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Fuel Rod Heat Conduction Model in CUPID for Subchannel Scale Thermal-hydraulic Analysis

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1. Introduction

With the advances in computing power, applications of the high-fidelity and multi-physics reactor core analysis using coupled T/H(Thermal-Hydraulics) code and neutronics code have been attempted [1]. For instance, the CASL program showed the feasibility of the full core pin-by-pin analysis and subchannel scale accident analysis. Using the subchannel scale TH code, COBRA-TF [2], transient full core analyses for the MSLB (Main Steam Line Break), RIA (Reactivity Initiated Accident) and CLOF (Complete Loss-of-Flow) transient were progressed.

KAERI is developing CUPID for the multi-dimensional two-phase flow analysis and one promising application of the code is the reactor core accident analysis. For that purpose, its capability has been extended to the subchannel scale analysis by implementing relevant models, such as the turbulent mixing and void drift [3]. However, the subchannel analyses were conducted with imposing volumetric heat directly into the liquid instead of modeling the heaters or fuel rods.

In the present study, the fuel rod conduction equation for the subchannel analysis was implemented into CUPID and subchannel scale analysis was conducted using it for demonstration. Distinctive feature of the fuel rod model is that a single rod is divided into four subsections and each quarter is assigned to an adjacent subchannel avoiding the average procedure to enhance the resolution of the simulation.

2. Fuel Rod Heat Conduction Model

The heat conduction equation is required to simulate the heat transfer from the fuel rod to coolant. The fuel rod is composed of the UO_2 fuel pellet, cladding made of zircaloy and the gap between pellet and cladding.

2.1 Governing equation

The heat transfer inside the fuel rod and cladding is assumed as a one-dimensional heat transfer about r_{pellet}, r_{gap} and $r_{cladding}$ as shown in Fig. 1. The governing equation used for calculation of one-dimensional heat transfer was implemented on CUPID as below [4],

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + \dddot{q}\ . \quad (1)$$

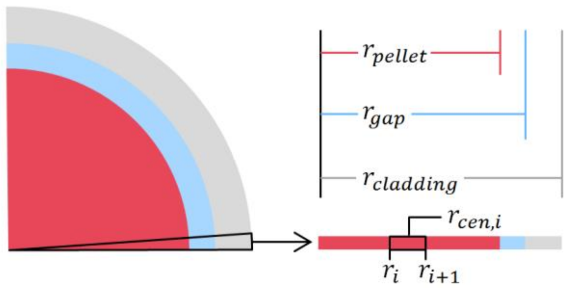


Fig. 1. Schematic view of one-dimensional heat transfer inside of the fuel rod

2.2 Gap conductance model

For the gap modeling between the pellet and the cladding, the assumption could be used; gap is the thin film which contains thermal resistance. The simulation of heat transfer from the pellet getting through the gap to the cladding is possible by the solving convection equation. If the contact effect caused by ballooning is neglected, it is the model [5] for determining the gap heat transfer coefficient h as below,

$$h_g = \frac{k_{gas}}{\delta_{eff}} + \frac{\sigma}{(1/\varepsilon_f)+(1/\varepsilon_c)}\frac{T_{fo}^4 - T_{ci}^4}{T_{fo} - T_{ci}}, \quad (2)$$

where, k_{gas} : thermal conductivity of the gas,
δ_{eff} : effective gap width,
σ : Stefan-Boltzman constant,
ε_f , ε_c : surface emissivity of the fuel and cladding,
T_{fo} : fuel surface temperature,
T_{ci} : cladding inner surface temperature.

3. Modelling of Fuel Rod for Subchannel Scale Analysis

3.1 Heat transfer from a quarter rod

The non-uniform power distribution was provided with each rod for the simulation of the fuel rod temperature and the liquid behavior. The single subchannel is adjacent to one, two, and four fuel rods if it is located at a corner, side, and center in the assembly, respectively, as shown in Fig. 2. Therefore, a single rod is divided into four sections and allocated to the adjacent subchannel for more accurate calculation of translated power on subchannel. Applying this methodology, an average procedure which may smear the temperature difference among the subchannels can be avoided and better resolution of the temperature and power distribution is expected. The azimuthal direction heat conduction in the rod is neglected.

It is required to solve the heat transfer equations as many as the number of fuel rods which are adjacent to each subchannel. As shown in Fig. 2, the total amount of power on single subchannel I is the quarter of the sum of power from the rods 1~4. Dittus-Boelter equation was used as a heat transfer coefficient.

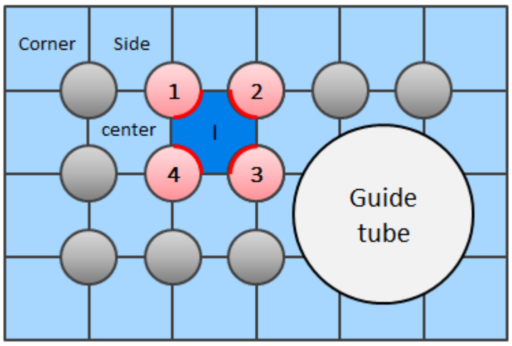


Fig. 2. Schematic view of subchannels

3.2 Visualization of calculation result

As the single subchannel could be adjacent to at most four fuel rods, the single rod contains four individual temperature informations. In this reason, it is necessary to visualize different temperatures at each quarter of the fuel rod. The post-processing module of CUPID was modified for this visualization using Paraview. As show in Fig. 3, the four subsections in a single rod are plotted and four different temperatures can be allocated. Additionally, the visualization considers the location and size of guide tubes.

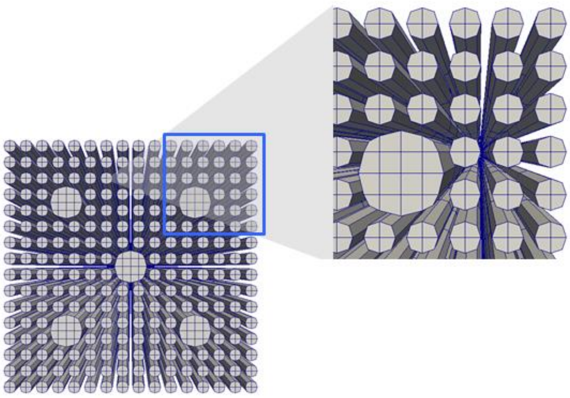


Fig. 3. Modeling of 16x16 single assembly including guide tube model

3.3. Demonstration for single assembly calculation result

For the verifying of fuel rod heat conduction model, the demonstration of subchannel scale calculation result of single assembly which consists of 16x16 rods was progressed. The implemented power on single assembly was obtained from the power distribution in APR1400 (3, 6) assembly indicated with a square box in Fig. 4. The power distribution is from the neutronics code, nTRACER [6]. The imposed power distribution was presented in Fig. 5 (a).

The power which transferred from the fuel rod to the coolant causes the change of coolant temperature distribution and the fuel rod surface temperature distribution. They are presented in Fig. 5 (b) and (c). The calculated liquid velocity is presented in Fig. 5 (d).

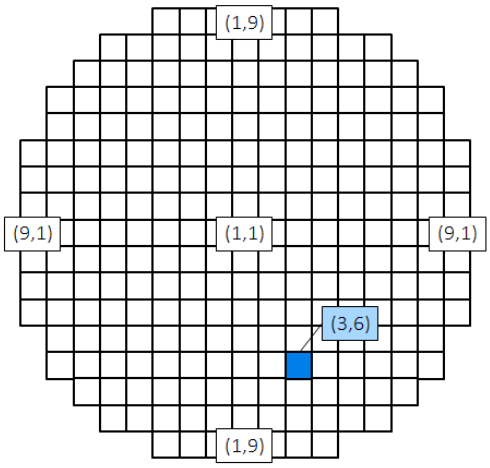
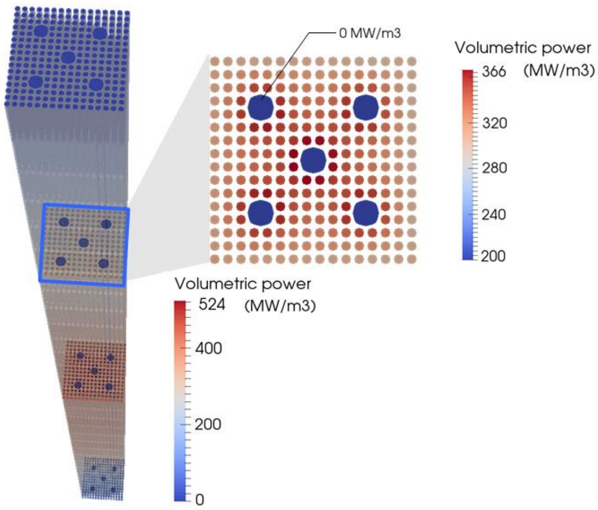
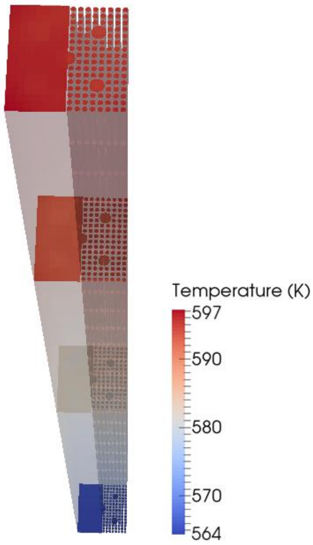


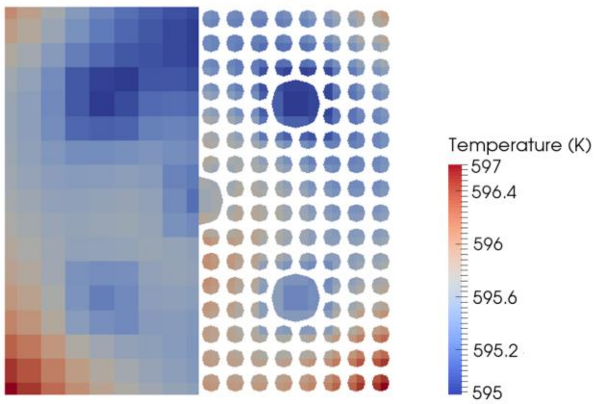
Fig. 4. Location of the imposed power distribution of the calculation of single assembly



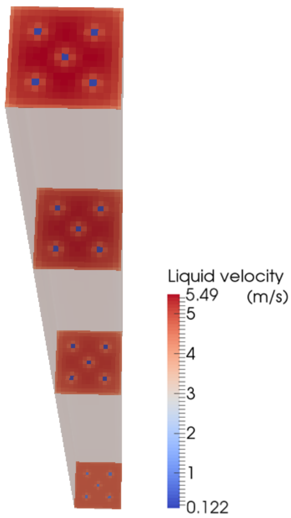
(a) Power distribution



(b) Liquid and cladding temperature distribution : isometric view



(c) Liquid and cladding temperature distribution : horizontal cross-sectional view at the outlet



(d) Liquid velocity distribution : isometric view

Fig. 5. Imposed power, calculated temperature and calculated liquid velocity distribution

4. Conclusions

In this paper, the fuel rod heat conduction model which considers the four different temperatures for a single fuel rod was implemented. Thereafter, the demonstration of the subchannel scale T/H analysis for a single assembly of APR1400 was progressed. The temperature distribution of the coolant and the surface cladding surface temperature were predicted to demonstrate the performance of the implemented model.

In the future, systematic validation will be conducted against available database of rod bundle two-phase flow experiments.

ACKNOWLEDGEMENT

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