Development of 3D FE transient hear transfer module for simulation of the nuclear fuel rod

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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. However, unexpected extreme thermal expansion of the fuel during nuclear reaction could lead to destruction of the cladding as shown in Figure 1. This phenomenon is called PCMI (Pellet Cladding Mechanical Interaction) [1]. Studies on this phenomenon are underway not only to estimate the safety of nuclear power plants but also to increase the fuel burn-up for economic reason.

In recent years, researchers have been developing fuel performance code based on FEM(Finite Element Method) to understand the PCMI phenomenon. The Japan Atomic Energy Research Institute developed FEMAXI[2] code which evaluated the physical behaviour such as fission-gas bubble swelling model and bonding model between the pellet and the cladding. To estimate the transient fuel performance under accident conditions, FRAPTRAN[3] was developed by Pacific Northwest National Laboratory. ALCYONE[4] was introduced by the Atomic Energy Commission(CEA) in France for three-dimensional PWR(Pressure Water Reactors) fuel application to represent accurately the PCMI problem. These FE codes could simulate the thermo-mechanical behaviour of the fuel rod. According to this research trend, the development of 3D fuel performance code based on FEM is in progress at KAERI in the Republic of Korea.

The accidents due to failure of fuel rod usually occur in the transition period, such as rapid increase in the burn-up of the fuel rods. Therefore, this study is associated with FE module development to estimate the transient thermal behavior in the overall behavior of the fuel. The FE module is verified through comparison with the results of the commercial software, ANSYS V.14.0.

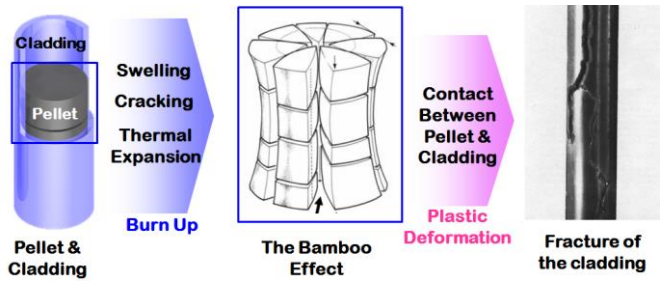


Fig. 1 Cladding damage path.

2. Formulation of 3D FE transition heat transfer

The governing equation of the general heat conduction analysis is as equation (1).

$$\rho C_p \dot{T} = (k_{ij} T_{,j})_{,i} + f \tag{1}$$

ρ = Density of the nuclear fuel
C_p = Specific heat of the nuclear fuel
k_{ij} = Thermal conductivity of the nuclear fuel
f = Heat flux of the nuclear fuel

Taking the weak form and discretizing for equation (1), the following equation is obtained.

$$\sum_{e=1}^{E} M_{\alpha\beta}^{e} \frac{\partial T_\beta}{\partial t} + \sum_{e=1}^{E} K_{\alpha\beta}^{e} T_\beta + \sum_{e=1}^{E'} K_{\alpha\beta}^{e,3} T_\beta = \sum_{e=1}^{E} f_\alpha^{e,1} + \sum_{e=1}^{E'} f_\alpha^{e,2,3} \tag{2}$$

$M_{\alpha\beta}^{e}$ = Stiffness matrix related to the density and the specific heat of the nuclear fuel
$K_{\alpha\beta}^{e}$ = Stiffness matrix related to the thermal conductivity of the nuclear fuel
$K_{\alpha\beta}^{e,3}$ = Stiffness matrix caused by the 3rd boundary condition (Newton's cooling condition)
$f_\alpha^{e,1}$ = Heat flux caused by the 1st boundary condition
$f_\alpha^{e,2,3}$ = Heat flux caused by the 2nd and 3rd boundary conditions

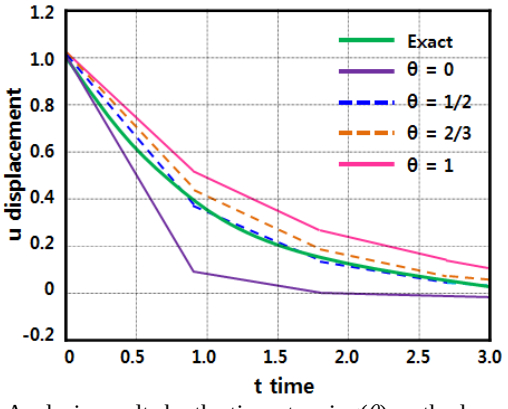


Fig. 2 Analysis results by the time stepping(θ) methods.

In order to represent the transient thermal equation as a FE module, the discrete approximation in time dimension is required. The comparison of various time-stepping schemes on a first-order initial value problem is shown in Figure 2.[5]

The Crank-Nicolson method(θ = 0.5) is known to ensure higher accuracy. Therefore, the method for the efficient transient calculation has been applied on the thermal analysis module. When the Crank-Nicolson's method is applied to the equation (2), the equation (3) is derived.

$$\left[\frac{M_{\alpha\beta}^{n}}{\Delta t}+\theta K_{\alpha\beta}^{n+1}\right]T_{\beta}^{n+1}=(1-\theta)\,f_{\alpha}^{n}+\theta f_{\alpha}^{n+1}+\left[\frac{M_{\alpha\beta}^{n}}{\Delta t}-(1-\theta)K_{\alpha\beta}^{n}\right]T_{\beta}^{n} \quad (3)$$

Flow charts of the FE module are shown in Figure 3. In case of temperature-dependent properties, the iteration calculation was continued until the percentage of the temperature difference went down lower than 0.1%. And then, the next time interval was calculated.

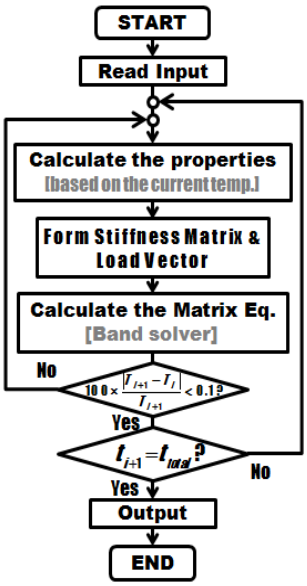
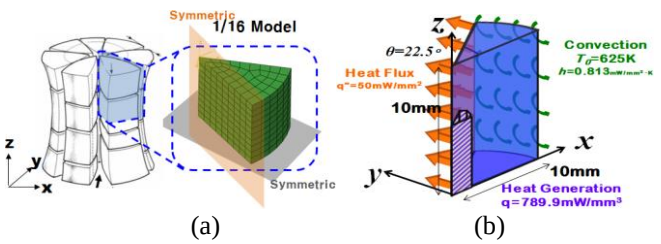


Fig. 3 Flow charts of the 3D FE transient module.

3. Evaluation

To evaluate the performance of the FE module, we have analyzed the 1/16 pellet model without cladding as shown in Figure 4(a). The 20-node hexahedral element was used in the FE model(elements=200, nodes=1201). The boundary conditions were shown in Figure 4(b). The total analyzing time took 5 seconds when employing the time increment of 1 second and the initial temperature was 300K. The result of the analysis with temperature-dependent properties is shown in Figure 5.



(a) (b)

Fig. 4 (a) 1/16 model of the pellet, (b) boundary conditions of the 1/16 pellet

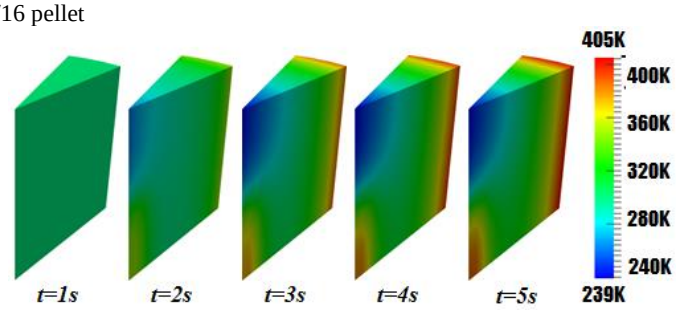


Fig. 5 The result of the analysis

The analysis result was compared with that of the commercial program(ANSYS V.14.0) to verify the FE module.

The error in temperature was calculated using equation (4). (T_c : calculated temperature by ANSYS, T_d : calculated temperature by developed FE module)

$$e(\%)=\frac{|T_c-T_d|}{T_c}\times 100(\%) \quad (4)$$

The biggest error was 1.07%, and the average error was 0.06%.

4. Conclusion

3D FE module for transient thermal analysis was developed to simulate the behavior of LWR fuel rod. The module employed the Crank-Nicolson's method for efficient discretization in time dimension. The change of material properties is considered according to temperature. The error of the calculated result between the FE module and ANSYS was less than 1%. It demonstrates that the developed module was well built in the developed FE module. In the future, the developed module will be merged into thermo-elasto-plastic FE code to simulate the fuel behavior during operation

Acknowledgement

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