Preliminary result of three-dimensional single assembly by STREAM3D and CUPID coupling system code

Kyeongwon Kim[a], Jae Ryong Lee[b], Wonkyeong Kim[a], Woonghee Lee[a], Deokjung Lee[a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea*
[b]*Korea Atomic Energy Research Institute, 111, 989 beon-gil, Daedeokdae-ro, Yuseong-gu, Daejeon, Republic of Korea*
[*]*Corresponding author: deokjung@unist.ac.kr*

1. Introduction

This paper presents the preliminary result of multi-physics simulation for the three-dimensional(3D) single assembly by STREAM3D and CUPID coupled code. These days, the Korean government is making efforts to develop i-SMR(Innovative-Small Modular Reactor), which is a new type of nuclear power plant. In the field of reactor physics, the study of nuclear reactor design is carried out to meet the design requirements of i-SMR. An accurate and practical reactor analysis code is essential for safe and economical nuclear reactor design. STREAM3D and CUPID coupling system code will be useful for i-SMR core analysis and nuclear reactor design.

CUPID has been developed for the realistic analysis of two-phase flows by KAERI(Korea Atomic Energy Research Institute). It adopts a two-fluid, three-field model for two-phase flow, and the governing equations are solved over unstructured grids with a semi-implicit two-step method [1, 2, 3]. STREAM3D, a high-fidelity neutron transport code, has been developed to perform a whole pressurized water reactor(PWR) core simulation in UNIST-CORE(Ulsan National Institute of Science and Technology-COmputational Reactor physics and Experiment laboratory) [4, 5].

2. Methods

The main studies of coupling system code development are exchange of variables between two codes and suitable data mapping between two different scales. As shown in Fig. 1, CUPID uses the pin power calculated by STREAM and STREAM gets the fuel temperature and moderator temperature data from CUPID. However, the CUPID and STREAM are based on the different scale. Generally, the thermal-hydraulic code use subchannel scale, on the other hand, neutronic code is based on the pin-cell scale. Fig. 2 shows lattice of the pin-cell scale and subchannel scale. This section describes which information is exchanged to each other and how to match the scale.

2.1. Data exchanging

STREAM3D source code is compiled in form of DLL(Dynamic Linked Library) file. When CUPID calls the STREAM3D dll file, CUPID provides the fuel temperature and moderator temperature data to STREAM3D during the simulation. STREAM3D is activated to run when CUPID calls the STREAM3D dll. STREAM3D calculates the pin power with fuel temperature and moderator temperature data from CUPID and passes it to CUPID. This process is repeated until convergence. There are three convergence criteria. If the average, RMS and maximum temperature difference between the previous iteration and the new iteration is less than 0.5 K, 3.0 K and 10.0 K, the simulation is converged.

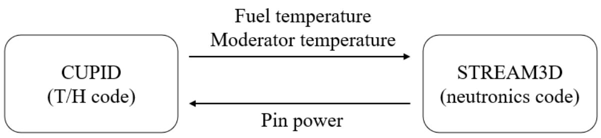


Figure 1. Exchanged data between CUPID and STREAM3D

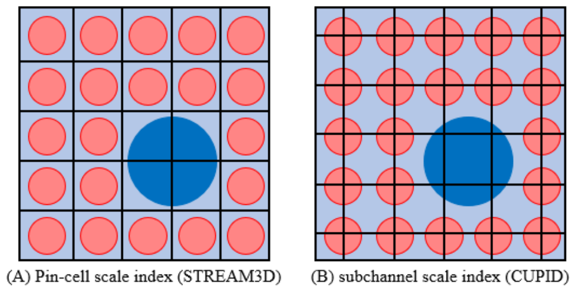


Figure 2. Lattice of the pin-cell scale and subchannel scale

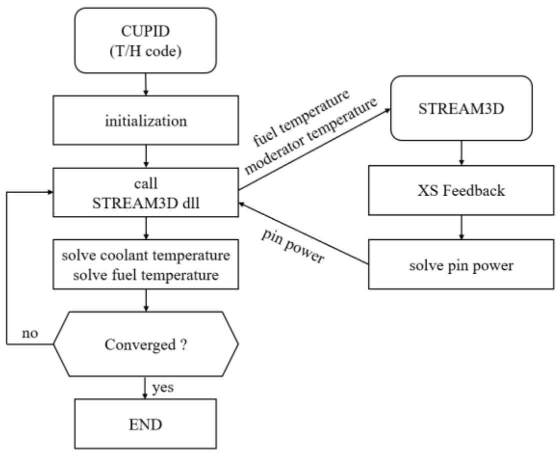


Figure 3. Flowchart of STREAM3D and CUPID coupling system code

2.2. Matching the index scale

Since the pin power is calculated by STREAM3D, it consists of the pin-cell scale. Therefore, as illustrated in Fig. 3, when CUPID obtains the pin power, each subchannel uses the sum of 1/4 of the adjacent fuel rod power.

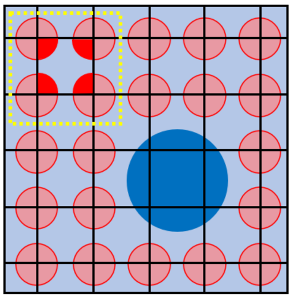


Figure 3. Pin power in subchannel scale

The other way, the moderator temperature in CUPID is based on the subchannel scale. CUPID calculates the average value of four subchannel(four Green Box in Fig. 4) data adjacent to the pin-cell(one Yellow Box in Fig. 4) in order to convert the moderator temperature data of the subchannel scale to pin-cell scale. However, the four adjacent subchannel regions and one pin-cell region are different from each other as shown in Fig. 4. In particular, subchannel 4(quadrant 4) of the green box contains a guide tube. It makes the coolant temperature on the pin-cell scale slightly lower than the actual temperature.

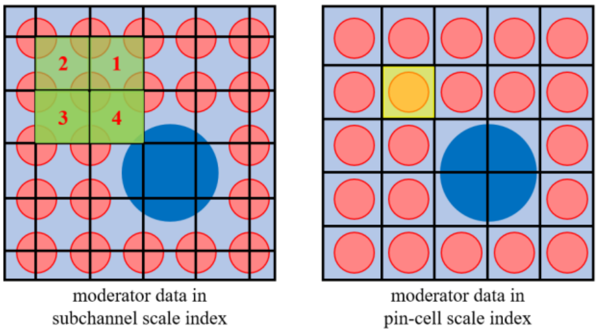


Figure 4. Moderator temperature in subchannel scale and pin-cell scale

3. Results

This section describes the results of pin power, fuel temperature and moderator temperature distribution for 3D single assembly by STREAM3D and CUPID coupling system code. In addition, these results are compared to STREAM3D and TH1D, STREAM3D and CTF coupled code.

3.1. 3D single assembly

Fig. 5. shows the radial and axial configuration of 3D single assembly problem. This assembly consists of 16 by 16 fuel rod, guide tubes and instrumentation tube having a fuel stack height of 381 cm. A moderator of 30 cm is present at the top and bottom areas. The fuel pin pitch is 1.260 cm and the outer radius of fuel rod is 0.41211 cm. The fuel material is uranium dioxide(UO_2). The assembly has 236 fuel rods, 4 guide tubes and 1 instrument tube. The simulation conditions are described in Table. I.

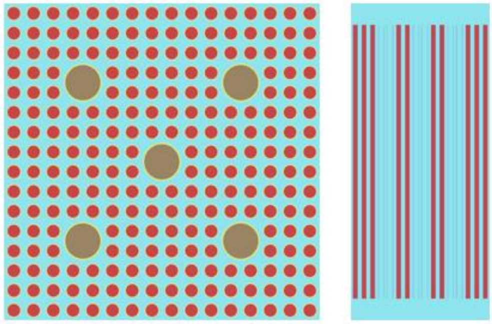


Figure 5. Radial and Axial configuration of 3D single assembly

Table I. Simulation Conditions

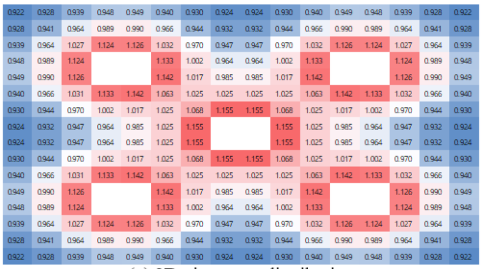
Variable	Value
Mass flow [kg/s]	84.25
Moderator Inlet Temperature [K]	594.74
Power [MW]	10

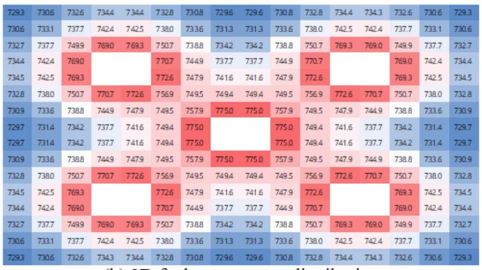
3.2. Simulation results

Using the STREAM3D and TH1D(ST3D-TH1D), STREAM3D and CTF(ST3D-CTF), STREAM3D and CUPID(ST3D-CUPID) coupling system code, the 3D single assembly was simulated to compare the results. Table II. shows the results of k_{inf}, fuel average temperature, moderator average temperature and moderator outlet temperature calculated by ST3D-TH1D, ST3D-CTF and ST3D-CUPID, respectively. In addition, the pin power distribution, fuel temperature distribution and moderator temperature distribution are shown in Fig. 6. – Fig. 8.

Table II. Summary of results

Variable	ST3D-TH1D	ST3D-CTF	ST3D-CUPID
k_{inf}	1.40632	1.40665	1.40605
Fuel Average Temperature [K]	744.60	743.20	754.72
Moderator Average Temperature [K]	581.35	581.53	582.00
Moderator Outlet Temperature [K]	590.76	590.76	591.41


(a) 2D pin power distribution


(b) 2D fuel temperature distribution

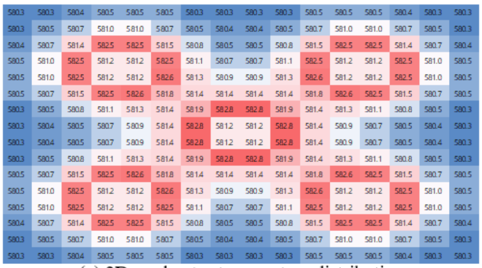
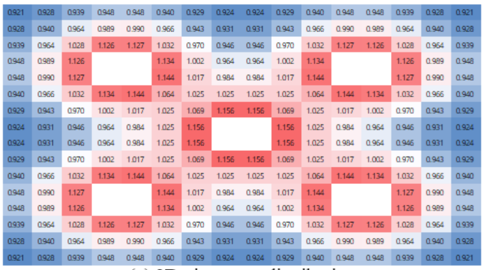
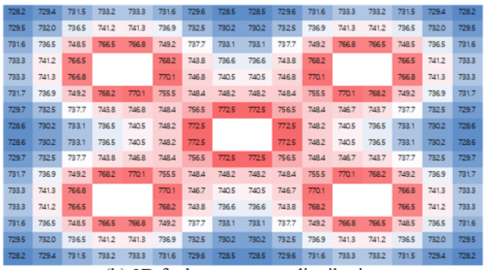

(c) 2D moderator temperature distribution

Figure 6. 2D distribution simulated by ST3D-TH1D


(a) 2D pin power distribution


(b) 2D fuel temperature distribution

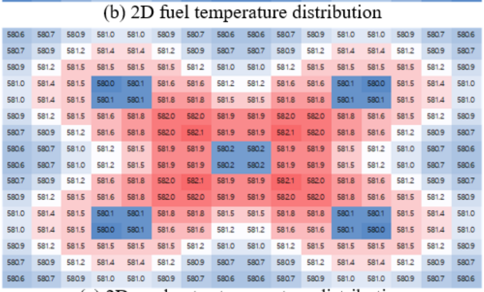
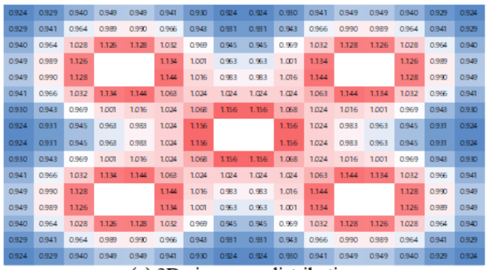
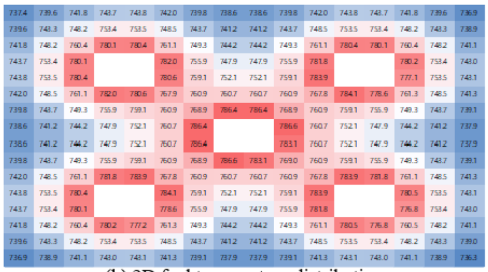

(c) 2D moderator temperature distribution

Figure 7. 2D distribution simulated by ST3D-CTF


(a) 2D pin power distribution


(b) 2D fuel temperature distribution

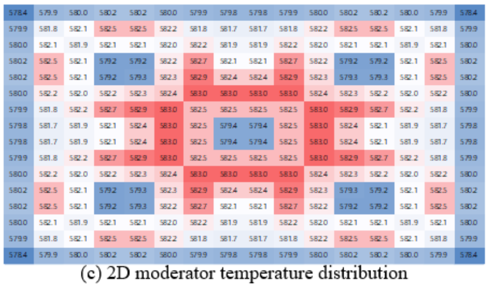

(c) 2D moderator temperature distribution

Figure 8. 2D distribution simulated by ST3D-CUPID

Compared with ST3D-TH1D coupled code, ST3D-CTF and ST3D-CUPID can consider the cross-flow effects among neighboring subchannel. The moderator temperature in the center of 2D moderator temperature distribution simulated by ST3D-CTF and ST3D-CUPID is higher than ST3D-TH1D result owing to cross-flow effect. However, the 2D moderator temperature calculated by ST3D-CUPID looks strange. This is because the area of the pin-cell scale and subchannel scale are different, as mentioned before. The way to match the area of the pin-cell and subchannel is required for the exact pin-cell scale moderator temperature. Nevertheless, the fuel average temperature, moderator average temperature, moderator outlet temperature and multiplication factor values are similar for all three results.

4. Conclusions

The results such as the fuel average temperature, moderator average temperature, moderator outlet temperature, multiplication factor calculated by ST3D-TH1D, ST3D-CTF, and ST3D-CUPID were compared. The difference of multiplication factor and fuel average temperature between ST3D-TH1D and ST3D-CTF was 33 pcm and 1.4 K. Similarly, the difference of multiplication factor and fuel average temperature between ST3D-TH1D and ST3D-CUPID was 27 pcm and 10.12 K.

Future work will be finding a way to accurately match the area of the pin-cell and subchannel scale and applying the parallel computation.

ACKNOWLEDGEMENT

This study was sponsored by the Korea Hydro & Nuclear Power Co.'s affiliated Central Research Institute (KHNP-CRI).

REFERENCES

[1] J. R. Lee, H. Y. Yoon, Preliminary study for a PWR steam generator with CUPID/MARS multi-scale thermal-hydraulics simulation, Applied Thermal Engineering, Vol. 115, pp. 1245-1254, 2017.
[2] J. J. Jeong, et al., The CUPID Code Development and Assessment Strategy, Nuclear Engineering and Technology, Vol. 42, No. 6, pp. 636-655, 2010.
[3] H. Y. Yoon, et al., Multi-Scale Thermal-Hydraulic Analysis of PWRs using the CUPID Code, Nuclear Engineering and Technology, Vol. 44, No. 8, pp. 831-846, 2012.
[4] S. Choi, et al., Development of high-fidelity neutron transport code STREAM, Computer Physics Communications, Vol. 264, 107915, 2021.
[5] J. Choe, D. Lee, Development of angle-dependent linear source approximation for three-dimensional method of characteristics transport analysis method in STREAM, Annals of Nuclear Energy, Vol. 181, 109572, 2023.