Development of Multidimensional Gap Conductance model using Virtual Link 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 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 have simulated thermo-mechanical behavior 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. For instance, once the gap size increases up to several micrometers in certain region, difference of pellet surface temperatures increases up to 100 Kelvin. Therefore, iterative thermo-mechanical coupled analysis is required to solve temperature distribution throughout pellet and cladding. Recently, multidimensional fuel performance codes have been being developed in the advanced countries to evaluate thermal behavior of fuel for offnormal conditions and DBA(design based accident) conditions using the Finite Element Method (FEM).

FRAPCON-FRAPTRAN code system, which is well known as the verified and reliable code, incorporates 1D thermal module and multidimensional mechanical module [1]. In this code, multidimensional gap conductance model is not applied. ALCYONE developed by CEA introduces equivalent heat convection coefficient that represents multidimensional gap conductance as a function of gap thickness [2]. BISON, which is multidimensional fuel performance code developed by INL, owns multidimensional gap conductance model using projected thermal contact [3]. In general, thermal contact algorithm is nonlinear calculation which is expensive approach numerically.

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, virtual link gap (VLG) element has been proposed to resolve convergence issue and nonlinear characteristic of multidimensional gap conductance. In terms of calculation accuracy and convergence efficiency, the proposed VLG model was evaluated.

2. Virtual Link Gap element

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.[4] Among three types of heat transfer, gas gap conductance is dominant factor.

To build up effective multidimensional gas gap conductance model, virtual link gap (VLG) element has been proposed instead of thermal contact algorithm. As shown in Figure 1, the role of VLG element is to transfer heat from pellet to cladding as thermal bridge. Because the VLG element does not exist in practice, it is applied only for thermal analysis.
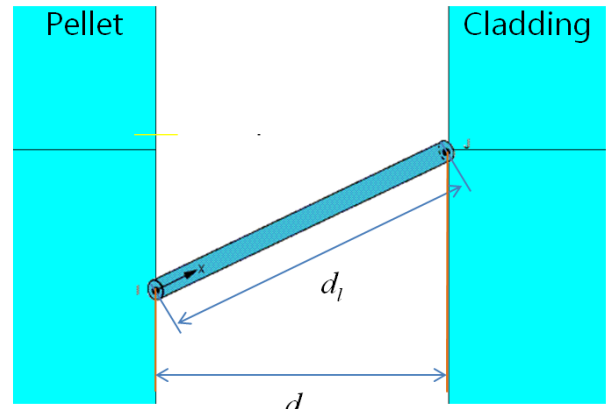

Fig.1 Concept of virtual link gap conductance model

The VLG element should be a function of gap thickness to represent characteristics of gas gap conductance. Therefore, equivalent thermal conductivity of the VLG element is defined as the following equation (2).

$$k^t_{eqv,i} = \frac{k_{gas}}{d^t_{n,i} + d_{min} + g_f + g_c} d^t_{l,i} \qquad (1)$$

where $k^t_{eqv,i}$ is equivalent thermal conductivity of i-element at t^{th} iteration step, $d_{n,i}$ is normal distance of i-element between pellet and cladding at t^{th} iteration step, $d_{l,i}$ is length of i-VLG element at t^{th} iteration step, d_{min} is

related to the roughness of the two surfaces, g_f and g_c are 'temperature jump distances' at the fuel and cladding surfaces, respectively. The VLG elements are automatically regenerated at each iteration step when the thermal deformation of pellet occurs. The algorithm for generation of the VLG element is to search node point on cladding surface that is positioned in minimum distance from node point of pellet surface. When the node on pellet surface is linked to the searched node on cladding surface, the VLG element is generated and equivalent thermal conductivity of the element is also calculated. Using ANSYS Parametric Design Language (APDL) which is a programmable language in ANSYS [5], we established thermo-mechanical coupled model with multidimensional gap conductance model.

3. Evaluation

In order to evaluate the proposed VLG element for multidimensional gap conductance, temperature distribution is compared with thermal contact coefficient (TCC) model that is able to simulate general gap conductance without assumptions. As well as convergence study of the VLG element has been carried out. Owing to sensitivity of gap conductance against gap thickness, it is significant issue to converge multidimensional gap conductance model.
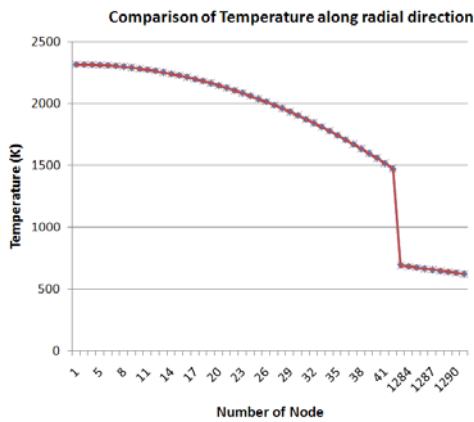

Fig.2 Comparison of temperatures against TCC model

As shown in Figure 2, temperature results calculated by the VLG model show a good agreement against that of TCC model. Therefore, the proposed VLG model is verified in terms of calculation accuracy. In order to complete verification of the proposed model in terms of accuracy, temperature results should be compared with the TCC model after deformation induced by thermal stress occurs. So far, comparable TCC model does not exist.

Figure 3 shows convergence trend of temperatures on pellet node. The X axis represents node number where bottom is '1' and top is '41'. At the first iteration step (ITER1), temperatures are low owing to high gap conductance. At the next step (ITER2) temperature

becomes high because gap size becomes wide. When the iteration step progresses, temperature difference between current step and previous step decreases suddenly. The trend demonstrates the VLG model can be converged within several steps.
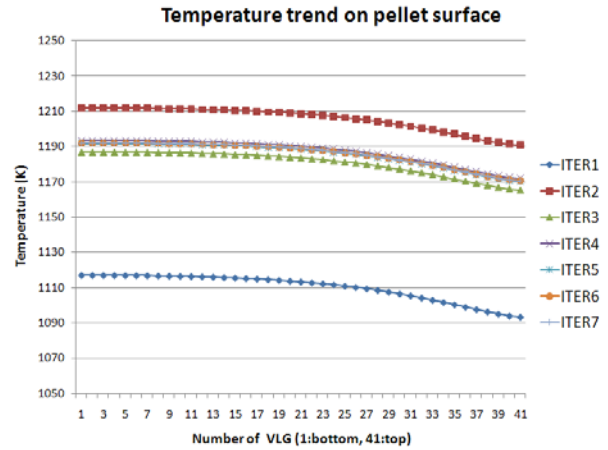

Fig.3 Convergence trend of the VLG model

4. Conclusion

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. This works proposed virtual link gap element for multidimensional gap conductance model. To evaluate the proposed model, thermo-mechanical module applying the VLG element has been established using APDL. Temperature results of the VLG model show a good agreement against that of TCC model. The convergence trend demonstrates the VLG model can be converged within several steps.

Acknowledgement

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