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Development of 2D (r-θ) Heat Conduction Model for Fuel Rod in FAMILY

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1. Introduction

The assessment of core coolability during a large-break loss-of-coolant accident (LBLOCA) in pressurized water reactors (PWRs) has been a major safety concern for several decades [1,2]. In relation to this issue, fuel deformation caused by fuel rod ballooning and burst can significantly alter the core geometry, leading to a deterioration of coolability from a thermal-hydraulic perspective. Additionally, from a heat source perspective, fragmented and pulverized UO_2 pellets may relocate within the cladding, modifying the distribution of heat sources [3].

If cladding deformation becomes severe enough to cause adjacent fuel rods to come into contact, convective heat transfer is hindered, while conductive heat transfer between fuel rods also becomes an emerging factor. To accurately account for these phenomena, the authors have previously developed several models, including thermal-hydraulic volume change, form loss, cladding contact and its resultant convective and conductive heat transfer, and fuel relocation. These models have been implemented in the FAMILY safety analysis code [4]. FAMILY is an integrated computational tool that combines the thermal-hydraulic capabilities of MARS-KS with the fuel performance analysis of FRAPTRAN-KS [5].

A preliminary evaluation of fuel performance during a LBLOCA in the APR1400 reactor was conducted, and the impact of these models was analyzed [4]. Fig. 1 illustrates the influence of these models on peak cladding temperature (PCT). The results indicate that each model has a distinct effect on PCT behaviors, with conductive heat transfer due to cladding contact also playing a crucial role. However, the conductive heat transfer model employed the previous study has limitations, as heat conduction of fuel rod in FAMILY is solved only in the one-dimensional radial direction. Thus, to simulate conductive heat transfer between fuel rods after cladding contact, the previous study employed the following assumptions:

- The outer cladding temperature at the contact area between two claddings is averaged from the temperatures of the respective outer cladding surfaces.
- Heat conduction between the contacted and uncontacted outer cladding areas is assumed to occur instantaneously, leading to temperature equilibrium between these regions.

However, the second assumption may not accurately represent actual fuel rod behavior. Because the outer layer of the fuel rod is covered with low conductance materials such as zirconium oxide or crud. Therefore, to accurately model heat conduction in fuel rod when cladding contact occurs, a two-dimensional (2D) heat conduction model accounting for both the radial and circumferential direction (r-θ) is necessary.

This paper presents the derivation and implementation of a 2D heat conduction model. The verification of the developed model is also provided.

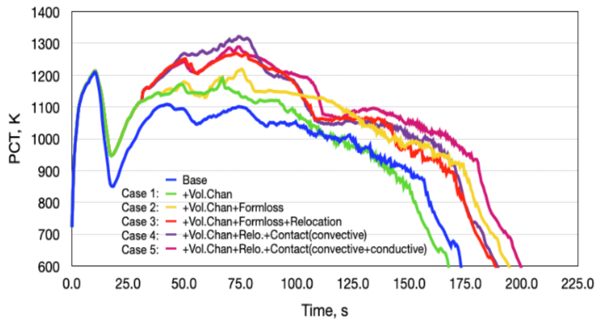

Fig. 1 Influence of fuel deformation-related models on the PCT evolution during a LBLOCA in APR1400 [4]

2. 2D Heat Conduction Model

As described in PNNL-19400, Vol.1, heat conduction in both the radial and circumferential directions within a fuel rod can be represented by the following equation [6]:

$$\int_V \rho C_p \frac{\partial T}{\partial t} dV = \int_s k\bar{\nabla}T d\bar{s} + \int_V q dV \tag{1}$$

Where,
T = temperature (K)
t = time (s)
q = volumetric heat generation rate (W/m^3)
C_p= specific heat (J/kg-K)
ρ = density (kg/m^3)
k = thermal conductivity (W/m-K)

The first integral represents the enthalpy change of an arbitrary infinitesimal volume V of material, the second integral accounts for heat transfer across the surface S of the volume, and the third integral represents the heat

generation within the volume. For boundary conditions, thermal symmetry is applied at the fuel centerline, and a prescribed fuel surface temperature or heat flux can be used at the outer fuel surface.
Referring to Fig. 2 for the geometric definitions, the finite difference approximation in a 2D heat conduction is formulated as follows.

$$\begin{aligned}
&\left(c_{ln,rj}h^{V}_{ln,rj} + c_{ln,lj}h^{V}_{ln,lj} + c_{rn,rj}h^{V}_{rn,rj} + c_{rn,lj}h^{V}_{rn,lj}\right)\frac{\left(T^{m+1}_{n,j} - T^{m}_{n,j}\right)}{\Delta t} \\
&= -\left(T^{m+\frac{1}{2}}_{n,j} - T^{m+\frac{1}{2}}_{n-1,j}\right)\left(k_{ln,rj}h^{S}_{ln,rj} + k_{ln,lj}h^{S}_{ln,lj}\right) \\
&+ \left(T^{m+\frac{1}{2}}_{n+1,j} - T^{m+\frac{1}{2}}_{n,j}\right)\left(k_{rn,rj}h^{S}_{rn,rj} + k_{rn,lj}h^{S}_{rn,lj}\right) \\
&- \left(T^{m+\frac{1}{2}}_{n,j} - T^{m+\frac{1}{2}}_{n,j-1}\right)\left(sk_{ln,rj}s^{S}_{ln,rj} + sk_{rn,rj}s^{S}_{rn,rj}\right) \\
&+ \left(T^{m+\frac{1}{2}}_{n,j+1} - T^{m+\frac{1}{2}}_{n,j}\right)\left(sk_{ln,lj}s^{S}_{ln,lj} + sk_{rn,lj}s^{S}_{rn,lj}\right) \\
&+ Q_{ln,rj}h^{V}_{ln,rj} + Q_{ln,lj}h^{V}_{ln,lj} + Q_{rn,rj}h^{V}_{rn,rj} + Q_{rn,lj}h^{V}_{rn,lj}
\end{aligned} \tag{2}$$

Where
$T_{n,j}{}^{m+1}$ = temperature at radial & circumferential node *n/j* and time point *m*+1 (K)
$T_{n,j}{}^{m+1/2}$ = 0.5 ($T_{n,j}{}^{m}$ + $T_{n,j}{}^{m+1}$) (K)
Δt = time step (s)
$_{ln,rj}$, $_{ln,lj}$, $_{rn,rj}$, $_{rn,lj}$ = left/right, left/left, right/right, right/left side of the node *n/j*
$c_{ln,rj}$, $c_{ln,lj}$, $c_{rn,rj}$, $c_{rn,lj}$ = volumetric heat capacity of the node *n/j* (J/m^3·K)
$k_{ln,rj}$, $k_{ln,lj}$, $k_{rn,rj}$, $k_{rn,lj}$ = thermal conductivity at radial direction of node *n/j* (W/m·K)
$sk_{ln,rj}$, $sk_{ln,lj}$, $sk_{rn,rj}$, $sk_{rn,lj}$ = thermal conductivity at circumferential direction of node *n/j* (W/m·K)
$h^{v}_{ln,rj}$, $h^{v}_{ln,lj}$, $h^{v}_{rn,rj}$, $h^{v}_{rn,lj}$ = volume weight of mesh spacing of node *n/j* (m^2)
$h^{s}_{ln,rj}$, $h^{s}_{ln,lj}$, $h^{s}_{rn,rj}$, $h^{s}_{rn,lj}$ = surface weight of node *n/j*
$s^{s}_{ln,rj}$, $s^{s}_{ln,lj}$, $s_{rn,rj}{}^{s}$, $s^{s}_{rn,lj}$ = surface weight on circumferential direction of node *n/j* (-)
$Q_{ln,rj}$, $Q_{ln,lj}$, $Q_{rn,rj}$, $Q_{rn,lj}$ = heat generation per unit volume for mesh spacing of node *n/j* (W/m^3)

If equation (2) is rearranging as temperature of *m+1* time step, following equation (3) is obtained.

$$a_{n,j}T^{m+1}_{n-1,j} + b_{n,j}T^{m+1}_{n,j-1} + c_{n,j}T^{m+1}_{n,j} + d_{n,j}T^{m+1}_{n,j+1} + e_{n,j}T^{m+1}_{n+1,j} = f_{n,j} \tag{3}$$

Where

$$a_{n,j} = -0.5\left(k_{ln,rj}h^{S}_{ln,rj} + k_{ln,lj}h^{S}_{ln,lj}\right)$$

$$b_{n,j} = -0.5\left(sk_{ln,rj}s^{S}_{ln,rj} + sk_{rn,rj}s^{S}_{rn,rj}\right)$$

$$c_{n,j} = g_{n,j} - \left(a_{n,j} + b_{n,j} + d_{n,j} + e_{n,j}\right)$$

$$e_{n,j} = -0.5\left(k_{rn,rj}h^{S}_{rn,rj} + k_{rn,lj}h^{S}_{rn,lj}\right)$$

$$d_{n,j} = -0.5\left(sk_{ln,lj}s^{S}_{ln,lj} + sk_{rn,lj}s^{S}_{rn,lj}\right)$$

$$\begin{aligned}
f_{n,j} = &-b_{n,j}T^{m}_{n,j-1} - a_{n,j}T^{m}_{n-1,j} \\
&+\left(g_{n,j} + a_{n,j} + e_{n,j} + b_{n,j} + d_{n,j}\right)T^{m}_{n,j} \\
&-e_{n,j}T^{m}_{n+1,j} - d_{n,j}T^{m}_{n,j+1} + h_{n,j}
\end{aligned}$$

$$g_{n,j} = \left(c_{ln,rj}h^{V}_{ln,rj} + c_{ln,lj}h^{V}_{ln,lj} + c_{rn,rj}h^{V}_{rn,rj} + c_{rn,lj}h^{V}_{rn,lj}\right)/\Delta t$$

$$h_{n,j} = Q_{ln,rj}h^{V}_{ln,rj} + Q_{ln,lj}h^{V}_{ln,lj} + Q_{rn,rj}h^{V}_{rn,rj} + Q_{rn,lj}h^{V}_{rn,lj}$$

The finite difference approximations of equation (3) at each node can be combined together to form one matrix equation. Then, the mesh point temperatures are solved by the Gauss-Jordan elimination method. This solution method is implemented in FAMILY as a ht1tdp2D subcode. Steady-state two-dimensional solution is also implemented in FAMILY as a ht1sst2D subcode.

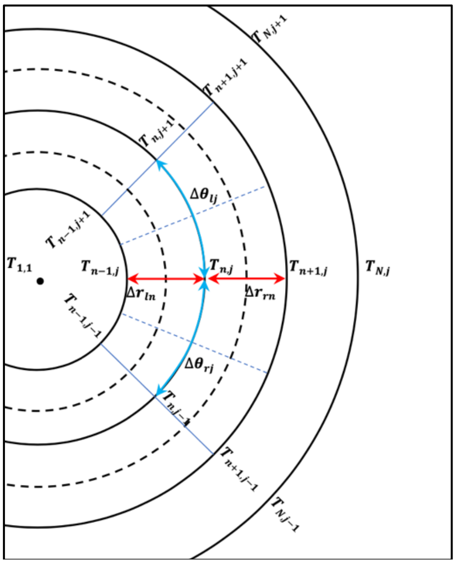

Fig. 2 Description of geometry terms in finite difference equations for 2D heat conduction

3. Verification

3.1 Simulation conditions

For the verification of the 2D heat conduction model, fuel temperature comparisons between the derived model and the original FRAPTRAN code one-dimensional (1D) model were conducted. The analyzed fuel is a single rod of PLUS7 fuel, operating at a rod average power of 28.6 kW/m with a burnup of 30 MWd/kgU. The thermal-hydraulic conditions are representative of a typical APR1400 reactor. The fuel rod was discretized into 40 axial nodes and 17 radial nodes, representing the fuel pellet, cladding, zirconium oxide layer, and crud. Additionally, the fuel rod was divided circumferentially into 8, 16, and 32 segments to analyze the effects of circumferential node on the 2D heat conduction.

To evaluate fuel temperature behavior under different power conditions, the fuel power was varied as shown in Fig. 3(a). Starting at 5 seconds, the rod power was reduced linearly, reaching zero at 10 seconds, where it was maintained for another 10 seconds. After that, the power was increased linearly again next 10 seconds until it reached 1.2 times the initial value.

The fuel rod temperature distribution within the fuel pellet was analyzed by examining a case where 1/8 of the segmented fuel pellet at a given radial plane and node experienced an abrupt 90 % power decrease starting at 5 seconds, followed by an abrupt 90 % power increase at 30 seconds, compared to the normal condition, as shown in Fig. 5(a). This corresponds to a fuel power reduction and increase of 11.25 % relative to the normal condition at the given node. The analysis was conducted to investigate the temperature distribution in the radial plane of the pellet.

3.2 Comparison of fuel temperatures

Fig. 3 presents the imposed fuel power and the analyzed fuel temperature evolution. When the original 1D FRAPTRAN model is used, before the power reduction begins, the fuel centerline temperature is 2552.3 K. It gradually decreases from 5 seconds, reaching a minimum of 764.5 K at 21 seconds, then increasing again to a maximum of 2892.0 K at 100 seconds. When the 2D heat conduction model is applied, with the circumferential node divided into 8, 16, or 32 segments, the fuel centerline temperature behavior remains identical to that of the original 1D model, as shown the figure. Similarly, the evolution of the cladding surface temperature exhibits the same behaviors, regardless of whether the 1D or 2D model is applied. The cladding temperature before power reduction is 721.4 K, which decreases to 605.6 K at 21 seconds, then rising to 742.5 K at 100 seconds.

Fig. 4 illustrates the 2D temperature distribution of the fuel pellet at 5, 21, and 100 seconds. These confirm that the temperature within the pellet is circumferentially symmetric, as expected.

Fig. 5 shows the imposed fuel power and the analyzed fuel temperature evolution as the power of 1/8 pellet changed, described in section 3.1. In this case, a direct comparison between the original FRAPTRAN 1D and the developed 2D model is not possible. Thereby, the temperature evolution and distribution are analyzed using the 2D model only with changing circumferential node. When the circumferential node is divided into 8 segments, the circumferentially averaged fuel centerline temperature before 5 seconds is 2552.3 K. It then decreases to 2342.4 K at 30 seconds before gradually increasing up to 2745.7 K at 100 seconds. The average cladding temperature before the power change is 721.4 K, which slightly decreases to 715.0 K at 30 seconds before rising to 727.5 K at 100 seconds. These average temperature behaviors remain unchanged regardless of the number of circumferential nodes (16 or 32).

Fig. 6 depicts the 2D temperature distribution within the fuel pellet at 5, 30, and 100 seconds. As expected, when the fuel power of 1/8 radial plane is reduced to 90 %, a corresponding reduction in fuel temperature is observed, as shown in 30 seconds case in the figure. Conversely, when the fuel power increases to 90 % at the same circumferential position, a rise in fuel temperature is observed at 100 seconds case. These temperature distributions are reasonable and expected. These results show consistent temperature distribution regardless of the number of circumferential nodes, suggesting that the developed 2D heat conduction model works as intended.

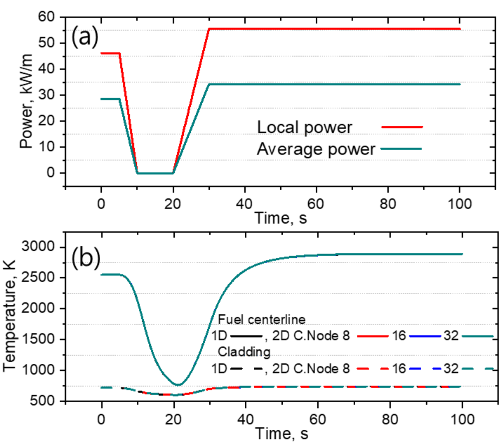

Fig. 3 (a) Fuel power and (b) temperature evolution (axial node # 26)

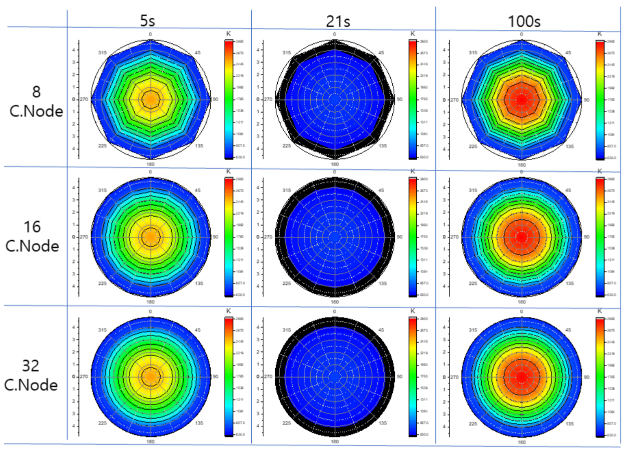

Fig. 4 2D fuel temperature distribution as a function of time and circumferentially segmented node (axial node # 26)

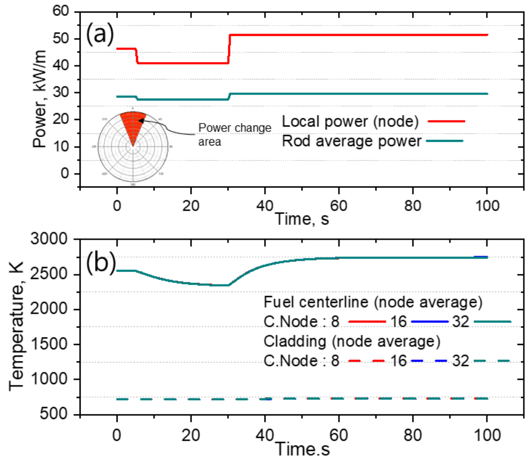

Fig. 5 Circumferentially averaged (a) fuel power and (b) fuel temperature evolution (axial node # 26)

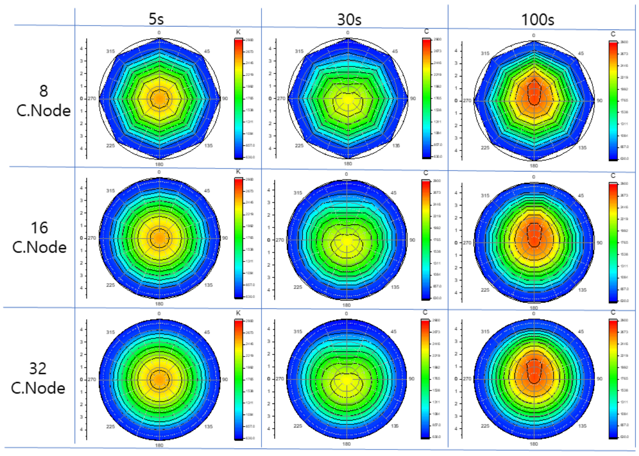

Fig. 6 2D fuel temperature distribution as a function of time and circumferential node (axial node # 26)

4. Summary

The development and implementation of a two-dimensional (2D) heat conduction model in the FAMILY safety analysis code have been carried out. The verification of the developed 2D model has also been conducted. The main findings are as follows:

- A 2D heat conduction model for fuel rod temperature analysis has been successfully developed and implemented in the FAMILY safety analysis code using the finite difference approach.
- By comparing fuel temperatures between the original 1D FRAPTRAN model and the developed 2D model, as well as through a circumferential node sensitivity study, it has been confirmed that the developed 2D model works well as expected.

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