adjusted so that the cladding temperature is similar to the experimental result. And also, it was assumed that the heat generation follows quadratic distribution along its axial position. From the above assumption and adjustment, the heat generation value at the center and the both ends of the pellet were set to $37.5\,\mathrm{mW/mm^3}$ and $18.75\,\mathrm{mW/mm^3}$, respectively, and the area between the center and the both ends were interpolated with a quadratic function. Figure 1 shows the deformed shape of the cladding and temperature field, and Figure 2 shows the temperature and the maximum principal strain histories at the center of the cladding of the simulation and experiment, respectively. It was found that the ballooning behavior was well captured and the temperature and the maximum principal strain history of the simulation were similar to the experimental result. However, after 160 seconds, the difference in strain between the simulation and experiment becomes larger. This could be the result of the creep model coefficients used in this study. Hence, it might be guessed that the coefficients in Rosinger [4] could be inappropriate to our material in the experiment. Thus, it would be expected that the result could be more close to the experiment if proper coefficients are obtained.

3. Conclusions

In present study, an axisymmetric analysis code based on coupled thermal-mechanical finite element method was developed. The gap conductance and creep deformation model were implemented to simulate the gap heat transfer and the cladding large deformation at high temperature. The developed code was validated with the out-of-pile test system and the results showed that the ballooned shape of the cladding and the temperature according to the gap heat transfer were well predicted. The difference of strain after some moment could be due to the creep coefficients for the material, so that this could be further improved if the proper coefficients are obtained through other experiments.

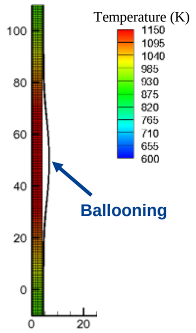

Fig. 1. Deformed shape of the cladding and temperature field of the pellet and the cladding.

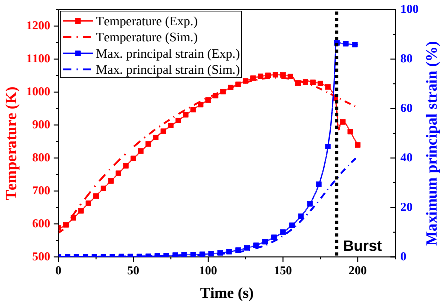

Fig. 2. Temperature and maximum principal strain histories of simulation and experiment.

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