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Practical reactor core pin-by-pin analysis using subchannel module of CUPID coupled with fuel performance code FINIX

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1. Introduction

The nuclear fuel burnup has continuously increased to improve energy efficiency. This leads to nuclear fuel behavior, such as oxidation, fuel fragmentation, and relocation, which can deteriorate the integrity of fuel [1]. For the safety analysis, multi-physics coupling technology has been noticeable to predict diverse and complex phenomena. Because each rod contacts with subchannel, it is important to consider the feedback between thermal-hydraulic and fuel behavior. Through this, optimal state of reactor core can be derived. Based on the multi-physics-coupled analysis, there is a need for a study to calculate entire fuel rods in the core [2]. By performing the pin-by-pin analysis, it is possible to apprehend the overall state of fuel such as internal pressure, oxide thickness, thermal properties and temperature, and to obtain an accurate rod state for initial conditions of accident analysis.

In our previous study, the development and verification of CUPID-FINIX, which is the coupled code between the CUPID subchannel module and the nuclear fuel code FINIX, was performed [3]. Postulated transient simulation was well demonstrated for VERA benchmark assembly geometry with 289 rods. For the code coupling, the multi-port method was selected to configure socket communication. However, there is a limit to the number of ports that can be opened for reactor core scale analysis.

In this study, CUPID-FINIX was applied to VERA benchmark quarter core geometry with 14,072 fuel rods. To this end, the single-port method, which has good extensibility, with parallelized FINIX was adopted. For parallelization of FINIX, both MPI and OpenMP methods were used, and comparative analysis was performed. Afterwards, one cycle calculation was conducted under the normal operation condition. Not only individual rod results but also assembly and overall reactor core level fuel state are presented.

2. Methodology of code coupling

2.1 Code description

CUPID is a three-dimensional two-phase flow thermal-hydraulic analysis code developed by KAERI. It has subchannel analysis capability by implementing cross flow, turbulent mixing, and void drift model [4]. The simple fuel module which can calculate one-dimensional heat transfer has been used in CUPID. However, the module cannot deal with rod deformation and realistic fuel behavior along burnup. Therefore, for the high-fidelity of safety analysis, FINIX was selected to reflect the thermal-mechanical behavior of nuclear fuel. FINIX has been developed by the Finnish research institution, VTT. Unlike other legacy fuel codes, it is possible to analyze both steady-state and transient situations. VTT has implemented and validated the fuel behavior model, such as densification, swelling, and creep, to consider the burnup effect and rod deformation [5, 6].

2.2 Code coupling

The coupling method of CUPID-FINIX is based on TCP/IP socket communication which is one of the external coupling methodologies. The interface program, FINIX2CPD, was developed to manage port connections and data transfers. Fig. 1 shows coupling variables and calculation procedure. From CUPID to FINIX, coolant temperature and heat transfer coefficient between rod and subchannel are transmitted. Adversely, fuel temperature and cladding radius reflecting rod deformation are sent from FINIX to CUPID. Because the basic principle of the fuel code is one execution for one rod, oversubscription and parallelization of FINIX are inevitable for the reactor core scale analysis.

In the previous study, a multi-port method with less code modification was adopted for assembly scale analysis. However, it has bad extensibility owing to the limits of processes and ports. In the case of core level analysis, the single-port method with parallelized FINIX is selected to minimize the number of ports and processes. Both multi-port and single-port methods are illustrated in Fig. 2. To devise the single-port method, parallelization of FINIX was conducted using MPI and OpenMP. Because MPI uses distributed memory, the probability of memory invasion between each rank is low, and additional data communication time occurs. In the case of OpenMP technology, there is no need for data communication between each rank because it uses shared memory space that all ranks can access.

Although the single-port method is used, there is a limit to the number of processes that one CPU can handle; therefore, the maximum processes of each CPU node had to be measured as summarized in Table 1. Based on these limits, calculations were distributed appropriately to each node as can be seen in Table 2. The CPU node numbers 1 to 4 are E5-2660 models and 5 to 15 are E5-2680 models. Since the measured maximum processes were 800 and 1,400, respectively, the distributed number of rod calculations was less than those limits. Regarding running FINIX on multiple nodes, there are two ways; one is to manually execute by accessing directly to each node, and the other is the MPI method using python script in the master node which enables one-click execution. This MPI method is for execution only and is a concept distinct from the method used for FINIX parallelization. Fig. 3 shows the relative calculation time based on the method that takes the least time. The combination of parallelized FINIX using OpenMP and automatic execution using MPI in the master node shows the best performance in initialization, which is the port connection step, and calculation.

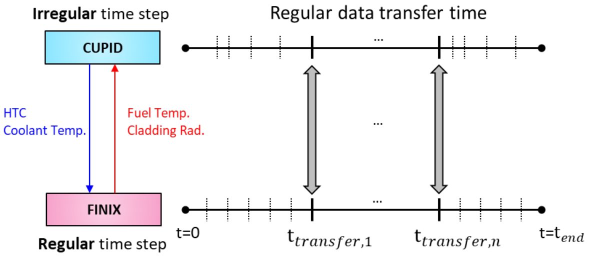
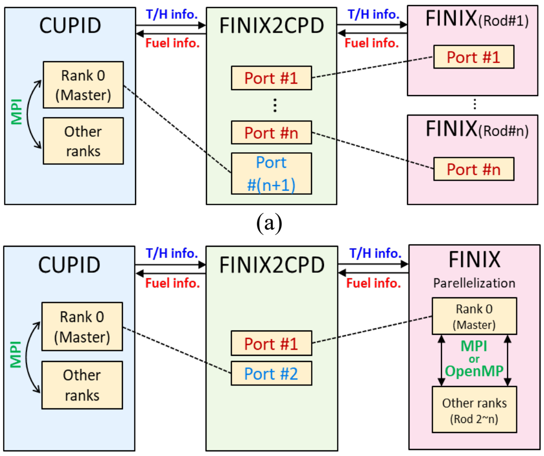


Fig. 1. Procedure of CUPID-FINIX calculation



(b)

Fig. 2. (a) Multi-port and (b) single-port method of CUPID-FINIX

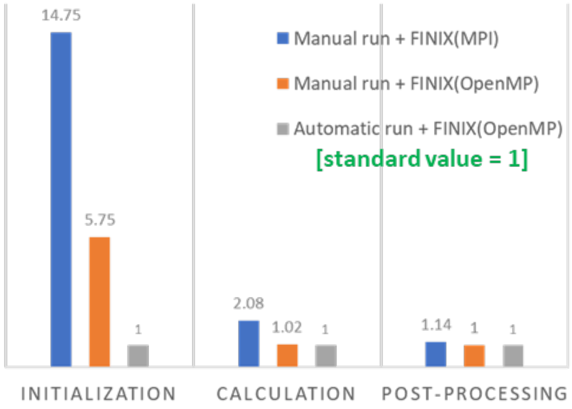


Fig. 3. Relative calculation time of Manual run + FINIX (MPI), Manual run + FINIX (OpenMP) and Automatic run + FINIX (OpenMP)

Table 1: CPU information and maximum processes

CPU name	Threads	Maximum processes
Intel(R) Xeon(R) CPU E5-2660 v2 @ 2.20GHz	20	~ 800
Intel(R) Xeon(R) CPU E5-2680 v4 @ 2.40GHz	28	~ 1,400

Table 2: Node distribution for VERA quarter core simulation

Node	Threads	Code	processes	Processes /threads
1-2	20/node	FINIX	736/node	36.8
3-4	20/node	CUPID	20/node	1
5-13	28/node	FINIX	1400/node	50
14-15	28/node	CUPID	28/node	1

3. Calculation results

3.1 Problem specification

The VERA benchmark core geometry is Watts Bar Nuclear 1 (WBN1) designed by Westinghouse (Fig. 4) [7]. Considering the symmetrical characteristic, a quarter core analysis with 14,072 rods and 15,633 subchannels was performed. The number of radial and axial fuel nodes are 18 and 40, respectively. The power distribution for each fuel rods was obtained from the results of pin-wise CUPID-nTER depletion calculation. As can be seen in Fig. 5, the initial power distribution is cosine shape with peaks biased downwards, gradually flattening out over time.

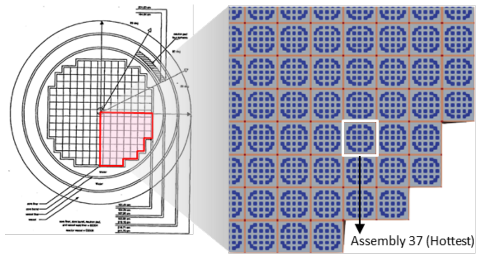


Fig. 4. VERA benchmark quarter core geometry (WBN 1) [7]

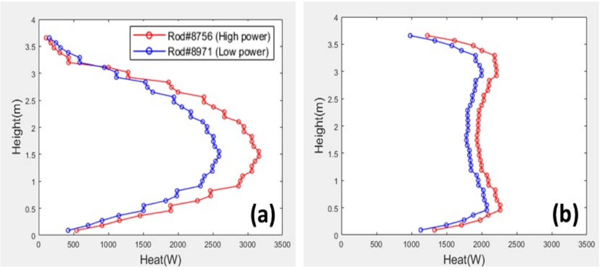


Fig. 5. Axial power of representative rod number 8756 and 8971 at (a) BOC and (b) EOC

One cycle (approximately 440 days) calculation with normal operating conditions was conducted. All of the FINIX fuel models, such as densification, swelling, creep, and oxidation, were activated. In Table 3, the design parameters of the fuel rod in FINIX are summarized.

Table 3: Design parameter of fuel rod in FINIX

FINIX rod inputs	Value
Pellet outer radius	0.004096 m
Cladding inner radius	0.00418 m
Cladding outer radius	0.00475 m
Fuel height	3.6576 m
Plenum length	0.16 m
Pellet roughness	2 μm
Cladding roughness	0.5 μm
Fill gas property	Helium (100%)
Fill gas pressure	1.207 MPa
Fill gas temperature	300 K

3.2 Results and discussion

Fig. 6 shows the deformation of rod number 8756, which is located at the hottest assembly. At the beginning of cycle (BOC), pellet expansion was noticeable due to thermal expansion while changes in the cladding were rarely observed. In the middle height range, it was confirmed that the gap, which was initially open, was closed owing to the expansion of the pellet and the contraction of the cladding at the end of cycle (EOC). The details of gap behavior can be seen in Fig. 7. Initially, the gap expanded because of densification, which is the pellet contraction phenomenon. After that, gap volume was shrunk because of the combined effect of pellet expansion due to swelling and cladding contraction due to creep deformation. The behavior of the gap directly affects the rod internal pressure calculated using the ideal gas equation of state. As can be seen in Fig. 8 and Fig. 9, the distribution of increasing rod internal pressure can be demonstrated at the assembly and core levels.

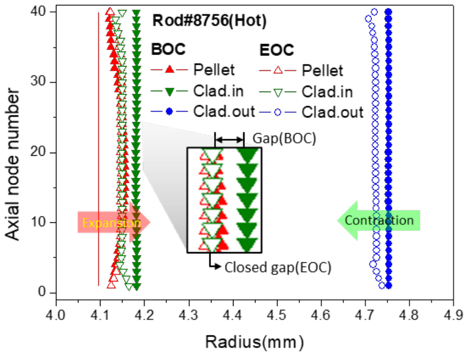


Fig. 6. Rod deformation of rod No. 8756 at BOC and EOC

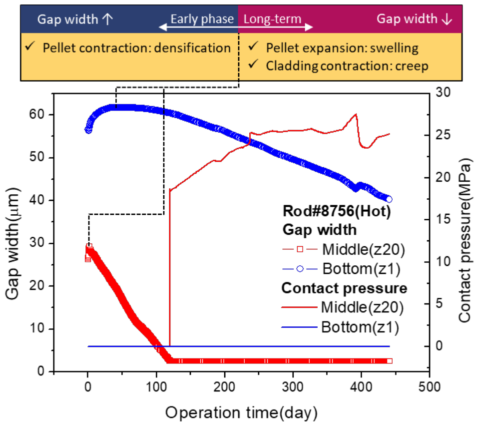


Fig. 7. Gap width and contact pressure of rod No. 8756 at the bottom (z1) and middle height (z20)

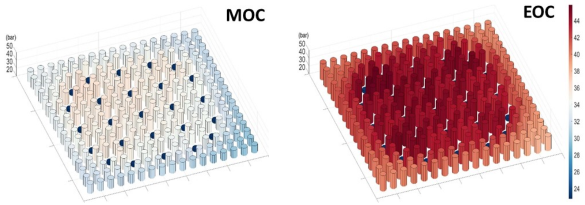


Fig. 8. Rod internal pressure at assembly No. 37 (hottest)

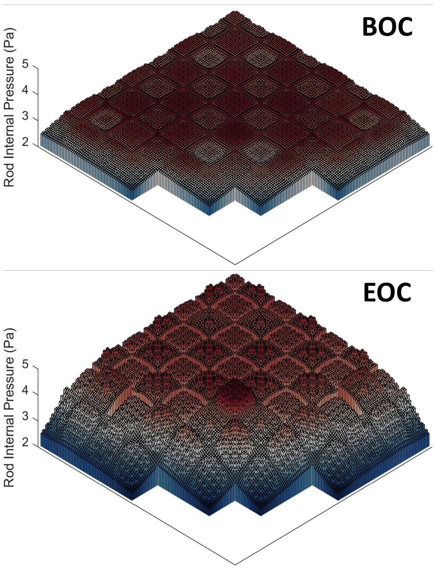


Fig. 9. Overall rod internal pressure in the quarter core

The changed cladding radius due to the rod deformation was transmitted to the CUPID, and the hydraulic diameter and porosity, which is related to flow area, were updated. In Fig. 11, the difference in porosity, which is proportional to flow area, between the CUPID standalone and CUPID-FINIX was demonstrated. The flow area temporarily decreased at the beginning, and then increased by reflecting the contracted rod radius at the end of the cycle. However, as can be seen in Fig. 12, the coolant temperature did not show significant difference because the change of radius was relatively very small to the flow area. In the case of fuel temperature, owing to the closing of gap demonstrated by CUPID-FINIX, the section where the temperature rapidly increases disappears. Therefore, the centerline temperature is lower than that of CUPID standalone as shown in Fig. 13. The distribution of maximum rod temperature excluding the guide tube is presented in Fig. 14. At BOC, it has a relatively high temperature, and a low peak is formed in the range of 1,400 to 1,600 K. At EOC, as the power distribution becomes flat and the gap closes, most rods have a maximum temperature of 1,200 to 1,300 K. Through this calculation, the feasibility of whole core pin-by-pin analysis was confirmed.

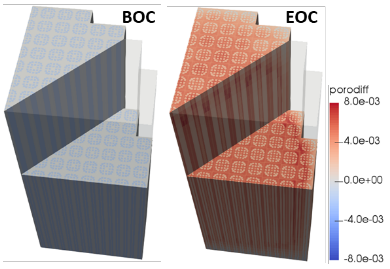


Fig. 11. Difference of porosity at BOC and EOC

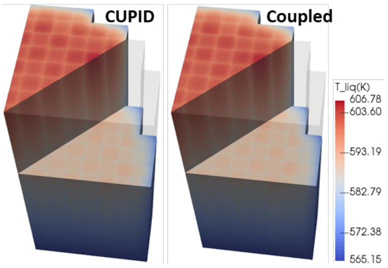


Fig. 12. Results of coolant temperature at EOC

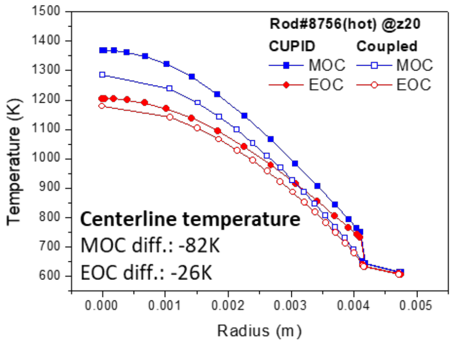
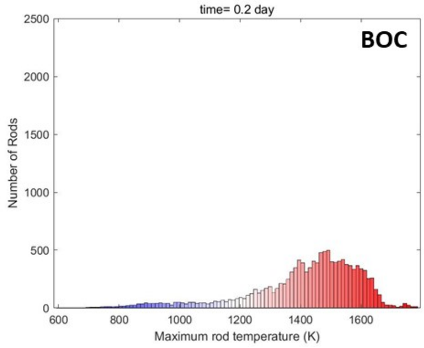


Fig. 13. Results of fuel temperature at MOC and EOC



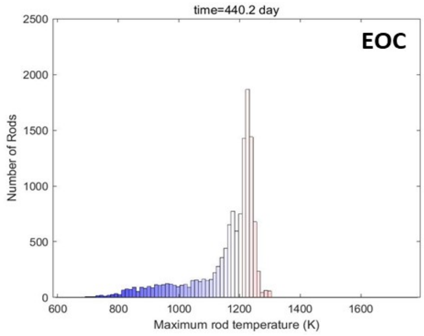


Fig. 14. Maximum rod temperature of fuel rod at BOC and EOC

4. Conclusions

To apply CUPID-FINIX for quarter core geometry, a single-port method with parallelized FINIX using OpenMP was adopted. By simulating the normal operating conditions, it was confirmed that the actual nuclear fuel phenomena were reflected. It is expected to provide indicators necessary for the safety analysis by identifying the overall status of the fuel rods. In future work, the validation of CUPID-FINIX should be performed by comparing legacy code. In addition, it will be possible to establish an integrated analysis tool by coupling with the CUPID-nTER, which is thermal-hydraulic and neutronic coupled code.

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