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Assessment of effective thermal conductivity model of the SPACE for fuel axial relocation in ballooning fuel rods

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1. Introduction

Under Loss of Coolant Accident (LOCA) conditions, clad ballooning can occur due to internal overpressure and fuel rods can be overheated and undergo a complex process known as fuel fragmentation, relocation, and dispersal (FFRD) [1] according to different fuel burnup. The first computational model for axial fuel presented by Siefken [2]. This model, implemented in the SCDAP for severe accident analyses, was based on experimental results and data available at that time. Since then, various computational models [3-5] have been proposed and used for evaluations of the tests. Among them, Quantum Technologies AB [6] has developed models for FRAPTRAN-1.5 for fuel fragmentation and relocation.

The models for FFRD phenomena have been added to the SPACE to take into account the effect of mass relocation on heat generation and thermal conductivity degradation during the LOCAs. Because only these models, which were fully integrated with a computer program used for fuel rod thermo-mechanical analyses of transients and accidents [7].

The purpose of this study is to implement the thermal conductivity model into the SPACE and verify the effect of thermal conductivity degradation by using simple conceptual problem when fuel axial relocation in ballooning the fuel rods occurs.

2. Methods and Results

In this section the model for an effective thermal conductivity of crumbled fuel is described. By introducing simple conceptual problem, we compare the result of the SPACE calculation with analytic solution to verify the implemented model.

2.1 Effective thermal conductivity of crumbled fuel

For crumbled fuel pellets in ballooned clad, it is difficult to define the properties of particles and the particle bed due to the irregularities of crumbled fuel particles. Various models have been proposed for calculating the effective thermal conductivity of particle beds, in which the particles are well defined. Therefore, we have to rely on simple models. In this study, the correlation proposed by Chiew and Glandt [8] was selected to determine the effective thermal conductivity of crumbled fuel. This correlation consists of the thermal conductivities of fuel fragmentation (λ_f) and the surrounding gas (λ_g), and packing fraction (ϕ) of the fuel particles. The correlation is

$$\frac{\lambda_{eff}}{\lambda_f} = \frac{(1-\beta)}{(1+2\beta)(1-\beta\phi)}\left(1+2\beta\phi+\left(K_2-3\beta^2\right)\phi^2\right) \quad (1)$$

Here, β is the reduced thermal polarizability and define in eq. (2).

$$\beta = \frac{\lambda_f - \lambda_g}{\lambda_f + 2\lambda_g} \quad (2)$$

$\lambda_{eff} / \lambda_f$ is the ratio of the effective thermal conductivity to the conductivity of fuel, and K_2 is a function of the reduced thermal polarizability and packing fraction. Chiew and Glandt approximated the function K_2 in eq. (3) and found the best fit to tabulated values as eq. (4) ~ (5).

$$K_2(\beta,\phi) \approx K_2^{(0)}(\beta) + K_2^{(1)}\phi \quad (3)$$

$$K_2^{(0)}(\beta) = 1.7383\beta^3 + 2.8796\beta^2 - 0.11604\beta \quad (4)$$

$$K_2^{(1)}(\beta) = 2.8341\beta^3 - 0.13455\beta^2 - 0.27858\beta \quad (5)$$

2.2 Methodology for implementation

The SPACE have recently added for the fuel fragmentation and relocation models to consider the FFRD phenomena Therefore, we focus on the verification of radially thermal calculation according to the changes of fuel relocation in this study. To calculated the fuel temperature in the SPACE, the heat conduction equation has to be solved. When the fuel balloon or collapse are occurred, basis conduction equation can still be applied but the material properties must be modified from eq. (6) to eq. (7).

$$\int_V \rho_f C_{pf} \frac{\partial T}{\partial t} = \int_s K_f \cdot \nabla T \, ds + \int_V P dV \quad (6)$$

$$\int_V \phi\rho_f C_{pf} \frac{\partial T}{\partial t} = \int_s K_{eff} \cdot \nabla T \, ds + \int_V \phi P dV \quad (7)$$

Here, fuel density is changed from ρ_f to $\phi\rho_f$, volumetric heat source is changed from P to ϕP .

As shown in Fig. 1, temperature distribution need to be synchronized according to the fuel relocation since it is difficult to consider the changes of computing nodes due to the fuel ballooning in real time.

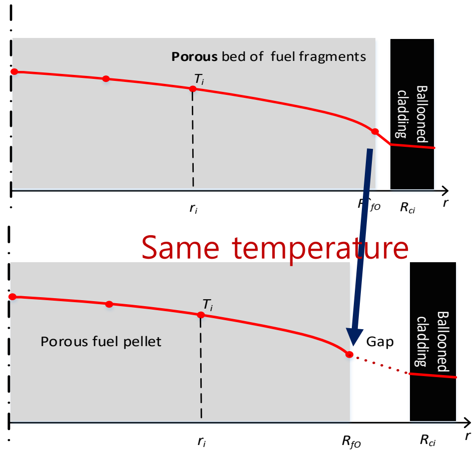

Fig. 1. Synchronized temperature distribution for crumbled fuel in ballooned clad

To synchronize the temperature distribution of crumbled fuel, the geometry effect is included in the effective thermal conductivity. Therefore, the effective thermal conductivity can be defined as $K_{eff} = \lambda_{eff}$ as the same in eq.(1).

2.3 Verification

To verify the implemented model for the radially thermal calculation in the SPACE, conceptual problem is introduced with simple boundary conditions. For this problem, we compared the SPACE results with analytic solutions.

The active length of the fuel rod is assumed to be 3.6 m and the fuel pellet diameter is 9.0 mm. The other parameters are assumed as in Table I. The axial profile for the cladding deformation is defined by a sine-shaped balloon with its peak at the fuel rod mid-plane (z=1.8 m) as shown in Fig. 2. We assumed that single phase liquid flows into the pipe with 0.1 kg/s of constant mass flow rate, 300 K at 15.5 MPa and the constant power per each node is initially applied with 20, 50 and 100 W and the outer temperature of clad was kept constant. Fig. 3 shows the SPACE modeling for this test.

Table I: Initial conditions & boundary conditions

Properties		Value
Radius of pellet [m]		0.00450
Gap thickness [m]		0.00001
Cladding thickness [m]		0.00099
Thermal conductivity [W/k-m^2]	Fuel	6.0
	Gap	0.2
	Clad	12.0

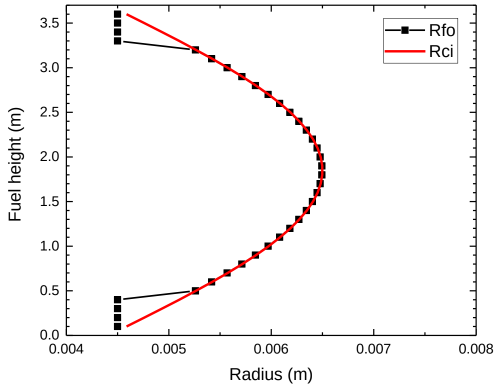

Fig. 2. Deformation pattern for conceptual problem (black line: fuel radius, red line: cladding inner radius)

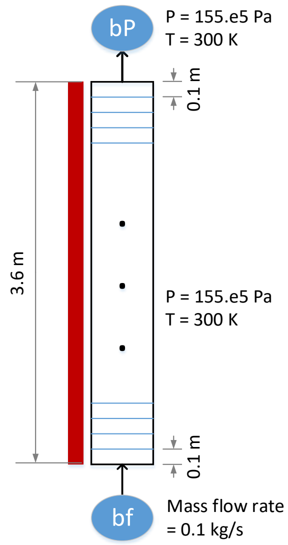

Fig. 3. SPACE modeling

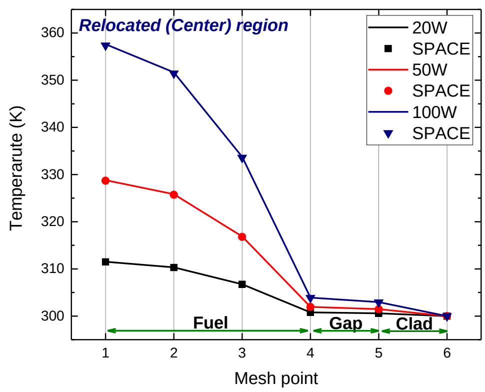

Fig. 4. Comparison of temperature radial distribution between calculated results and analytic solution at maximum ballooned region (Z=1.8 m)

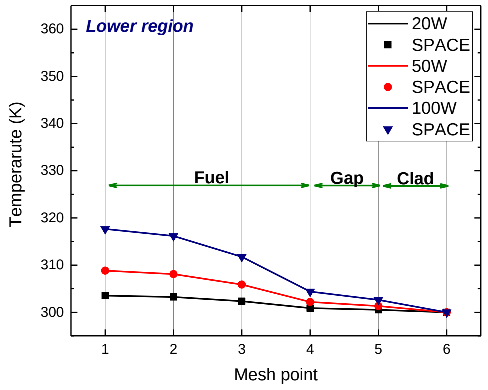

Fig. 5. Comparison of temperature radial distribution between calculated results and analytic solution at lower region (Z=0.3 m)

Fig. 4~5 shows the comparison of temperature distribution between calculated results and analytic solutions at z = 1.8 and z = 0.3 m along axial direction, respectively. As the cladding is ballooned, fuel fragments are relocated to that region. In this regard, the volumetric heat source is concentrated and the inner temperature of the fuel is higher than the one at the lower part. This is the reason for different temperature distributions between above results.

All calculated results are well-matched with the analytical solutions. Based on these, we can conclude that the effective thermal conductivity model is well-implemented and verified in the SPACE

3. Conclusions

During LOCAs, fuel pellet can be fragmented and relocated due to the ballooned clad, high burnup, and internal overpressure and so on. To simulate these phenomena, the models considering FFRD phenomena have recently implemented in the SPACE. As a part of these improvements, thermal calculation model was newly implemented in the SPACE and verified by comparing with analytic solutions. The calculated results are reasonable and well-matched with analytic solution. Based on these, we can conclude that the model, especially used by the inputs to heat conduction equation, is well-implemented and verified in the SPACE. As a further work, we will simulate an integral effect test to validate the newly implemented models for FFRD phenomena.

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