Coupling of CUPID subchannel module with neutron kinetics code and fuel performance code for pin-wise multi-physics

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1. Introduction

Recently, multi-physics simulation tools such as MARS/FRAPTRAN [1] and multi-scale & multi-physics (MSMP) coupled code [2] have been developed for realistic safety analysis. These simulation tools aim to reduce the safety margins typically observed in traditional conservative safety analysis by employing high-fidelity simulations, potentially enhancing cost-effectiveness. In particular, it was confirmed that using the MSMP approach with the same initial fuel rod conditions for whole rods calculated from a hot pin reduces the safety margin [2]. For a more realistic simulation, pin-wise initial fuel rod conditions are necessary, and CUPID was coupled with a fuel performance code, GIFT, to provide the whole fuel rods information in our previous study [3].

In this study, a neutron kinetic code, MASTER [4], was additionally coupled with CUPID/GIFT to incorporate a realistic rod-wise power distribution. The rod-wise power distributions were compared between CUPID/MASTER [5] and CUPID/GIFT/MASTER to assess the effect of the feedback from the fuel performance code.

2. Numerical methods

This section provides a brief introduction to the CUPID/MASTER/GIFT coupled code and coupling methodology.

2.1 CUPID/MASTER/GIFT coupled code

CUPID [6] is a 3D thermal hydraulics code developed by KAERI. It is extended to subchannel-scale thermal hydraulics analysis by SNU and validated against subchannel experiments [7]. MASTER is a 3D neutron kinetics code developed by KAERI. It is based on the multi-group diffusion theory to calculate the steady-state and transient PWR core design. GIFT [8] is a 2D steady-stated fuel performance code developed by SNU. It can evaluate 2D (r-z) cladding deformation different from conventional 1-D fuel performance codes such as FRAPCON [9] and FINIX [10].

2.2 Coupling methodology

The configuration for the coupled code developed in this study is schematically summarized in Fig.1. Basically, CUPID has its heat structure model which includes a simple gap conductance model. In order to capture realistic fuel rod behavior, GIFT replaced it coupling through socket communication. GIFT provides the fuel temperature and deformation information based on the fluid boundary conditions obtained by CUPID. Additionally, CUPID can modify the subchannel geometry considering fuel deformation and calculate thermal-hydraulics based on the deformed geometry. Furthermore, to obtain realistic power distribution, MASTER is coupled with CUPID using a dynamic link library (DLL). It can calculate power distribution using fuel temperature from GIFT and coolant information from CUPID including fuel deformation. The coupled code utilized Picard iteration to obtain converged results at each steady-state during normal operation. The relative changes in power and coolant temperature during several Picard iterations were used to check convergence in this simulation. The criteria were set at 0.1 W for power and 0.01 K for coolant temperature.

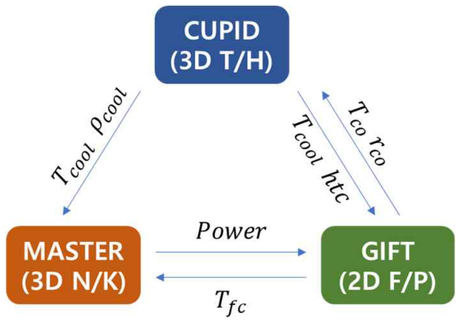

Fig 1. Schematic diagram of CUPID/MASTER/GIFT coupled code and coupled variables

3. Simulation results

The steady-state simulation is conducted for the OPR1000 full core at the end of cycle (EOC) of the first cycle. The reactor geometry consists of 177 fuel assemblies which are composed of 16x16 fuel rod arrays with 5 guide tubes. The computational meshes have 22 axial meshes and each axial plane has 51,135 meshes as shown in Fig.2. There are reflector meshes at the top and bottom for neutron kinetic calculation. For thermal-hydraulic and fuel performance calculation, the active core region without reflector cells is utilized. The boundary condition and initial condition for simulation are summarized in Table 1 and Table 2.

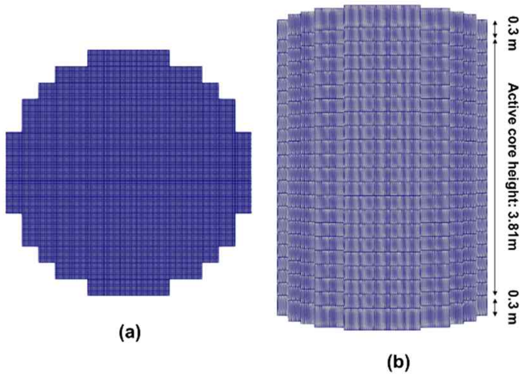

Fig 2. Computational mesh ((a) top view, (b) side view)

Table 1. Boundary condition of CUPID

Parameter	Value
Inlet temperature (K)	563.9
Inlet velocity (m/s)	4.8
Outlet pressure (MPa)	15.93

Table 2. Initial condition of GIFT

Parameter	Value
Cladding diameter (mm)	9.5
Cladding thickness (mm)	0.57
Gap thickness (mm)	0.084
Pellet roughness (mm)	2.0E-3
Pellet roughness (mm)	5.0E-3
Fill gas property (-)	Helium (100%)
Fill gas pressure (MPa)	1.27
Cold work (-)	0.5

To verify the coupled code for fuel deformation, a change of porosity, representing the volume fraction of coolant at each cell, is calculated. Fig.3(a) shows the distribution of the porosity differences between the initial and deformed fuel rods, and Fig.3(b) shows the deformation of the fuel rods. The radius of the fuel rods decreased, leading to an increase in the porosity calculated from the deformed fuel rods.

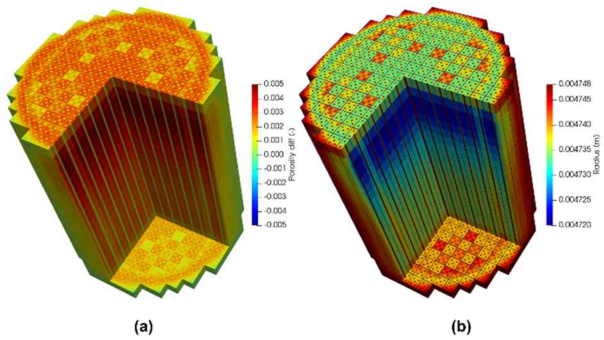

Fig 3. Simulation results ((a) change of porosity, (b) radius distribution)

The simulation results of the coupled code are shown in Fig.4(a) and Fig.5(a). As shown in Fig.4(b), the power distribution calculated by CUPID/MASTER/GIFT differs from that calculated by CUPID/MASTER. In this simulation, the density and temperature of the coolant were observed to be similar, whereas a significant difference was observed in the fuel centerline temperature between CUPID/MASTER/GIFT and CUPID/MASTER as shown in Fig.5(b). Therefore, the disparity in power distribution is attributed to the variation in the fuel centerline temperature, which is affected by gap conductance.

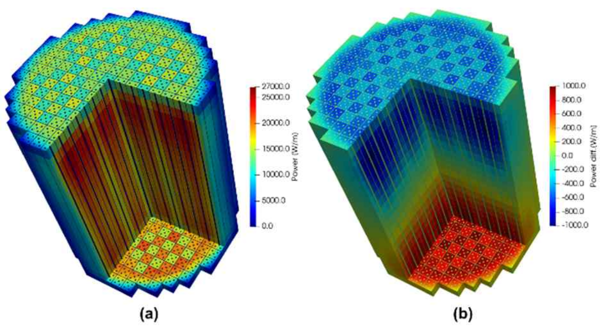

Fig 4. Simulation results of power distribution ((a) [CUPID/MASTER/GIFT], (b) [CUPID/MASTER/GIFT] – [CUPID/MASTER])

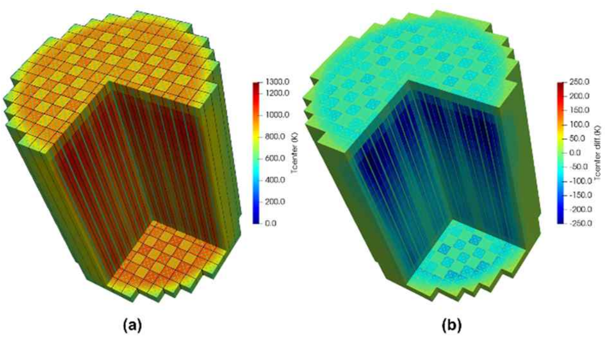

Fig 5. Simulation results of fuel centerline temperature ((a) [CUPID/MASTER/GIFT], (b) [CUPID/MASTER/GIFT] – [CUPID/MASTER])

Fig.6(a) and Fig. 6(b) show the distribution of the thermal gap and gap conductance calculated by CUPID/MASTER/GIFT. The thermal gap closure, caused by outward pellet deformation and inward cladding creep, was observed in the upper region of the fuel rod, which has the highest power. This was accompanied by an increase in gap conductance. Consequently, the fuel centerline temperature in the upper region decreased significantly due to the higher gap conductance. This phenomenon could not be reproduced in the CUPID/MASTER simulation.

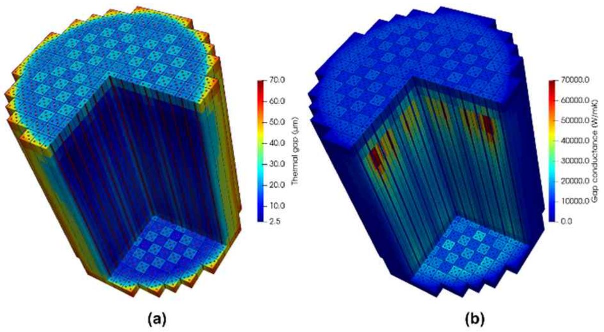

Fig 6. Simulation results ((a) thermal gap distribution, (b) gap conductance distribution)

4. Conclusions

In this study, the CUPID/MASTER/GIFT coupled code was established and preliminary multi-physics simulation was performed. It is confirmed that a realistic power distribution is calculated considering thermal-hydraulics and fuel deformation. Thus, the coupled code can generate accurate fuel rod information for each fuel rod including realistic power and spatial thermal-hydraulics during normal operation. It is expected to support a more realistic safety analysis using the MSMP approach with accurate initial conditions of each fuel rod.

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