Preliminary Coupling of MATRA Code for Multi-physics Analysis

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1. Introduction

A multi-physics coupling analysis is essential for the best prediction of the reactor core conditions in which various physics are intrinsically incorporated. A subchannel analysis code, MATRA [1], has been developed at KAERI to design a nuclear reactor, and has a capability to calculate a thermal-hydraulic in steady-state or transient condition in the core. The boundary conditions such as the inlet temperature, mass flux, averaged heat flux, power distributions of the rods, and core geometry is given by constant values or functions of time. These conditions are separately calculated and provided by other codes, such as a neutronics or a system codes, into the MATRA code. In addition, the coupling of several codes in the different physics field is focused and embodied.

In this study, multiphysics coupling methods were developed for a subchannel code (MATRA) with neutronics codes (MASTER [2], DeCART [3]) and a fuel performance code (FRAPCON-3 [4]). Preliminary evaluation results for representative sample cases are presented. The MASTER and DeCART codes provide the power distribution of the rods in the core to the MATRA code. In case of the FRAPCON-3 code, the variation of the rod diameter induced by the thermal expansion is yielded and provided. The MATRA code transfers the thermal-hydraulic conditions that each code needs. Moreover, the coupling method with each code is described.

2. MASTER-MATRA Coupling

2.1 Description of MASTER-MATRA Coupling

MASTER (Multi-purpose Analyzer for Static and Transient Effects on Reactors) has been developed by KAERI to analyze and design the pressurized water reactor core or the boiling water reactor core. The MASTER code can calculate the steady-state and depletion and produce the fuel rod information for a 3-dimensional Cartesian or hexagonal geometry [2].

A MASTER-MATRA coupling was conducted as a part of the SMART simulator, as shown in Fig. 1. The engines consisting of the SMART simulator were coupled on the 3-KEYMASTER(3KM[5]) platform. The 3KM provides pipes to connect each code. As registering the common variables to be connected in an OGD file of 3KM, the values of those variables can be accessed in any code on the 3KM platform.

In case of the MATRA code, the heat flux distribution of the target core and operating conditions such as an inlet temperature, mass flux, and exit pressure are needed. On the other hand, in the MASTER code, the temperature distribution on the rod and coolant temperature distribution is needed. In this way, the MATRA code sends the coolant density and rod temperature distribution to the shared memory of the 3KM after one time step is finished (this means that the solution is converged or reaches limited iterations). Then, the MATRA code updates the heat flux distribution of the rod obtained from the 3KM, which is produced by the MASTER code. In the same way, the MASTER code records the heat flux distribution on the 3KM memory for the MATRA code to be able to update those values. Then the MASTER code obtains the updated coolant density and rod temperature calculated by the MATRA code and recalculates. This method is repeated until the simulation is terminated.

In addition, the MATRA code with FORTRAN language is developed in DLL form and is executed by the interface code with C++ language on 3KM GUI.

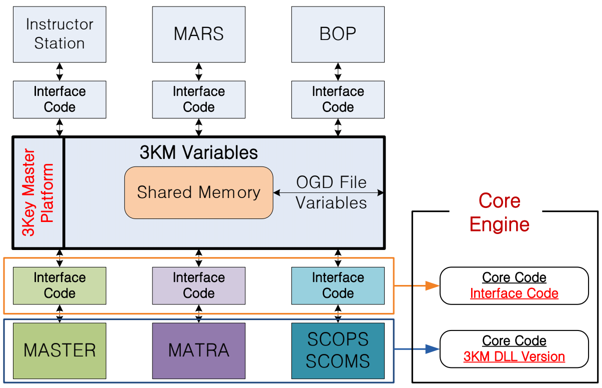

Fig.1. Structure of MASTER-MATRA coupling in SMART simulator

2.2 Evaluation of MASTER-MATRA Coupling

An example of MASTER-MATRA coupling is shown in Fig. 2. The figure shows the coolant temperature and density variation produced by the MATRA code when the core power is decreased from 100% to 0%. The variation of the radial peaking from the MASTER code is also shown. It turned out that the MASTER-MATRA coupling on the 3KM platform was successful. Moreover it was evaluated that the MASTER-MATRA coupling can calculate 18 times per second on an i7-4770 environment. At this time, a 58-subchannel model

[6] is applied to the MATRA code. In addition, an axial and a radial node mapping process between two codes is not necessary when applying a code input that is previously consulted.

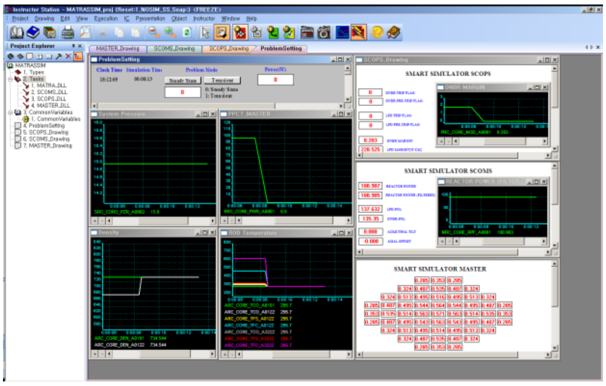

Fig.2. Example of MASTER-MATRA coupling in SMART simulator

3. DeCART-MATRA Coupling

3.1 Description of DeCART-MATRA Coupling

The DeCART (Deterministic Core Analysis based on Ray Tracing) code is a whole core neutron transport code, which has been developed by KAERI. The DeCART can calculate a flux at the sub-pin level under the power generating conditions of a PWR. The thermal-hydraulic conditions for all nodes of this code can be determined as the extrinsic inputs by a user or can be solved as simplifying the problem by itself. The coolant temperature and density, and the fuel temperature derived from these thethods, are used to reflect the thermal-hydraulic feedback in the neutron cross section [3].

In this section, the DeCART-MATRA coupling is described. The DeCART-MATRA coupling was conducted using a network socket unlike the MASTER-MATRA in section 2. The common variables between the DeCART and MATRA are directly transferred from one to the other through a network socket. The distinct server program to control the data transfer is developed. The coupling procedures by the socket are depicted in Fig. 3. The server program is ready for the socket and stands by. The coupled variables are transferred from each code to the server program as soon as the DeCART and MATRA code is ready. The DeCART and MATRA code starts to execute the calculation separately after the transfer of the coupled variables from server program is completed. If one of the two codes is converged or reached at limited iterations, the code waits for the other to be converged or reach limited iterations. After each iteration of the two codes is completed, the common variables to be coupled are updated by the server program through the network socket, and these procedures are repeated. In Fig. 3, the numbers "2" and "3" indicate a stage for each code to essentially calculate.

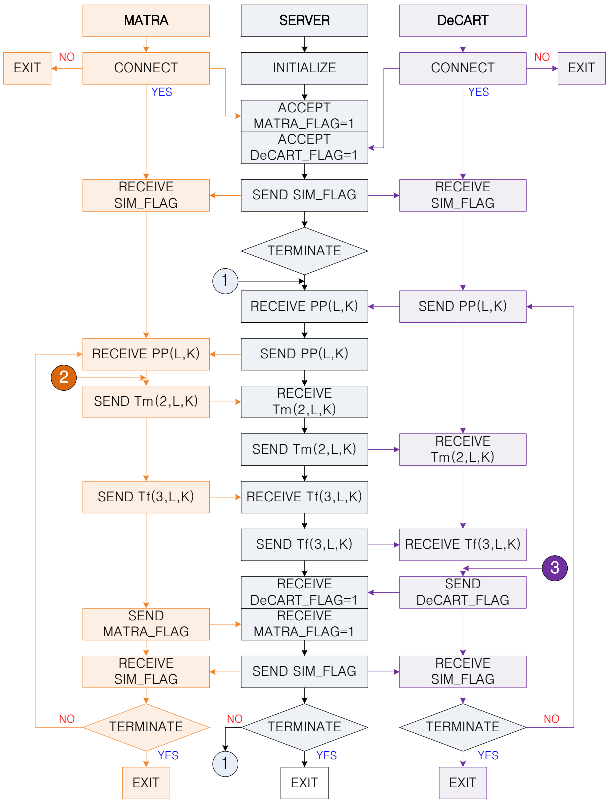

Fig.3. Flowchart of DeCART-MATRA coupling

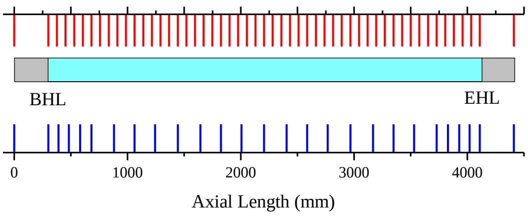

Fig.4. Axial mapping of DeCART-MATRA coupling

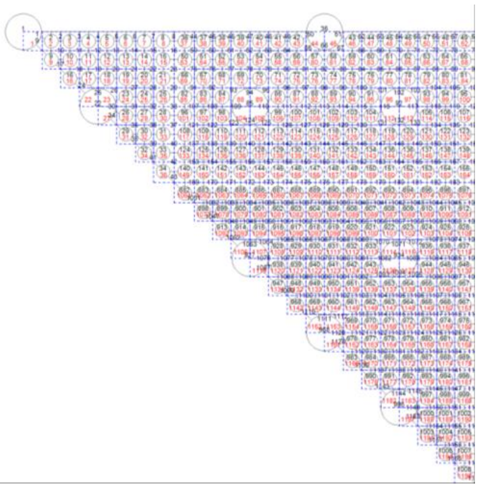

Fig.5. Radial mapping of DeCART-MATRA coupling

In this preliminary study, a 1/8 core of YG34 is decided as the target model. In the case of a 1/8 core, a subchannel model of the MATRA code is modeled to have radially 5706 subchannels, axially 52 nodes and 5372 rods. On the contract, the DeCART code is modeled to 7764 pins and axial 26 planes. Therefore, the server program has a function for radial and axial mapping of the grid between two codes. The mapping examples for these models are shown in Figs. 4 and 5. In Fig.4, the blue and red lines mean the axial location of the grid for the DeCART and the MATRA code, respectively. The coupled variables are radially area weighted and axially length weighted by the differences between two code's grids in the server program. At this time, the weighted power distribution is used to improve the convergence as follows:

$$\left(POW^{(n)}(i,j)\right)^{*} = 0.5\times POW^{(n-1)}(i,j) + 0.5\times POW^{(n)}(i,j)$$

The coupled variables are the same as the MASTER-MATRA coupling.

3.2 Evaluation of DeCART-MATRA Coupling

A comparison between the DeCART stand-alone calculation and DeCART-MATRA coupled calculation is achieved. The difference in the power peaking distribution is summarized in Table I. In the table, the difference means (Couple – SA). Here, Couple and SA are a DeCART-MATRA coupled calculation and DeCART stand-alone calculation, respectively. In the case of 3-dimensional pin-wise distribution, the difference induced by a feedback effect by the MATRA code is evaluated as within -5.1%/+4.2%. The power peaking distribution of the DeCART-MATRA coupled calculation and (Couple-SA) distribution are shown in Fig. 6 at 2957.5 mm from BHL. In the figures, it can be seen that the difference in 3-dimensional peaking at the corner is larger than at the side or center subchannels.

Table I: Power peaking difference between Couple and SA

	3D-Pin Wise	2D Pin Wise	3D-Assembly Wise	2D-Assembly Wise
MEAN	0.00053	0.00000	0.00039	-0.00021
STD	0.01803	0.00344	0.01840	0.00172
MIN	-0.05090	-0.01210	-0.03280	-0.00390
MAX	0.04160	0.01150	0.03630	0.00280

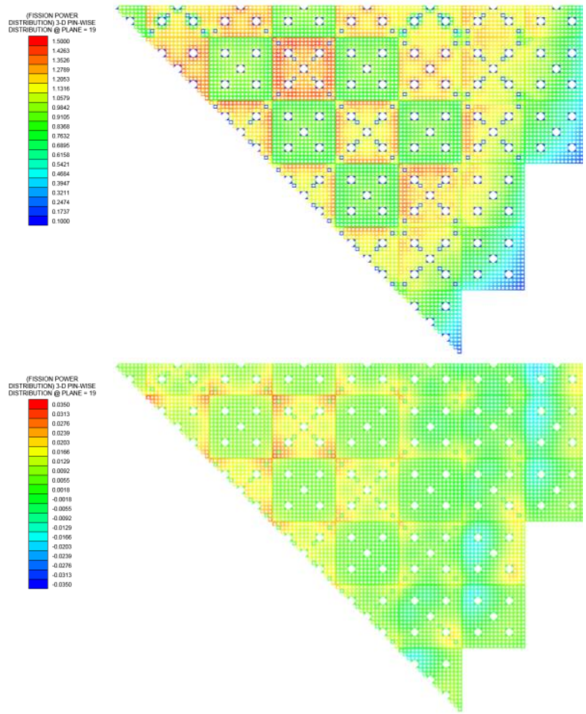

Fig.6. 3-Dimensional pin-wise peaking distribution at 2957.5 mm from BHL (Up: DeCART stand-alone / Down: difference between couple and stand-alone)

4. FRAPCON-MATRA Coupling

4.1 Description of FRAPCON-MATRA Coupling

The FRAPCON-3 is a code to calculate the steady-state response of fuel rods during a long-term burnup in a light-water reactor. The temperature, pressure, and deformation of a fuel rod can be estimated by this code according to the variation of the coolant and rod power. The code's manual describes the phenomena modeled in this code as follows[4]:

1) heat conduction through the fuel and cladding to the coolant
2) cladding elastic and plastic deformation
3) fuel-cladding mechanical interaction
4) fission gas release from the fuel and rod internal pressure
5) cladding oxidation

The FRAPCON-MATRA coupling is conducted as shown in Fig.7. The FRAPCON-MATRA coupling was also achieved using the network socket. The server program to control codes to be coupled and the common variables was used. In the case of the FRAPCON-MATRA coupling, the MATRA code receives the geometrical information from the FRAPCON code and sends the heat transfer coefficient to the FRAPCON code. In this preliminary coupling between the FRAPCON and MATRA code, a simple subchannel model is considered as shown in Fig. 8. The model consists of 4 subchannels and 1 rod. The MATRA code is modified subchannel information such as the flow area, wetted and heated perimeter can be changed as the rod diameter is changed. Therefore, as the rod diameter transfers from the FRAPCON, the flow area, and wetted and heated perimeter are updated and the solution is recalculated.

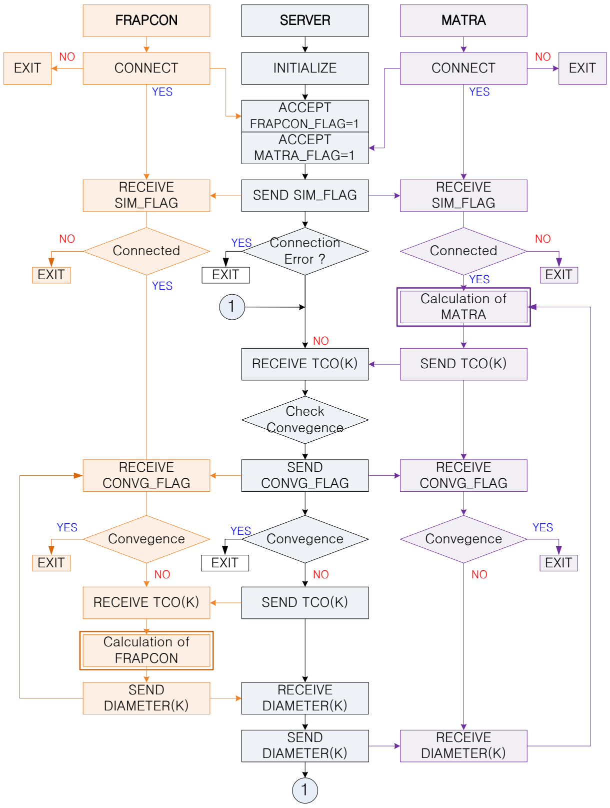

Fig.7. Flowchart of FRAPCON-MATRA coupling

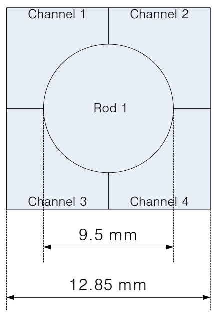

Fig.8. Subchannel model of FRAPCON-MATRA coupling

4.2 Evaluation of FRAPCON-MATRA Coupling

The results of FRAPCON-MATRA coupling are shown in Figs. 9 and 10. Figure 9 shows the axial variation of the rod diameter in the MATRA code. The rod diameter is increased in the upward direction due to thermal expansion. The ratio variation of the coupled results to the SA results is depicted in Fig.10. At this preliminary calculation, the axial heat flux distribution is a cosine shape.

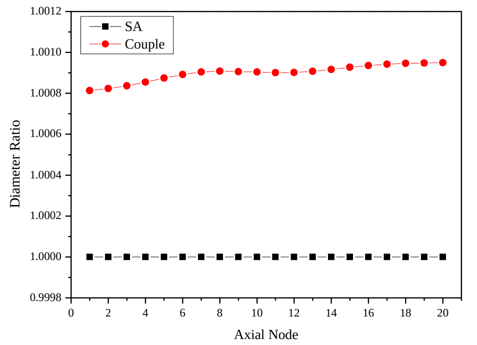

Fig.9. Rod diameter variation by FRAPCON-MATRA coupling

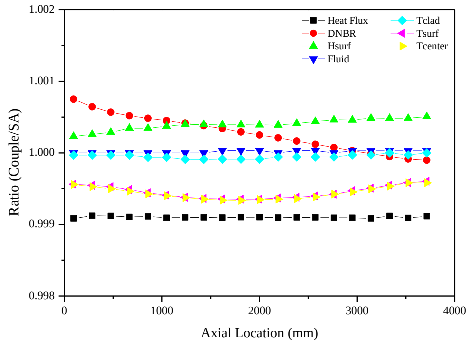

Fig.10. Rod variables variation ratio of FRAPCON-MATRA coupling result

5. Summary

Multi-physics coupling methods for a subchannel code MATRA were developed using neutronics and fuel performance codes. Preliminary evaluations with the MASTER-MATRA, DeCART-MATRA, and FRAPCON-MATRA code systems were conducted for representative sample cases. In view of the results thus far achieved, it turned out that the coupling algorithms properly reflect the multi-physics effects, and the MATRA code revealed a reasonable performance in coupling with other code based on different physics.

ACKNOWLEGEMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) (No. 2012M2A8A4026261)

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