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Simulation of Missing Pellet Surface thermal behavior with 3D dynamic gap element

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1. Introduction

A light water reactor (LWR) fuel rod consists of zirconium alloy cladding and uranium dioxide pellets, with a slight gap between them. Therefore, the mechanical integrity of zirconium alloy cladding is one of the most critical issues in terms of safety because it is an important barrier for fission products released into the environment. To evaluate the stress and strain of the cladding during operation, fuel performance codes have simulated thermo-mechanical behavior of LWR fuel since the 1970s.

A LWR fuel performance code should incorporate thermo-mechanical model owing to the existence of the fuel-cladding gap. Generally, the gap that is filled with helium gas before burning results in temperature drop along radius direction. The gap conductance that determines temperature gradient between pellet and cladding can be quite sensitive to gap thickness.

Most of the fuel performance codes that are able to simulate a multidimensional analysis are used to calculate the radial temperature distribution and perform a multidimensional mechanical analysis based on a one-dimensional (1D) temperature result. The FRAPCON-FRAPTRAN code system incorporates a 1D thermal module and two-dimensional (2D) mechanical module when FEM option is activated [1]. In this method, the multidimensional gap conductance model is not required because one-dimensional thermal analysis is carried out. On the other hand, a gap conductance model for a multi-dimension should be developed in the code to perform a multidimensional thermal analysis. ALCYONE developed by CEA introduces an equivalent heat convection coefficient that represents the multidimensional gap conductance [2]. However, the code does not employ dynamic gap conductance which is a function of gap thickness and gap characteristics in direct. The BISON code, which has been developed by INL (Idaho National Laboratory), employed a thermo-mechanical contact method that is specifically designed for tightly-coupled implicit solutions that employ Jacobian-free solution methods [3]. Owing to tightly-coupled implicit solutions, the BISON code solves gap conductance and gap thickness simultaneously with given boundary conditions. On the commercial finite element package (ANSYS), thermo-mechanical simulation in 2D and 3D states can be carried out with a thermal contact coefficient (TCC), which is not varied as a function of the gap thickness [4]. The gap conductance model for multi-dimension is difficult issue in terms of convergence and nonlinearity because gap conductance is function of gap thickness which depends on mechanical analysis at each iteration step.

In this paper, 3D dynamic gap element has been proposed to resolve convergence issue and nonlinear characteristic of multidimensional gap conductance. To evaluate 3D dynamic gap element module, 3D thermo-mechanical module using FORTRAN77 has been implemented incorporating 3D dynamic gap element. To demonstrate effect of 3D dynamic gap element, thermal behavior of missing pellet surface (MPS) has been simulated by the developed module.

2. 3D gap conductance model

The 3D thermo-mechanical module was implemented to calculate the temperature of the fuel and the cladding considering 3D dynamic gap element. The flow chart of the developed module is shown in Figure 1.

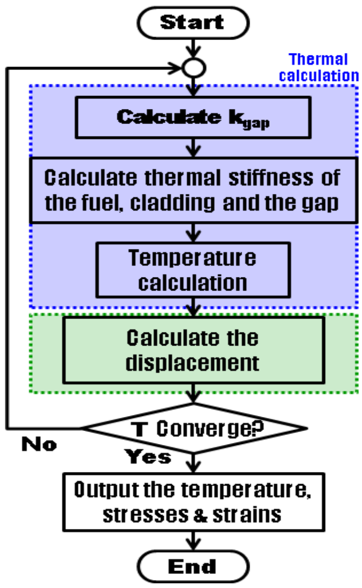

Fig. 1. Flowchart of 3D thermo-mechanical calculation

The algorithm for 3D dynamic gap element is described as follows; when calculation of thermal deformation by mechanical module ends, 3D gap element was generated with the node on pellet surface and the faced node. The equivalent thermal conductivities of the gap elements are calculated based on the gap sizes of each gap element. After that, the global stiffness matrix and the heat flux vector are calculated. The gap elements also are added into the components of the global stiffness matrix. When the constructed the matrix equation is resolved by skyline method, the temperatures of nodes can be obtained. Based on temperature results, thermal deformation can be recalculated. The iterative procedure between thermal calculation and mechanical calculation is carried out until the convergence is achieved.

To implement the 3D thermo-mechanical module incorporating 3D dynamic gap element, FORTRAN77 (IntelFORTRAN 2011 complier) was employed in WINDOW system.

3. Evaluation of the model

Missing pellet surface (MPS) is one of pellet imperfection issues. Since MPS geometry is asymmetric, 3D thermo-mechanical analysis should be required to simulate its behavior [5]. In particular, gap shape and size in the MPS model is various while gap shape of typical fuel is uniform. The MPS can be modeled with 1/4 model as shown in Figure 2. The elements are 8-node hexahedral elements. The pellet consists of 1090 elements and 1496 nodes. The cladding consists of 600 elements and 1023 nodes. The 382 mW per unit volume of heat is uniformly generated inside the pellet. The temperature of the coolant is 600 K and the convective heat transfer coefficient is 1000 mW/mm•K.

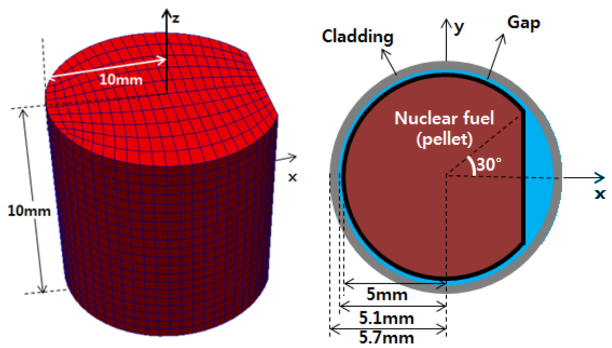

Fig. 2. Generation of elements for MPS simulation

To demonstrate the effect of 3D dynamic gap element in the MPS, temperature results of the proposed model has been compared with them of the uniform gap model. The uniform gap element in 3D was generally employed in several codes to simplify the calculation. As shown in figure 3, the centerline temperature with uniform gap element is 1145K, which is 140K lower than the result with 3D dynamic gap element. The remarkable difference between two methods is that when the gap variation is considered, the temperature at the center of MPS is 1166K, which is 400K higher than the case with uniform gap element.

It demonstrates that the uniform gap model calculates non-conservative temperature as well as inaccurate temperature. The higher temperatures of pellet which typical gap model cannot predict result in increase of thermal strain and fission gas release. The increase of thermal strain affects increase of cladding stress by pellet cladding mechanical interaction (PCMI). The increase of fission gas release causes the increase of rod internal pressure.

Therefore, 3D dynamic gap element model should be applied to simulate the asymmetric geometry such as MPS and eccentricity problem.

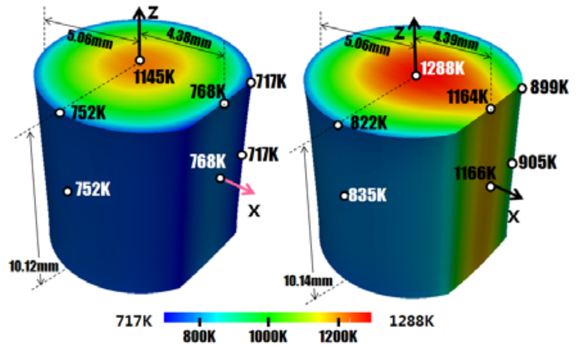

Fig. 3. Temperature distribution of uniform gap conductance (left) and 3D dynamic gap conductance (right) for MPS simulation

4. Conclusions

LWR fuel performance codes should incorporate thermo-mechanical loop to solve gap conductance problem, iteratively. However, gap conductance in multidimensional model is difficult issue owing to its nonlinearity and convergence characteristics. In this work, 3D thermo-mechanical module has been developed considering 3D dynamic gap element. In order to evaluate 3D dynamic gap element, MPS thermal behavior which is asymmetric geometry was simulated. The comparison results with uniform gap model demonstrate that 3D dynamic gap model should be required to simulate the asymmetric geometry. As the further work, mechanical behavior including 3D mechanical contact module will be evaluated.

Acknowledgement

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