Preliminary analysis using CUPID subchannel module including CRUD heat transfer model coupled with fuel performance code GIFT

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1. Introduction

With an increased discharge burnup of fuel, a revision of the emergency core cooling system (ECCS) acceptance criteria was proposed to consider fuel deterioration. Therefore, there is an increasing demand for a more realistic simulation tool for safety analysis, considering fuel deformation and thermal hydraulics. In particular, fuel deformation, which is known as CRUD on fuel cladding, should be considered. CRUD refers to the fouling deposits of corrosion products from steam generators and pipes due to subcooled nucleate boiling on fuel cladding. It is composed of a porous medium and steam chimney and has a different heat transfer mechanism known as wick boiling.

In this study, the CRUD heat transfer model used in the simulation code to predict CRUD growth was implemented into CUPID subchannel module, coupled with fuel performance code GIFT. Using this coupled code system, s multi-physics analysis was conducted.

2. Numerical methods

This section provides a brief introduction to the coupled code system CUPID/GIFT and CRUD heat transfer model that incorporates wick boiling phenomena.

2.1 CUPID/GIFT coupled code system

In the previous study, CUPID/GIFT coupled code system was established for multi-physics simulations. For the establishment of the coupled code, 3D thermal hydraulics code, CUPID, and 1.5D fuel performance code, GIFT was coupled. CUPID was developed by KAERI and has subchannel analysis capability with models such as cross-flow, mixing vane, and turbulent mixing [1]. In addition, GIFT was developed by Seoul National University and calculates robustly the stress and strain of cladding using both axial and radial meshes [2]. The multi-physics analysis was conducted using this coupled code, and the results reasonably demonstrate the effect of subchannel flow and fuel deformation [3].

2.2 CRUD heat transfer model

The CRUD heat transfer model was based on Cohen's 1D wick boiling model [4] and this type of model is typically used in simulation code to predict CRUD growth, such as BONATI [5]. In this model, water is transported through a porous medium, and evaporation and steam transfer processes are simulated using a steam chimney as shown in Figure 1. It is also assumed that the heat transfer is caused by conduction across a porous medium from the fuel to bulk coolant and by evaporation of the chimney surface.

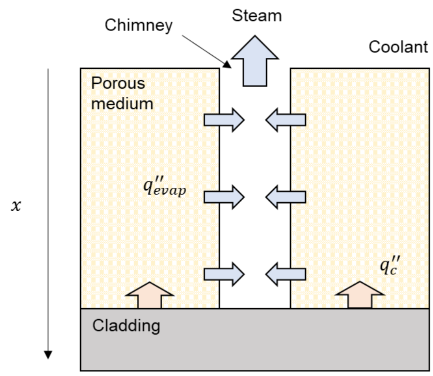


Figure 1. Schematic diagram of heat transfer process during wick boiling through CRUD structure

The governing equation is given by

$$\frac{d^2T}{dx^2} - \frac{2\pi r_c N_c h_e}{k_{eff}}(T - T_{sat}) = 0$$

where r_c is the chimney radius, N_c is the area density of chimneys, h_e is the evaporative heat transfer coefficient, k_{eff} is the thermal conductivity of the porous medium, and T_{sat} is the saturation temperature. The boundary condition of this equation is given by

$$k_{eff}\left(\frac{dT}{dx}\right)_{x=0} = h_c(T - T_{bulk}) \text{, } at\ x = 0$$

$$k_{eff}\left(\frac{dT}{dx}\right)_{x=d} = q''_c \text{, } at\ x = d$$

where h_c is the convective heat transfer coefficient, T_{bulk} is the bulk coolant temperature, and d is the thickness of the CRUD, and q_c'' is the heat flux at the surface of the fuel. CUPID calculates the evaporative volumetric heat sink and vapor generation rate using this model during subcooled nucleate boiling region. The evaporative volumetric heat sink and vapor generation rate are given by

$$q_{evap}''' = 2\pi r_c N_c h_e (T - T_{sat})$$

$$\Gamma_{\text{wall}} = \frac{q_{evap}'''}{h_{fg}}$$

where h_{fg} is the latent heat. The evaporative heat transfer coefficient is given by

$$\text{h}_\text{e} = \left(\frac{2A}{2-A}\right)\left(\frac{M}{2\pi R}\right)^{1/2} \frac{H_v^2}{T^{\frac{3}{2}}(\bar{V}_W^v - \bar{V}_W^l)}$$

where A is the evaporation or condensation coefficient and M is the molecular weight of water, R is the gas constant, H_v is the vaporization enthalpy, and $\bar{V}_W^v$, $\bar{V}_W^l$ are the molar volumes of steam and liquid water.

3. Simulation results

The simulation is conducted with a 3×3 fuel rod array. The geometric configuration of the rod array is depicted in Figure 2, while the boundary conditions employed for simulation are presented in Table 1. An axially consistent CRUD thickness of 25 μm is assumed, and the specific properties of CRUD are listed in Table 2. The axially uniform linear heat generation rate of 30 kW/m is applied to 9 fuel rods to simulate the subcooled nucleate boiling heat transfer region.

Table 1. Boundary condition of CUPID

Parameter	Value
Inlet temperature (K)	565
Inlet velocity (m/s)	4.76
Outlet pressure (MPa)	15.5

Table 2. Material properties of CRUD

Parameter	Value
Chimney density ($\#/mm^2$)	3000
Chimney radius (μm)	2.5
Porosity (-)	0.5
Thickness (μm)	25
Thermal conductivity (W/mK)	4.5

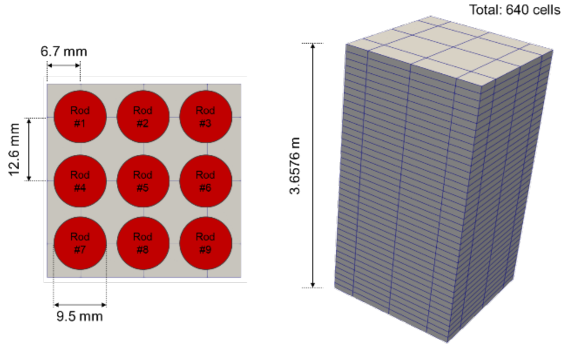
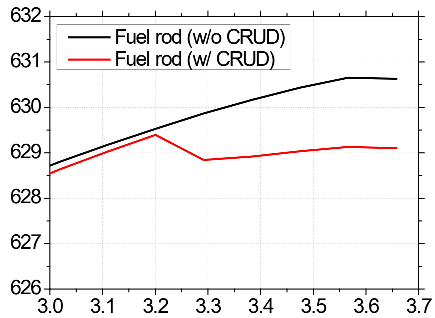
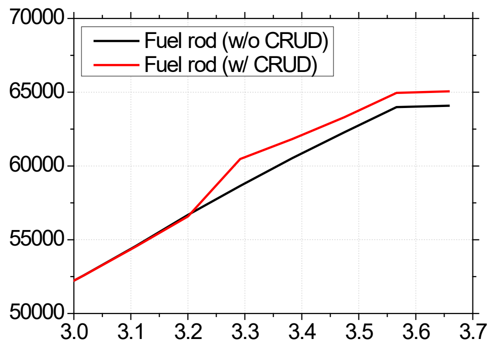


Figure 2. Geometry and size of a 3×3 fuel rod array

As a result, the wall temperature distribution is similar between fuel rods with clean surface and with CRUD deposition during the single-phase convection heat transfer region. Thus, the wall temperature and heat transfer coefficient of the upper part of fuel rod is presented in Figure 3 to investigate subcooled nucleate boiling region. The wall temperature of fuel rod with CRUD is reduced about 2 K. As the wall temperature decreases, the local heat transfer coefficient increases by 3%.



(a)Wall temperature distribution



(b)Heat transfer coefficient distribution

Figure 3. Distribution of (a) Wall temperature and (b) Heat transfer coefficient of rod #1 as the height

The heat of the fuel rod with CRUD is more removed by evaporation compared to the fuel rod with a clean surface due to wick boiling phenomena as shown in Figure 4. Thus, the void fraction of the fuel rod with CRUD is larger than the fuel rod with a clean surface as shown in Figure 5.

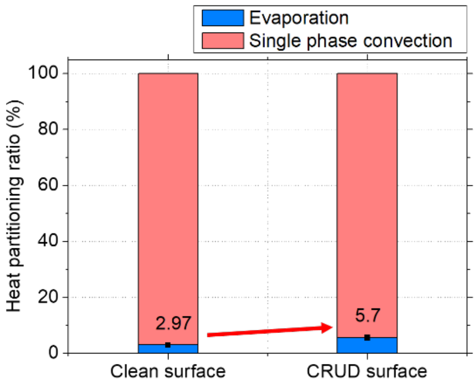


Figure 4. Heat partitioning ratio of fuel rods with a clean surface and CRUD surface

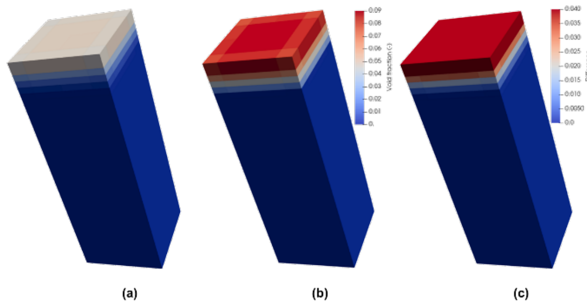


Figure 5. Calculation results of (a) void fraction of clean surface, (b) void fraction of CRUD surface, and (c) difference of void fraction between clean surface and CRUD surface

4. Conclusions

In this study, the CRUD heat transfer model is applied to CUPID/GIFT coupled code, and the effect of CURD on heat transfer in a 3×3 fuel rod array was investigated. In this simulation, axial uniform CRUD deposition is assumed and the CRUD heat transfer model calculates the evaporation heat flux and vapor generation rate on the wall. As a result, the wall temperature of the fuel rod with CRUD decreases, and the local heat transfer coefficient increases during the subcooled nucleate boiling region.

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