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Preliminary Multi-Physics Analysis of OPR1000 Reactor Core using Coupled CUPID and nTER

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1. Introduction

As the multi-physics phenomena such as Axial Offset Anomaly (AOA), Fuel Fragmentation, Relocation and Dispersion (FFRD) became critical issues in respect to reactor design and safety margin in the nuclear power industry, the necessity of high-fidelity and multi-physics simulation has increased for their application to the safety analysis [1, 2]. With the increasing demand, multi-physics high-fidelity simulation platforms have been developed such as MOOSE [3], VERA [4], NURESIM [5], etc. In the simulation platforms, subchannel thermal-hydraulic analysis codes are widely used as they are the practical tools with reasonable accuracy and endurable calculation time for a whole reactor core simulation.

CUPID [6] is a three-dimensional two-phase flow analysis code developed by KAERI, which adopts the two-fluid/three-field model with unstructured mesh. In our previous studies [7, 8], the fundamental subchannel models such as friction models, turbulent mixing model, void drift model, and grid-directed cross-flow model were implemented to extend the capability of CUPID to the subchannel analysis.

As a next step toward the high-fidelity multi-physics simulation, coupling between CUPID and a neutron transport code was established in the present study. nTER was used for the neutronics simulation, which is under development by KAERI with the cooperation of KHNP-CRI aiming at whole core pin-wise analysis [9]. This paper introduces the coupling method and data mapping strategy utilizing a socket-based data communication and preliminary coupled simulation results for the quarter core of OPR1000.

2. Coupling Methods and Data Mapping

Multi-physics analysis using coupled CUPID and nTER is aimed for considering reactivity feedback in the process of whole core pin-by-pin simulation. Two codes were coupled through the socket based server program, NTER2CPD developed by KAERI, and required data for the coupling are exchanged under its control.

2.1 Coupling Variables and Method

The variables exchanged between two codes during the coupled simulation are listed in Table 1. CUPID and nTER run simultaneously and perform its own calculation independently for initialization of data exchange. After the designated time, the variables are exchanged via NTER2CPD and its frequency depends on the problem time in CUPID, generally 0.8 sec. in the present simulation. The schematic diagram of the coupling mechanism is shown in Fig. 1.

Table 1: CUPID-nTER coupling variables

Code	Variables
CUPID	Coolant temperature Coolant density Pellet centerline temperature Pellet surface temperature Cladding surface temperature
nTER	Pin power

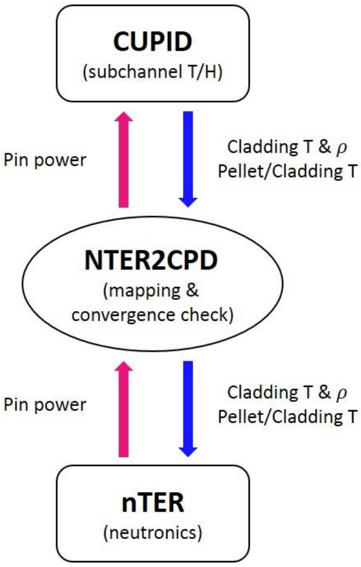


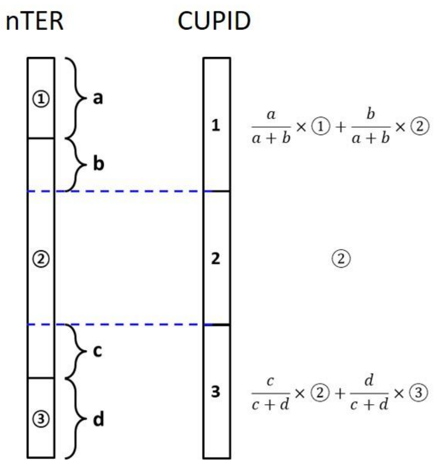
Fig. 1. Schematic diagram of coupled CUPID and nTER

2.2 Data Mapping

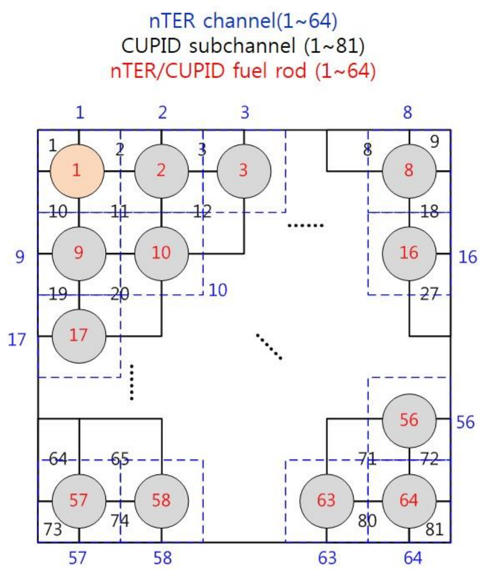
Since geometrical modeling for a reactor core can be different from each other depending on the physics they deal with, the data mapping should be performed to conserve the physical quantities during the coupled simulation. In the procedure of variable exchange, the mapping is progressed in NTER2CPD for both axial and radial directions.

The number of axial grids for CUPID and nTER is 41 and 26, respectively, and the mapping in the axial direction is progressed by adopting a weighting factor, which is proportional to the axial length of each corresponding grid. Fig. 2 (a) shows an example of axial mapping between two different grids.

The radial mapping is performed on the basis of subchannels and fuel rods. In the recent study, fuel rod conduction model in CUPID was improved and the existing rod-centered method was replaced with the channel-centered method for more realistic simulation by removing an averaging procedure for subchannel TH information [10]. Therefore, as shown in Fig. 3, a single fuel rod in CUPID encounters four different subchannels and has four different temperature distributions for each quarter rod. For a radial mapping, a fuel rod in nTER was matched with a fuel rod and surrounding four subchannels in CUPID. The guide tube illustrated in Fig. 3 replaced four fuel rods in CUPID and nTER modeled it as four fuel pins with zero-power. To guarantee a one-to-one match for fuel rods between CUPID and nTER, the averaged temperature of four quarter rods is used as a representative value of each fuel rod in CUPID.



(a) Axial mapping



(b) Radial mapping

Fig. 2. Data mapping method for (a) axial and (b) radial directions

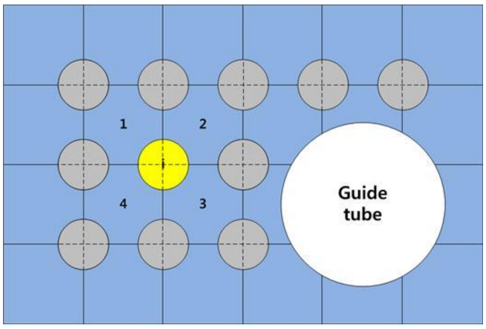


Fig. 3. Channel-centered geometry in CUPID

3. Preliminary Analysis for OPR1000 Rector Core

Using the coupled CUPID and nTER code, the preliminary subchannel analysis against a quarter of the OPR1000 reactor core was performed under the steady-state condition. The objective of this preliminary calculation was to confirm whether the coupled simulation is well performed and the convergence of the exchange variables in CUPID.

3.1 Simulation Condition

The computational mesh of the OPR1000 quarter core for CUPID was generated using the open-source tool, SALOME [11]. In the axial direction, the heated length of 3.81m was divided into 40 uniform cells and an additional cell was added to the top in order to apply the pressure boundary condition at the core exit. The total numbers of fluid and solid cells are 598,928 and 464,448, respectively. By adopting a porous medium approach, porosity and permeability were applied in accordance with the subchannel type. Fig. 4 shows the configuration of the mesh used in CUPID.

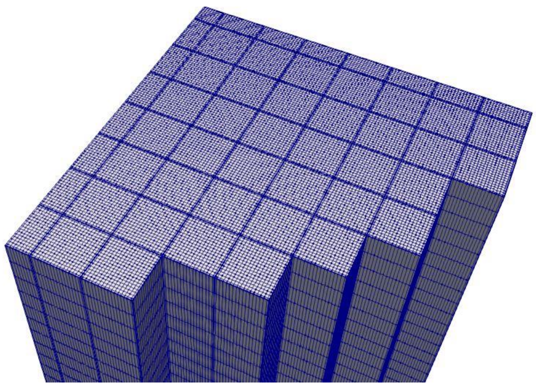


Fig. 4. Isometric view of mesh in CUPID

For a numerical scheme, energy coupled Implicit Continuous Eulerian (ICE) method was used for CUPID [6] and the time interval for exchanging coupling variables was set as 0.8 seconds based on the problem time of CUPID. The initial and boundary conditions are listed in Table 2.

Table 2: Initial and boundary conditions

Initial and boundary conditions	Value
Pressure	155.13 (bar)
Liquid velocity	4.69 (m/s)
Liquid temperature	296 (℃)
Solid temperature	296 (℃)
Boundary pressure	155.13 (bar)

3.2 Simulation Result

The coolant and fuel rod temperature distributions were obtained through the coupled simulation in CUPID. As illustrated in Fig. 5, the coolant temperature distribution at the core exit changed according to the pin power input from nTER. It shows reactivity feedback phenomena during the coupled TH/neutronics simulation. In addition, by solving the fuel rod conduction equations, pellet centerline, pellet surface, and cladding surface temperatures were obtained. Fig. 6 shows the pellet centerline and cladding surface temperature of assembly 30, which is marked as a yellow box in Fig. 5, at Z/H=0.6.

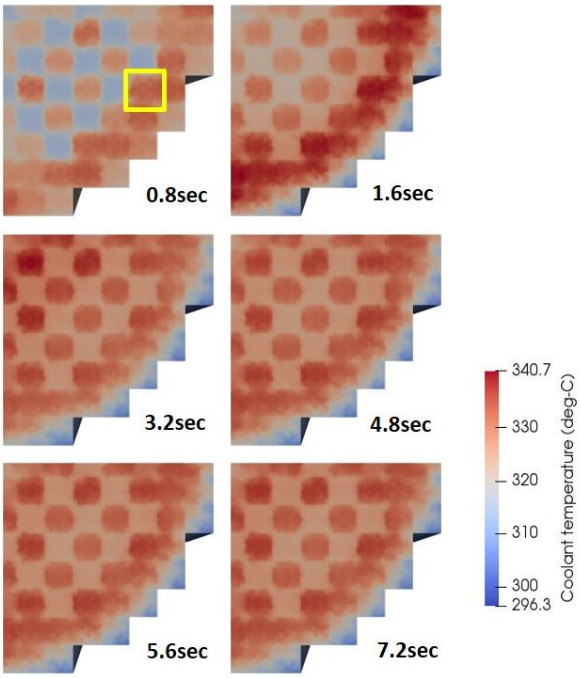
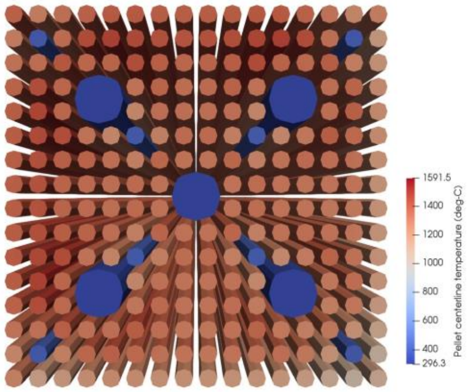
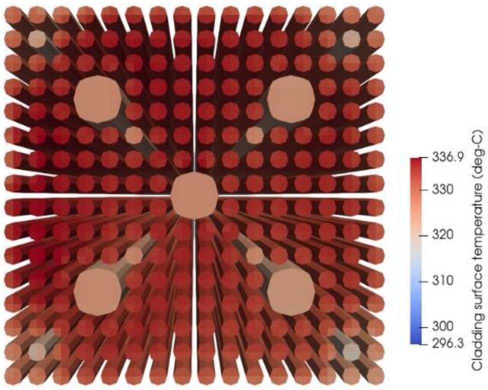


Fig. 5. Coolant temperature distribution at the core exit



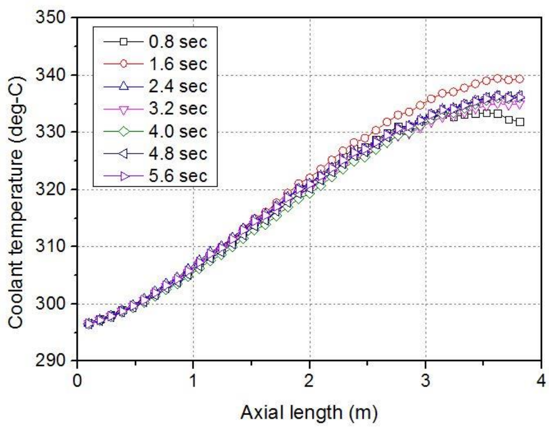
(a) Pellet centerline temperature



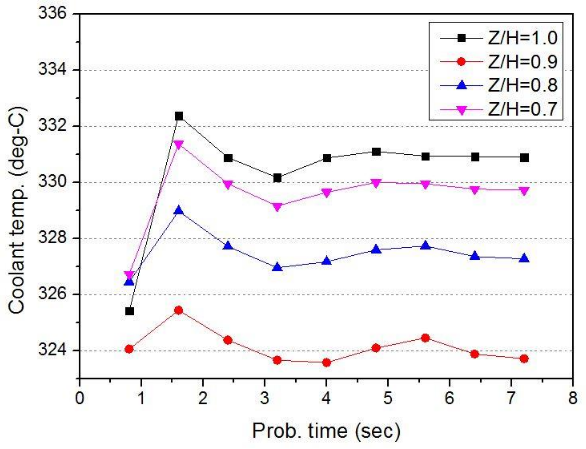
(b) Cladding surface temperature

Fig. 6. Fuel rod temperature distribution of assembly 30 at Z/H=0.6

To check the convergence of coupled simulation for CUPID, the axial coolant temperature of the particular center subchannel was confirmed. The axial coolant temperature distributions in the period of exchange frequency are illustrated in Fig. 7 (a). In addition, Fig. 7 (b) shows the coolant temperature variation during the simulation at four different axial locations. From these figures, around 5 seconds, it was confirmed that the coolant temperature converged to the specific value. The quantitative criteria for convergence need to be set in future work.



(a) Axial coolant temperature distribution



(b)

Fig.7. The convergence of coolant temperature at the assembly 42 center subchannel

4. Conclusion

As multi-physical phenomena in the nuclear reactor become critical issues related to nuclear safety, the necessity of high-fidelity and multi-physics analysis has also increased. In this study, using a two-phase flow analysis code, CUPID and whole core neutron transport code, nTER, preliminary thermal-hydraulics/neutronics coupled simulation was performed on a subchannel scale for a quarter core of OPR1000 reactor. As a result, the coolant and fuel rod temperature distributions considering reactivity feedback were obtained.

In the future, the improvement of the robustness and stability of the coupled code would be progressed. In addition, the benchmark problem for coupling simulation would be chosen and the validation shall be performed.

ACKNOWLEDGEMENT

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REFERENCES

[1] M. P. Short, Finding the Cure for CRUD: Combined Simulations & Experiments at CASL & MIT, CASL Technical Report: CASL-U-2015-0109-000, 2013.

[2] H. Sonnenburg et al., Report on Fuel Fragmentation, Relocation and Dispersal, NEA/CSNI/R(2016)16, 2016.

[3] D. Gaston et al., MOOSE: A parallel computational framework for coupled systems of nonlinear equations, Nuclear Engineering and Design, Vol. 239 (10), pp. 1768-1778, 2009.

[4] S. Palmtag, Demonstration of neutronics coupled to thermal-hydraulics for a full-core problem using VERA, CASL Technical Report: CASL-U-2013-0196-000, 2013.

[5] C. Chauliac et al., NURESIM - A European simulation platform for nuclear reactor safety: Multi-scale and multi-physics calculations, sensitivity and uncertainty analysis, Nuclear Engineering and Design, Vol. 241 (9), pp. 3416-3426, 2011.

[6] Korea Atomic Energy Research Institute, "CUPID Code Manuals Vol. 1: Mathematical Models and Solution Methods Version 1.9", 2014.

[7] S. J. Yoon, S. B. Kim, G. C. Park, and H. K. Cho, Application of subchannel-scale thermal-hydraulic analysis of pressurized water reactor core under single-phase conditions, Nuclear Engineering and Technology, Vol. 50, pp. 54-67, 2018.

[8] S. B. Kim, J. H. Lee, G. C. Park, and H. K. Cho, The im8plementation of Mixing Vane Directed Cross Flow Model in CUPID for Subchannel Scale T/H Analysis, Transactions of the Korean Nuclear Society Spring Metting, Jeju, Korea, May 17-18, 2018.

[9] J. Y. Cho et al., Performance of a Whole Core Transport Code, nTER, The 6th International Conference on Nuclear and Renewable Energy Rsources (NURER 2018), Jeju, Korea, Sep. 30-Oct. 3, 2018.

[10] S. B. Kim (2018). Improvement of Subchannel Scale Analysis Capability of CUPID with Grid-directed Cross Flow and Fuel Rod Models (Unpublished master's thesis). Seoul National University, Seoul, Republic of Korea.

[11] A. Ribes, and C. Caremoli, Salome platform component model for numerical simulation, In Computer Software and Applcations Conference, COMPSAC 2007, 31th Annual International, Vol. 2, pp. 553-564, IEEE, 2007.