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Coupled Neutronics and Thermo-Fluid Simulation of Full-Core Prismatic Gas-Cooled Reactor Using DeCART/CORONA Code System

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing a core thermo-fluid analysis code named CORONA [1] for analysis and design of a prismatic gas-cooled reactor core. DeCART [2] is a whole-core neutron transport code. It was originally developed for neutronics analysis and design of light water reactor (LWR) but its capability was extended for prismatic gas-cooled reactor under the I-NERI project [3]. During the I-NERI project, a coupled code system of DeCART and CORONA was established. However, a whole core simulation capability of DeCART/CORONA code system has not been verified yet. In this paper, therefore, a whole core calculation was carried out using the design parameters of MHTGR-350 which is used for the OECD/NEA benchmark problem [4]. The main objectives of the present DeCART/CORONA coupled calculation are to verify a whole core simulation capability, to investigate general characteristics of prismatic core with high fidelity model, and to identify technical challenges for future development.

2. Code System

Fig. 1 shows the DeCART/CORONA code system for neutronics and thermo-fluid coupled analysis of a prismatic gas-cooled reactor core. A server program named CDECGAM was developed to control the coupled analysis [3].

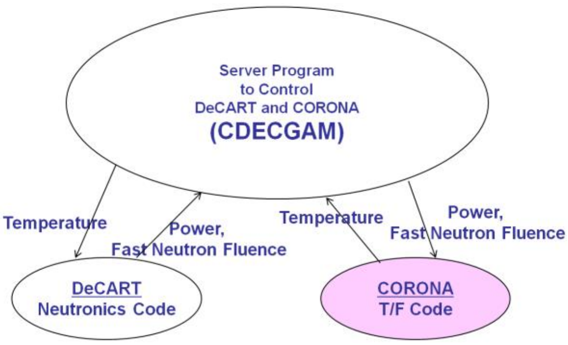

Fig. 1. Coupled code system using DeCART and CORONA.

Initially, assuming constant temperature and power distribution, the DeCART code calculates the power distribution and the CORONA code calculates the temperature distribution. Then DeCART sends the power and fast neutron fluence to CORONA and receives the temperature distribution calculated from CORONA. At the same time, CORONA sends the calculated temperature distribution to DeCART and receives the power and fast neutron fluence distributions from DeCART. Each code updates the calculation using the received data. The calculation is continued until the power and temperature distributions are converged.

3. Coupled Analysis and Results

The design parameters of the MHTGR-350 core used in the OECD/NEA benchmark are selected to achieve the main objectives of this work.

3.1 MHTGR-350 Core

Fig. 2 shows the reactor core layout of MHTGR-350. The main design parameters of MHTGR-350 are provided in Table I.

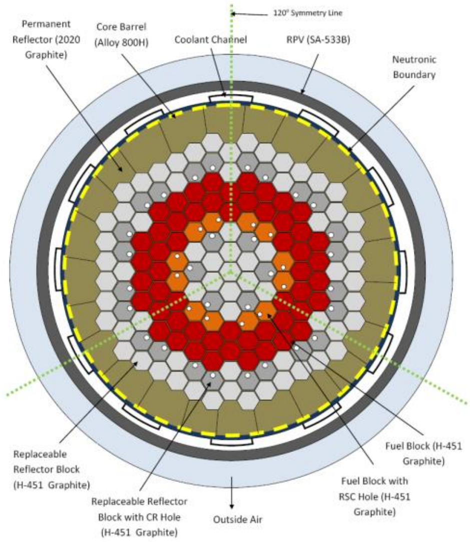

Fig. 2. Reactor core layout of MHTGR-350 [4].

3.2 Simulation Model

It was found that the DeCART code has some technical challenges to simulate large coolant holes (i.e., control rod and reserved shutdown holes) for 3-dimensional calculations. Therefore, it was decided that the core model has to be simplified. As shown in Fig. 3, the control rod and reserved shutdown holes were removed to avoid the challenges in the present calculation. Then the geometry of the core becomes 1/6 symmetric. However, 360 degree full core model was used for the coupled calculation due to the mapping issue between the computational cells of DeCART/ CORONA. It should be noted that exactly same mesh structures are used in both codes. It means that there is no additional error during the mapping of the computational cells.

Table I: Main Design Parameters of MHTGR-350 Core

	Values
Thermal power (MW_{th})	350
Coolant inlet/outlet temperatures (^oC)	259/687
System pressure (MPa)	7
Coolant flow rate (kg/s)	157.1
No. of fuel columns	66
Active core height (m)	7.93
Bypass flow gap size (mm)	2, 3.5
Crossflow gap size (mm)	0

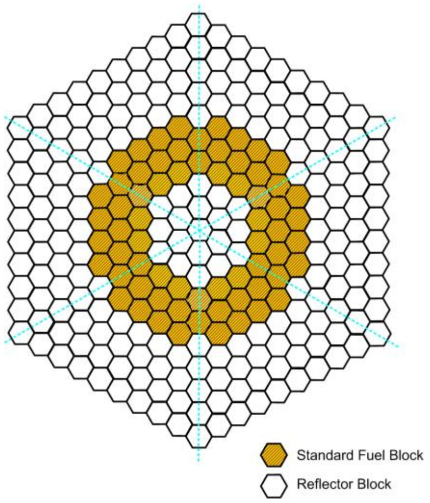

Fig. 3. Full-core model for coupled analysis for MHTGR-350 core using the DeCART/CORONA code system.

3.3 Simulation Results

The DeCART code was run on the Linux cluster system, whereas the CORONA code was run on the Windows PC. Table II shows the hardware specification of the 14 nodes used for the present DeCART calculation. The specification is the same for all the 14 nodes. The calculation of DeCART was carried out using 27 CPUs, which is the maximum limit of the present model since 27 axial planes were simulated.

About 11 days were spent for the computation. Such a long computational time was required due to the DeCART code. The CORONA code requires a few hours for a stand-alone thermo-fluid calculation. After four times of data exchange between the codes, a convergence was reached.

Table II. Hardware Specification of Nodes Used for DeCART Calculation

	Specification
CPU	2.6 GHz Intel Xeon 8 core x 2 ea
RAM	DDR3 16 GB x 12 ea (=192 GB)

Fig. 4 shows the calculated column-wise power distribution. Due to symmetric characteristics, the result for the 1/6 section of the core is provided. It shows that the hot spot fuel column is located near the central reflector columns. It is well-known that more power is produced near reflector due to a better moderation of fast neutron. Fig. 5 shows the calculated axial power distribution. A top-skewed shape is shown. Such a shape is very reasonable since the top region is colder than the bottom one. Due to the temperature feed-back, the axial power profile is shifted toward the top region.

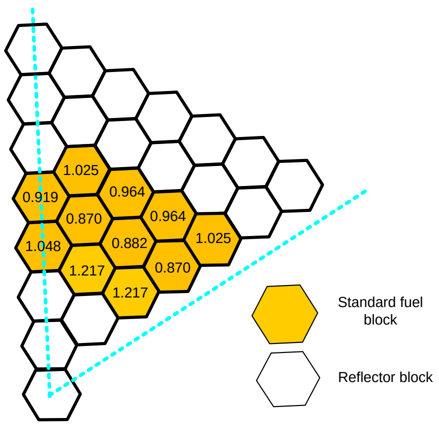

Fig. 4. Calculated column-wise power peaking factor.

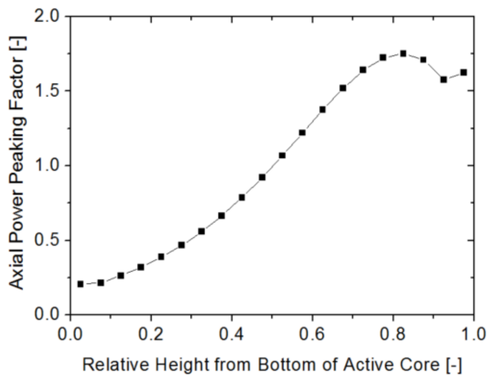

Fig. 5. Calculated axial power peaking factor.

Fig. 6 shows the calculated pin-by-pin power distribution of the hot spot fuel column. It clearly shows the large gradient of the power profile within a column. The highest peaking factor is 2.53 times larger than the lowest one (2.10/0.83 = 2.53). It means that the design specification in the benchmark document is not practical. The high peaking factors shown in Figs. 4 and 6 could be significantly reduced in a real core design.

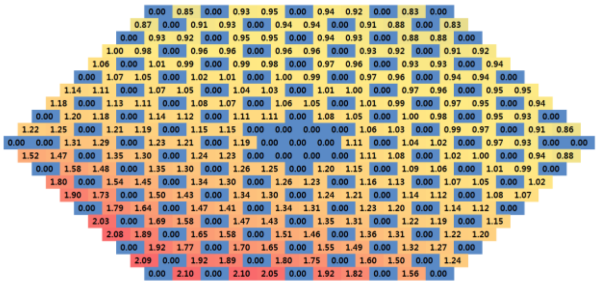

Fig. 6. Calculated pin-by-pin power peaking factor of hot spot fuel column (normalized by column average value).

The calculated maximum fuel temperature at each fuel column is shown in Fig. 7. The maximum fuel temperature exists at the fuel column which has the largest power peaking factor. It also shows that the maximum fuel temperature of each column is increased with the column power peaking factor. Fig. 8 shows the calculated axial temperature distributions at typical fuel and coolant unit cells. Very reasonable distributions are observed. Fig. 9 shows the pin-by-pin fuel temperature distribution within hot spot fuel column. A large temperature gradient can be seen. The maximum difference in the fuel temperature is 653 ^{o}C (= 1379-726 ^{o}C).

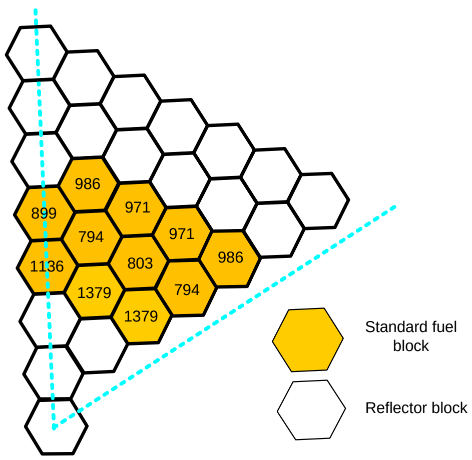

Fig. 7. Calculated maximum fuel temperature for each fuel column (unit: ^{o}C).

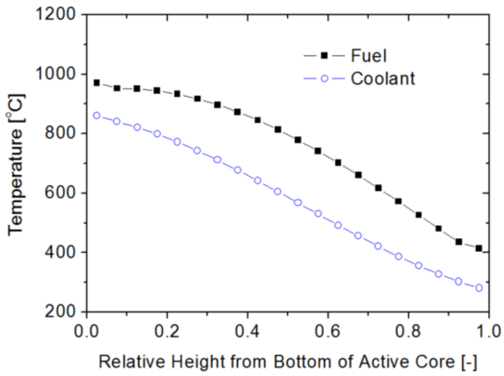

Fig. 8. Calculated axial temperature distribution at typical fuel and coolant unit cells.

For a comparison, a stand-alone calculation of DeCART was performed with the temperature feed-back option using the thermo-fluid module incorporated. DeCART has a simple thermo-fluid model using a single average channel. Table III compares the results of coupled and stand-alone calculations. The difference in the multiplication factor is as high as 2597 pcm. Significant difference in the axial power profile is also observed. Such impacts result in the difference of 100 ^{o}C in the maximum fuel temperature.

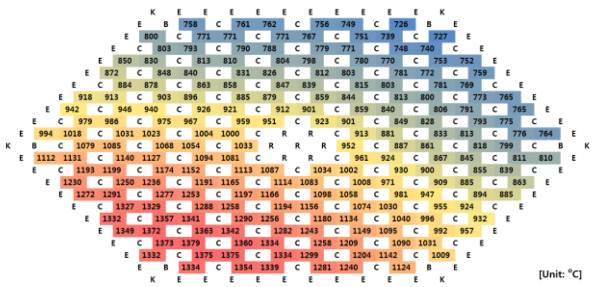

Fig. 9. Calculated fuel temperature within hot spot fuel column.

Table III. Comparison of Results of Coupled and Stand-alone Calculations

	Coupled	Stand-alone
Multiplication factor	1.07969	1.05372
Max. radial peaking factor	2.16	2.21
Max. axial peaking factor	1.75	1.44
Axial offset	0.52	0.32
Max. fuel temp. (^{o}C)	1379	1279

4. Conclusions

In this work, the full-core simulation capability was demonstrated for the DeCART/CORONA coupled code system. A great advantage of the DeCART/CORONA code system is the capability of high fidelity calculation. The capability for the detailed pin-by-pin power and temperature distribution was also demonstrated. As expected, however, long calculation time was the largest demerit. Therefore, future research is required to speed up the calculation. Above all, the modeling capability of DeCART for the control rod and reserved shutdown holes in 3-dimensional calculations has to be established with the highest priority.

Acknowledgements

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