Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Study of Gap Conductance model for Thermo-mechanical fully coupled Finite Element model

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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 the most critical issue, as 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 with a one-dimensional (1D) approach have been reported since the 1970s. However, it is difficult for a 1D model to simulate the stress and strain of the cladding accurately owing to a lack of degree of freedom.

A LWR fuel performance code should include thermo-mechanical coupled model owing to the existence of the fuel-cladding gap. Generally, the gap that is filled with helium gas results in temperature drop along radius direction. The gap conductance that determines temperature gradient within the gap is very sensitive to gap thickness. For instance, once the gap size increases up to several microns in certain region, difference of surface temperatures increases up to 100 Kelvin. Therefore, iterative thermo-mechanical coupled analysis is required to solve temperature distribution throughout pellet and cladding. Consequently, the Finite Element (FE) module, which can simulate a higher degree of freedom numerically, is an indispensable requirement to understand the thermo-mechanical behavior of cladding.

FRAPCON-3, which is reliable performance code, has iterative loop for thermo-mechanical coupled calculation to solve 1D gap conductance model [1]. In FEMAXI-III, 1D thermal analysis module and FE module for stress-strain analysis were separated. 1D thermal module includes iterative analysis between them [2]. DIONISIO code focused on thermal contact model as function of surface roughness and contact pressure when the gap is closed [3].

In previous works, gap conductance model has been developed only for 1D model or hybrid model (1D and FE). To simulate temperature, stress and strain accurately, gap conductance model for thermo-mechanical fully coupled FE should be developed. However, gap conductance in FE can be difficult issue in terms of convergence because all elements which are positioned in gap have different gap conductance at each iteration step. It is clear that our code should have gap conductance model for thermo-mechanical fully coupled FE in three-dimension.

In this paper, gap conductance model for thermo-mechanical coupled FE has been built using commercial FE code to understand gap conductance model in FE. We coded commercial FE code using APDL because it does not have iterative gap conductance model. Through model, convergence parameter and characteristics were studied.

2. Gap conductance

The conductance across the interface between UO_2 and zircaloy can be considered as the sum of three terms: heat transfer across the gap by conduction through the gas, h_g; solid conductance across contact areas when the gap is closed, h_s; a radiative heat transfer term, h_r.

$$h = h_g + h_s + h_r \tag{1}$$

Generally, convective heat transfer within the gap is neglected. It is also normally assumed that the gas composition is uniform throughout the fuel rod. In steady-state operation h_r is of little importance because range of surface temperature is below 1000 K. When the gap opens, h_s should be zero.

Typical design gaps between fuel and cladding are below 100 ㎛. After correction for differential thermal expansion the hot gaps during operation get even smaller. The hot gaps are so small that for light gases the approximation should be replaced by a form such as eq. (2).

$$h_g = \frac{k_{gas}}{d + d_{\min} + g_f + g_c} \tag{2}$$

where d_{min} is related to the roughness of the two surfaces and g_f and g_c are 'temperature jump distances' at the fuel and cladding surfaces, respectively. These jump distances are extrapolations of the true gap size to account for discontinuities in temperature at the bounding surface of a gas. The jump distance is strongly dependent on gas temperature and composition.

3. Modeling and results

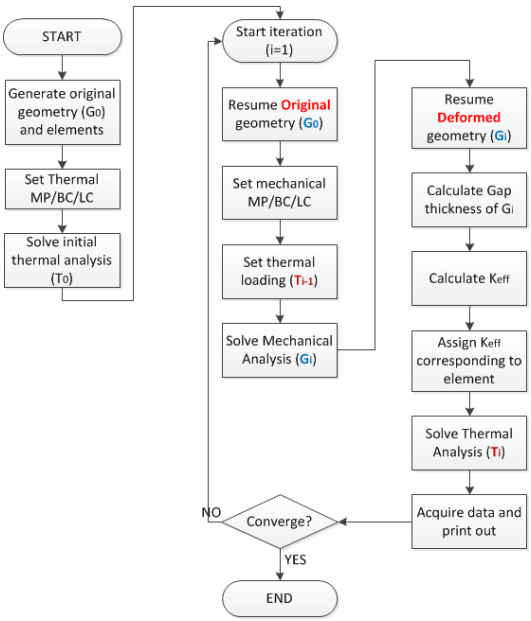

Fig.1 Flowchart of gap conductance model

Using APDL which is a programmable language in ANSYS, We established gap conductance model for thermo-mechanical coupled FE, as shown in Figure 1. Initial temperature analysis was performed in advance of the iteration. With initial temperature loading (T0), the mechanical analysis starts. Subsequently, thermal analysis starts with the deformed geometry from mechanical analysis. Thermal model calculates gap thickness from the deformed geometry and gap conductance for current step. To define the specified element for gap conductance model, thermal link elements which connect pellet and cladding at each node were applied. In addition, effective thermal conductivity of link (K_{eff}) was proposed to replace gap conductance of eq. (2).

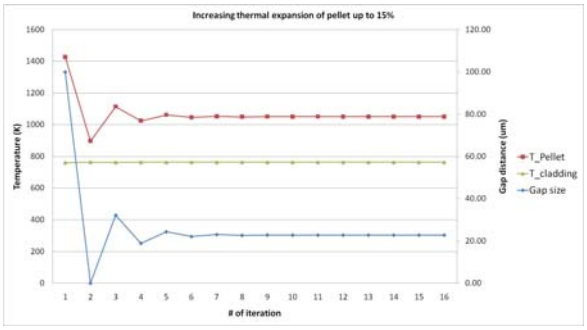

Fig.2 Analysis results of 1D gap conductance model

Fig.2 shows iterative results of gap thickness and temperature at gap surfaces in 1D model. To converge the calculation, number of iteration should over 7. On the contrary, Fig.3 shows iterative results of gap thickness in FE model. In comparison with 1D model, our model improves two times convergence speed. The reason was studied as follows; FE model is able to make heat balance along two directions simultaneously whereas 1D model only consider one direction during iteration. As matter of fact, behavior of FE model is much more practical than that of 1D model.

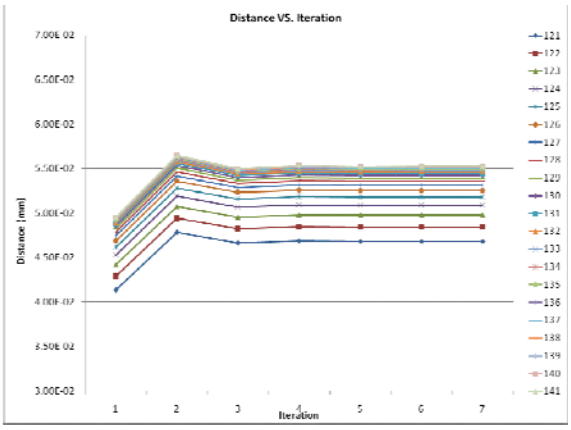

Fig.3 Analysis results of FE gap conductance model

4. Conclusion

It is importance that gap conductance model in fuel performance code is strongly dependent upon gap thickness. LWR fuel performance codes includes thermo-mechanical loop to solve gap conductance problem, iteratively. However, gap conductance in finite element model can be difficult to converge it because all gap conductance of elements are not identical. This works developed gap conductance model for FE using APDL. Consequently, gap thickness and temperature distribution can be obtained from iterative calculation. On the contrary of our concern, the model for FE improves convergence speed compared with 1D model because of heat flow along Y direction

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