3D FE simulation of the nuclear fuel rod considering the gap conductance between the pellet and cladding

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1. Introduction

Nuclear fuel rod, as an important component of a nuclear power plant, is composed of nuclear fuel and its cladding. The heat that generated inside of the pellet is transferred to the coolant passing through the cladding and gap, which is the void between the pellet and cladding as shown in Fig. 1. Normally, the gap thickness is under 0.1mm. But the gap changes as a result of thermal expansion of the pellet and cladding.

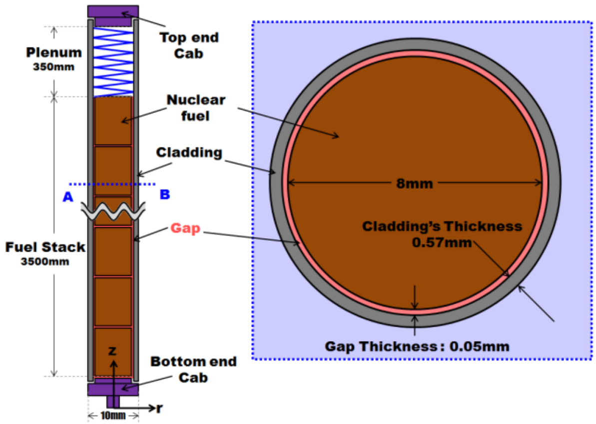

Fig. 1 The gap between pellet and cladding

The heat transfer coefficient of the gap, so called the gap conductance, was formularized by A.M. Ross and R.L. Stoute in 1962[1]. The gap conductance can be calculated as following equation (1).

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

h_g : gap conductance caused by gas
h_s : gap conductance caused by contact(solid contact)
h_r : gap conductance caused by radiation

When the gap is opened, the h_s can be neglected. And also the value of h_r is relatively low compared to h_g. The value of h_g can be calculated as following equation (2)

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

d : gap distance between the fuel and cladding
d_{min} : the mean roughness of the fuel and cladding
g_f ,g_c : thermal jump distance of the fuel and cladding

Many nuclear fuel rod performance codes are adopted this gap conductance model. FRAPCON-FRAPTRAN, the well-known and verified fuel performance code calculates the heat transfer equation in one-dimension [2]. ALCYONE, which was developed by CEA of France, adopted the equivalent convective heat transfer coefficient between each surface element of the outer pellet and inner cladding [3]. The thing that we have done is that we simulated the nuclear fuel rod considering the gap conductance using the 3D gap element. So, the gap conductance is adopted as a thermal conductivity of the gap element.

2. Formulation and application of the gap conductance

The conductive heat transfer equation, the Fourier's equation is the equation (3).

$$q'' = -k\frac{\Delta T}{\Delta x} \tag{3}$$

q'' : Heat flux per unit area
k : conductive heat transfer coefficient(gap element)

The heat flux can also be calculated adopting the gap conductance as following equation (4).

$$q'' = h_g \Delta T \tag{4}$$

We can assume that the amount of heat that flows through the gap by the gap conductance is equal to the amount that flows through the gap element, which is the equation (3). So we can say that equation (3) is equal to equation (4). It can be organized as following equation (5)

$$k = h_g d_l = \frac{k_{gas}}{d + d_{\min} + g_f + g_c} d_l \tag{5}$$

d_l : Length of the gap element

Flow charts of the FE module are shown in Figure 2. The gap conductance is calculated in every iteration step for considering the gap distance change caused by the thermal expansion of each iteration step. When the temperatures of the pellet nodes and cladding nodes are converged, the iteration procedure is ended.

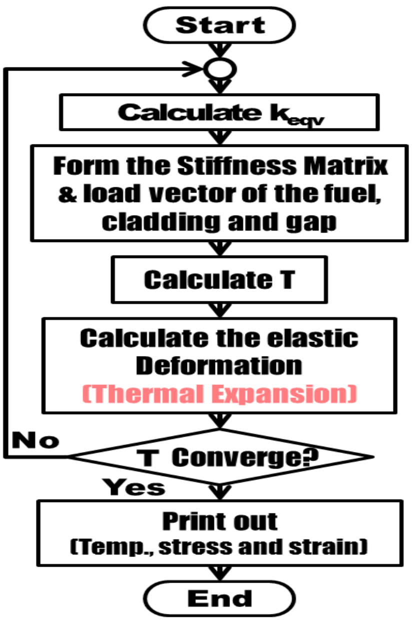

Fig. 2 Flow chart of the 3D FE module considering the gap Conductance between the pellet and cladding

3. Evaluation

To evaluate the performance of the FE code, we have analyzed the 1/16 pellet and cladding model as shown in Figure 3. The 8-node hexahedral element was used in the each FE model (The pellet: 380 nodes, 583 elements, the cladding: 288 nodes, 463 elements). The symmetric condition is also shown in Figure 3. The symmetric areas have adiabatic thermal boundary conditions and 1st mechanical boundary conditions (specified displacements).

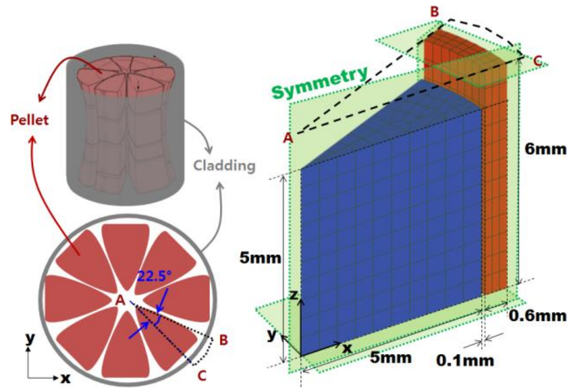

Fig. 3 1/16 model of the pellet and cladding, and its symmetric condition

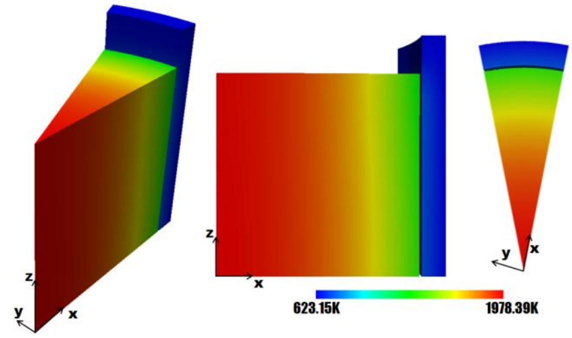

Fig. 4 The result of the analysis

The final result is shown in Figure 4. It shows that the total number of iteration step for convergence was 9 steps. The analysis result was compared with that of the commercial code(ANSYS) to verify the FE code. We compared both of them in just one step. It shows that the maximum difference of the temperature between the developed module and the commercial code was 5.41K.

4. Conclusion

3D FE Module adopting the gap conductance model was developed as a basis for the development of fuel rod behavior analysis module to simulate LWR fuel rod behavior during off normal operation. The code based on the Ross-Stoute gap conductance model which is very sensitive about the gap distance between the fuel and cladding. The thermo-mechanical calculation is performed to converge the value of temperature of the pellet and cladding. The calculation result shows that the considered tin error of the calculated result between the in-house code and commercial code was not greater than 1%. Further work will be the elasto-plastic code that considers contact between pellet and cladding.

Acknowledgement

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REFERENCES

[1] S. Aas, Mechanical interaction between fuel and cladding, Nuclear Engineering and Design, Vol.21, p.237, 1972.

[2] M. E. Cunningham, C. E. Beyer, P. G. Medvedev, G. A. Berna, FRAPTRAN: A computer code for the transient analysis of oxide fuel rods, NUREGICR, 2001.

[3] G. Thouvenin, J. M. Ricaud, B. Michel, ALCYONE: the PLEIADES fuel performance code dedicated to multidimensional PWR studies, TopFuel2006 meeting, 2006.