Coupling between subchannel analysis module of CUPID and fuel rod analysis code FINIX for transient simulation of a PWR core: preliminary analysis

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1. Introduction

Multi-physics analysis, especially demonstrating the fuel behavior, has attracted attention as to high fidelity safety analysis. During a nuclear reactor operation, nuclear fuel undergoes mechanical deformations such as relocation, swelling, creep and ballooning as well as heat transfer variation due to changing the pellet thermal conductivity or gap conductance. In multi-physics analysis, it is important to adopt fuel rod analysis code because it can provide more realistic feedback related to the state of nuclear fuel to thermal-hydraulics code or neutronics code [1]. When performing the thermal-hydraulics and fuel performance coupled simulation, nuclear fuel state reflecting the thermal-hydraulic characteristics and thermal-hydraulic data reflecting the fuel rod characteristics can be obtained. Therefore, it is possible to derive the optimum state of the reactor core.

There have been several studies with respect to multi-physics analysis containing fuel behavior code. The summary of coupled codes and individual codes describes in Table 1 and Table 2.

Table 1: Summary of coupled code [1, 2, 3]

Code name	Organization	Coupling method
CUPID-FRAPTRAN	KAERI	FRAPTRAN library
MATRA-FRAPCON	KAERI	Socket (single port-MPI)
MCS-CTF-FRAPCON	UNIST	Modularized CTF&FRAPCON

Table 2: Summary of code used for coupling [4, 5, 6, 7]

Code name	Organization	Analysis
CUPID	KAERI	Thermal-hydraulics
FRAPTRAN	U.S.NRC	Fuel performance
MATRA	KAERI	Thermal-hydraulics
FRAPCON	U.S.NRC	Fuel performance
MCS	UNIST	Neutronics
CTF	PSU	Thermal-hydraulics

In this study, CUPID-FINIX code coupling was performed based on multi-port and socket communication method. In addition, preliminary calculation on single assembly of a PWR core [8] was executed and compared with CUPID standalone simulation.

2. Development of CUPID-FINIX coupled code

2.1 CUPID

CUPID adopts a two-fluid/three-field model for two-phase flows analysis on nuclear reactor component. In the previous research, subchannel models such as cross flow, void drift and turbulent mixing model were implemented and validated. Moreover, to achieve high fidelity numerical simulation, nTER [9] which is a neutron transport code developed by KAERI was coupled with CUPID. Using CUPID-nTER coupled code, OPR1000 steady-state simulation [10] and VERA benchmark quarter core simulation [11] were performed for considering feedback effect between neutronics and thermal-hydraulics. Recently, CUPID Reactor Vessel (CUPIDRV) has been developed by KAERI which equips with the system scale two-phase flow model and one- and two-dimensional heat structure models. Fig. 1(a) shows CUPIDRV subchannel centered geometry and one-on-one connectivity between fuel rod and subchannel. Therefore, it provides flexible coupling with codes which have rod centered geometry or fuel rod analysis code. In fact, since one rod is faced with four adjacent subchannels, the information of these channels should be collected and averaged at the channel connected to rod. This procedure is illustrated in Fig. 1(b).

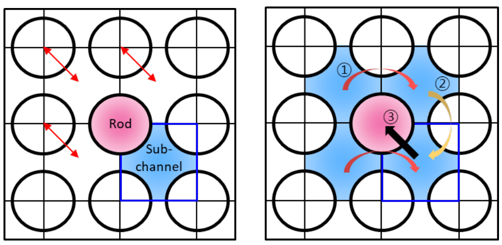


Fig. 1. CUPIDRV (a) subchannel centered geometry and rod-subchannel connectivity (b) collecting and averaging the subchannel information

2.2 FINIX

VTT Technical Research Center of Finland has developed and improved FINIX [12], which is a fuel rod analysis code in steady-state and transient condition, since 2013. It has been designed to provide a fuel performance model to be used in a multi-physics simulation. It is intended to facilitate the coupling with other physics codes and to give a middle-level module between elaborate fuel behavior and thermal structure. To demonstrate a complex fuel behavior, several thermo-mechanical models such as gas gap conductance and cladding plastic deformation model have been implemented and burnup effect model has recently been adopted in FINIX. Therefore, it has capability to analyze thermal and mechanical fuel behavior as described in Fig. 2. It has performed validation work by comparing FRAPTRAN and experimental data for steady-state or accident condition such as RIA and LOCA [13].

2.3 Demonstration of code coupling

For coupling with CUPID and FINIX, socket communication was adopted among various coupling strategies to minimize modification of both codes and facilitate the parallel computing. As can be seen in Fig. 3, FINIX2CPD is an interface program that controls the socket connections and exchange of variables. During the coupled simulation, CUPID sends coolant temperature and heat transfer coefficient between rod and fluid to FINIX and receives fuel temperature from FINIX. Since FINIX can calculate only single rod at a time, it is inevitable to run the codes simultaneously as many times as the number of fuel rods for a transient analysis. For this reason, python script based on MPI was written that can execute FINIX at the same time. Moreover, multi-port method of assigning ports to CUPID and all FINIX independently was used. It is intuitive and convenient method to establish the coupling, but there are limitations with respect to the number of ports and CPU cores as the number of fuel rods increases.

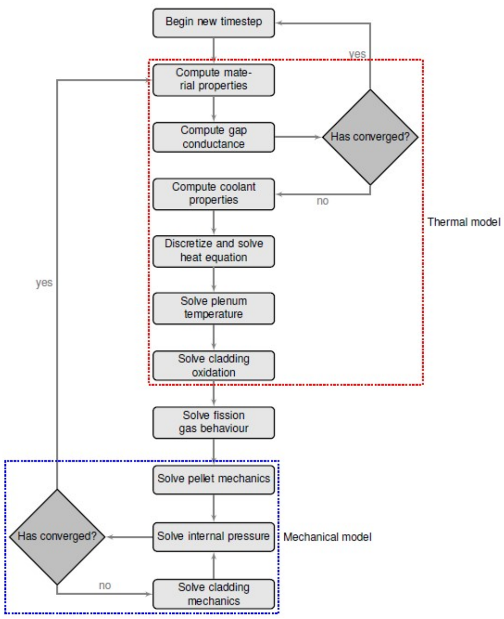


Fig. 2. Iteration scheme of FINIX code [12]

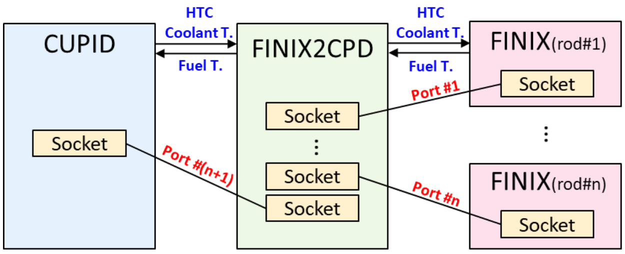


Fig. 3. Coupled scheme of CUPID-FINIX coupled code

3. Calculation results

3.1 Problem specification

To verify the CUPID-FINIX coupled system, single assembly of VERA benchmark problem 9 with 289 rods and 324 subchannel was selected. As shown in Fig. 4, among the rods, 25 rods are unheated rods like guide tube or instrument tube. The heated section was equally divided into 40 cells within both of CUPID and FINIX. CUPID mesh has the ghost cell on the top of the heated section, so that the total number of cells is 13,284. Subchannel size and rod geometry are summarized in Table 3.

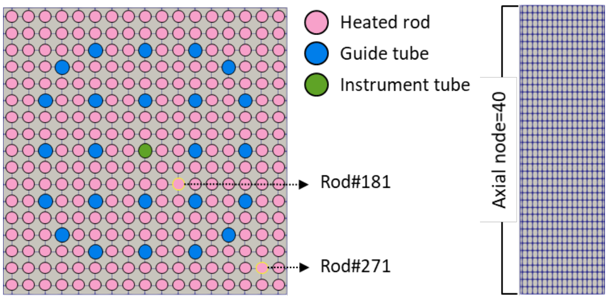
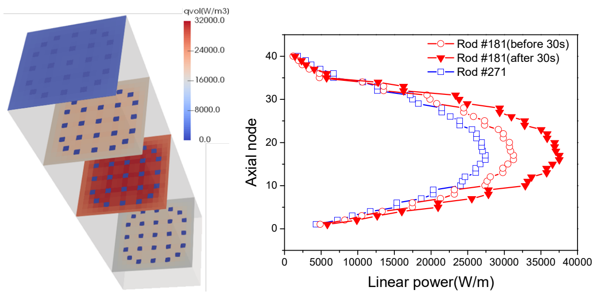


Fig. 4. VERA benchmark single assembly geometry

Table 3: VERA benchmark geometry [8]

Geometry	Values
Total height	3.6576 m
Rod pitch	0.0126 m
Corner width	0.0067 m
Heated rod diameter	0.0095 m

The power condition at BOC was obtained from the nTER depletion calculation. The power profiles for each fuel rod was applied for the FINIX, which means each FINIX executable has its own power input file separately. Because 25 unheated rods have zero power as described in Fig. 5(a), provided volumetric heat at connected subchannels have also zero. In addition, the peak power is slightly skewed toward the core inlet as illustrated in Fig. 5(b). Thermal-hydraulic initial and boundary condition for CUPID are shown in Table 4. In FINIX, only the relocation model that can cause a large deformation at the early phase was activated and other models, such as swelling, creep, densification, etc., were deactivated as long-term phenomena or negligible effect under this condition. Both codes conducted transient calculation simultaneously and problem time was set by 60 seconds. For the initial 30 seconds, calculation with constant power distribution was conducted. After that, power of rod 181 is increased by 1.2 times to perform the transient calculation again.



(a) (b)

Fig. 5. Distribution of (a) volumetric heat of VERA single assembly (b) linear power at rod 181 and 271

Table 4: CUPID boundary condition

Boundary condition	Values
Pressure	155.13 bar
Inlet velocity	4.76 m/s
Initial fluid/solid temperature	565 K

3.2 Results and discussion

For the first 30 seconds results are proposed by comparing CUPID standalone with CUPID-FINIX coupled code. Fig. 6 depicts the coolant temperature distribution on total assembly. They showed similar results from both calculations because the same constant power distribution was applied. When the coupled code simulation, fuel deformation was captured by FINIX as can be seen in Fig. 7. While the deformation in the pellet was severe, relatively little deformation occurred in the cladding. Therefore, the outer radius of the fuel rod did not change noticeably, although the width of the gap significantly reduced. In terms of thermal-hydraulics, this does not have a significant effect on the cooling capacity because the change in the flow path area is negligible. Fig. 8. shows the radial temperature distribution in the rod 181 and 271. The temperature difference on the fuel surface is small, however the centerline temperature in CUPID-FINIX is much larger than CUPID standalone (Approximately 110K). It is because the difference in gap conductance as shown in Table 5. and thermal conductivity as depicted in Fig. 9. CUPID does not consider the Lucuta's recommendation [14] associated with the fabricated density and therefore, thermal conductivity is slightly higher than FINIX. From the nuclear fuel point of view, structural integrity may be adversely affected by an increase in the fuel center temperature due to deterioration of heat transfer within the fuel rod. As a result, it can lead to another mechanical deformation.

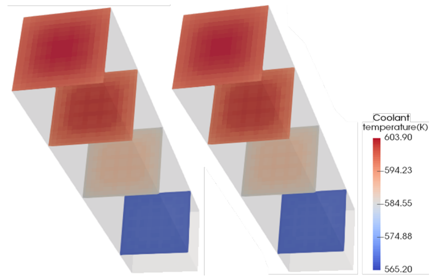


Fig. 6. Coolant temperature distribution CUPID standalone (left), CUPID-FINIX (right)

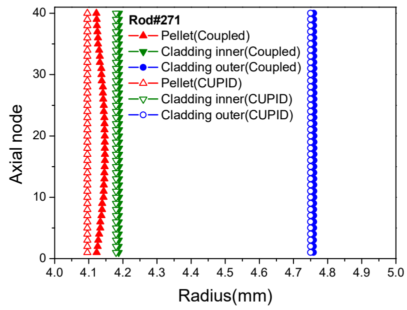


Fig. 7. Radius of pellet and cladding in CUPID standalone and CUPID-FINIX

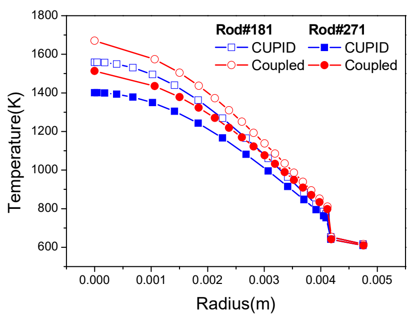


Fig. 8. Radial temperature distribution at rod 181 and 271

Table 5: Gap conductance (W/m^2K) at axial node 20

	CUPID	CUPID-FINIX
Rod #181	9920.8	7498.0
Rod #271	9348.0	6606.8

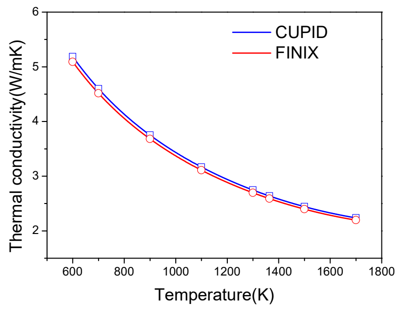


Fig. 9. Thermal conductivity distribution in CUPID and FINIX

After the first 30 seconds, since the power of rod 181 was increased, it can be seen that the radial temperature distribution inside the nuclear fuel increased with time and reached a steady-state as shown in Fig. 10. In addition, fluid temperature change around the rod 181 was well demonstrated as described in Fig. 11. Through these preliminary calculation results, it was confirmed that CUPID-FINIX coupled code can perform transient calculation with variable power condition successfully.

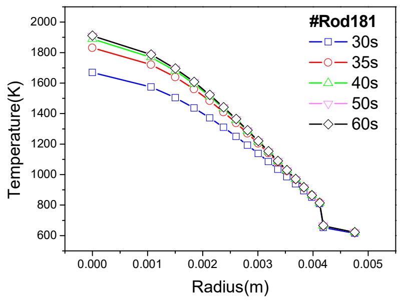


Fig. 10. Increasing radial temperature distribution over time

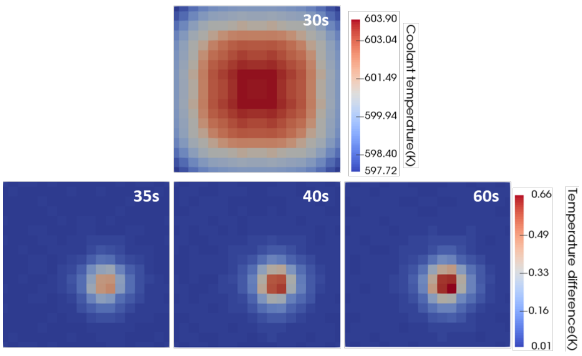


Fig. 11. Exit temperature at 30 seconds (1st steady-state) and differences (at 35, 40 and 60 seconds) from temperature at 30 seconds

4. Conclusions

The subchannel analysis module of CUPIDRV and fuel behavior code, FINIX, were coupled based on socket communication with multi-port and MPI method. Preliminary calculation was performed on VERA benchmark single assembly geometry with 289 rods. Through this study, transient coupling analysis was set up including the fuel behavior code that had to be calculated simultaneously. However, multi-port method has limitations as the number of rods to be analyzed increases. Therefore, single-port method with MPI should be considered. The current preliminary coupled system does not consider the change in flow area like the hydraulic diameter. In the future work, it is essential to reflect that phenomena in thermal-hydraulic analysis by calculating the variable hydraulic diameter using the fuel radius evaluated from FINIX.

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