Development of 3D FE module for fuel rod considering gap model

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1. Introduction

The heat and force from pellets as they affect the cladding is an essential element in typical nuclear fuel performance modeling. Traditionally, these assessments are done using a one-dimension or axisymmetric model. However, the applicability and accuracy of these models can be limited. In order to overcome this drawback, 3D FE models were developed recently. ALCYONE [1] and BISON [2] are well-known 3D performance codes which are used for each surface element of an outer pellet and the inner cladding. This paper introduces finite simple element algorithms for the transfer of the heat and force considering the degree of gap conductance using a 3D gap element.

2. Nuclear fuel rod simulation with the gap elements

2.1 Ross-Stoute Model

Gap conductance between a pellet and cladding was introduced by A.M. Ross and R. L. Stoute [3] in 1962. It consists of three components, as shown in equation (1).

$$h_{gap} = h_{gas} + h_{solid} + h_{radiation} \quad (1)$$

The three components are the gas conductance (h_{gas}), the solid conductance (h_{solid}), and the radiation conductance ($h_{radiation}$). The gas conductance is the thermal resistance between the pellet and the cladding caused by the filling gas, especially helium (He). Before contact between the pellet and its cladding tube, the gas conductance in the gap conductance is an important factor.

$$h_{gas} = \frac{k_g(T_g)}{d_g + C_r(r_1 + r_2) + g_1 + g_2} \quad (2)$$

Here, k_g is the conductivity of the gas in the gap model, d_g is the gap width (computed in the mechanics solution), C_r is a roughness coefficient with r_1 and r_2 the roughness levels of the two surfaces, and g_1 and g_2 are jump distances at the two surfaces.

2.2 Gap element

Generally, gap elements are two-node elements formulated in a three-dimensional space. The element is used to determine the contact force between two parts mainly under a load. Unlike mechanical approaches, Kim [4] used an adaptively linked gap element to consider thermal transfer in a fuel rod gap model. For the gap element, a node-node connection, heat transfer occurs only from one node of a surface to one node of a counter surface. There is a limit when describing the actual behavior during the heat transfer process. By using 3D FE model, the gap model can resolve the multidimensional gap conductance issue and represent the accuracy deformation behavior of a fuel rod. In this paper, a 3D gap element with gap conductance is used.

2.3 FE Model

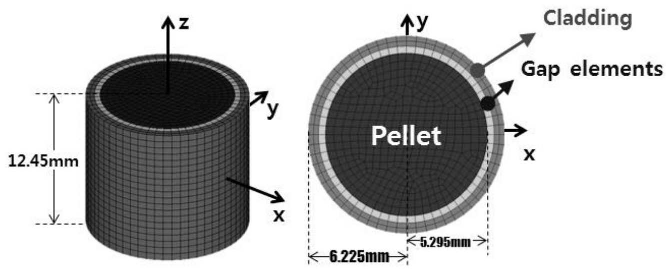

Fig. 1. Formation of gap elements between a pellet and its cladding

A finite element simulation module was developed to simulate a nuclear fuel rod considering the change of the gap conductance due to gap variations using 3D gap elements(8-node hexahedron). The model of the finite element simulation module is shown in Fig. 1.

Nuclear fuel has a tendency to undergo the initiation of radial cracks upon the initial radiation of a nuclear fuel rod. The most frequently occurring crack pattern is a radial crack pattern of eight pieces. For this reason, many studies have simulated nuclear fuel rods with radial cracks eight sections. In this study, a 1/32 model was simulated to reduce the computation time (nuclear fuel: 380 elements and 580 nodes, cladding tube: 240 elements and 396 nodes).

2.4 Simulation of a nuclear fuel rod with a radial crack

The simulation was performed while increasing the linear power rate of the nuclear fuel rod. The simulation tool is Intel Parallel studio XE with the format FORTRAN 90 and the post-processor is PARAVIEW[5], an open-source program.

The simulated results are shown in Figure 2. They show that an increase of the linear power rate causes an increase of the temperature. The temperature difference between the centerline temperature and the temperature of the outer surface of the pellet increases as the linear power rate increases. At a linear power rate of 20kW/m, for example, the temperature difference is almost 400K.

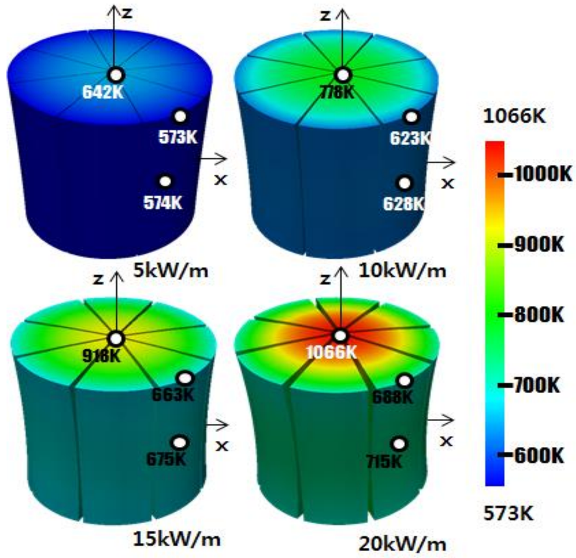

Fig. 2. Temperature distribution of nuclear fuel with respect to the linear power rate

This occurs because the thermal conductivity of the pellet is low (3~5mW/mm·K). The temperature at the top of the outer surface is lower than the temperature at the middle of the outer surface. The radial displacement at the top of the pellet caused by thermal expansion is larger than the radial displacement at the middle of the pellet owing to the "bamboo effect" of the nuclear fuel. For this reason, the gap distance at the top of the fuel is smaller than the gap distance at the middle part of the fuel. The temperature difference at the top of the outer surface of the pellet and in the middle of the outer surface of the pellet is 27K when the linear power rate is 20kW/m.

For verification, the simulated results are compared to experimental values [6]. Figure 3 illustrates the experimental results and the FE simulation results. As shown in Fig. 3, the simulation result with the gap elements is located between the upper limit and the lower limit of the experimental values. The results without a gap element, however, are a slightly higher than the upper limit of the experiments.

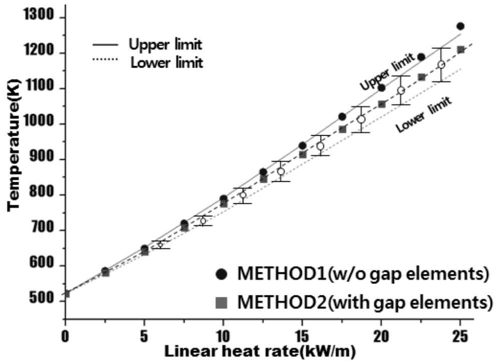

Fig. 3. Comparison of the centerline temperature with and without a gap element at a linear power rate (filling gas: He)

3. Conclusions

A finite element simulation module considering the gap variation with 3D gap elements was developed and simulated. When the simulation is performed with the gap elements, the gap variation caused by the bamboo effect is considered. In a comparison, the FE results and experimental results were similar. A heat transfer code using a gap element has been shown to be a powerful approach.

Further works should include the contact between the pellet and the cladding. The contact between two bodies is a critical phenomenon, especially with regard to the cladding.

Acknowledgement

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