

DEVELOPMENT OF PIN-LEVEL NEUTRONICS/THERMAL-FLUID ANALYSIS COUPLED CODE SYSTEM FOR A BLOCK-TYPE HTGR CORE

Seungsu Yuk*, Nam-il Tak, and Chang Keun Jo

Korea Atomic Energy Research Institute
111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Korea, 34057

syuk@kaeri.re.kr, takni@kaeri.re.kr, jck@kaeri.re.kr

ABSTRACT

Recently, the coupling between computer codes that simulate different physical phenomena has attracted for more accurate analysis. In the case of high-temperature gas-cooled reactor (HTGR), the coupling between neutronics and thermal-fluid analysis is necessary because of large change of temperature in the reactor core. Korea Atomic Energy Research Institute (KAERI) has developed the coupled code system between a reactor physics analysis code CAPP and a thermal-fluid system safety analysis code GAMMA+ for a block-type HTGR. The CAPP/GAMMA+ coupled code system provides more accurate block-wise distribution data than CAPP or GAMMA+ stand-alone analysis. However, the block-wise distribution data has the limitation in order to predict safety parameters such as the maximum temperature of the nuclear fuel. It is necessary to calculate refined distribution, for example, pin-level (fuel compact level) distribution. In this study, we tried to solve this problem by coupling CAPP and a high-fidelity thermal-fluid analysis code CORONA. CORONA can perform a high-fidelity thermal-fluid analysis of Computational Fluid Dynamics (CFD) level by dividing a block-type HTGR core into small lattices. On the other hand, CAPP can provide a pin power distribution. It is expected that the refined, more accurate distribution data for a block-type HTGR can be obtained by coupling these two codes. This paper presents the development of coupled code system between CAPP and CORONA, and then it is tested on a simple HTGR column problem with encouraging results.

KEYWORDS: CAPP, CORONA, Multi-physics analysis, HTGR, VHTR, Maximum fuel temperature

1. INTRODUCTION

High-Temperature Gas-cooled Reactor (HTGR), or Very-High-Temperature Reactor (VHTR) is one of the next-generation reactor types that guarantees high passive safety. Researches of technology development on HTGR is underway in various research groups around the world. Reactor analysis codes for HTGR, for example, DYN3D-HTR [1], PHYSICS/RELAP5-3D [2], has developed during such researches. Korea Atomic Energy Research Institute (KAERI) has also developed key reactor core design codes such as reactor physics analysis code CAPP [3-5], high-fidelity thermal-fluid analysis code CORONA [6,7], and thermal-fluid/system safety analysis code GAMMA+ [8,9], which are targeted at block-type HTGRs.

* Corresponding author

Through these, it is possible to perform the reactor core analysis and the safety analysis for block-type HTGRs.

In recent years, there are many attempts to perform more precise calculations by coupling between the analysis codes simulating different physical phenomena. KAERI developed a coupled code system between CAPP and GAMMA+, which can obtain the block-wise power and temperature distribution on HTGR cores at once [10,11]. The CAPP/GAMMA+ coupled code system provides more accurate solution than CAPP or GAMMA+ stand-alone analysis. This enables more precise core analysis and safety analysis. However, the block-wise distribution data has the limitation in order to predict safety parameters such as the maximum temperature of the nuclear fuel. It is necessary to calculate refined distribution, for example, pin-level (fuel compact level) distribution. In this study, we tried to solve this problem by coupling CAPP and CORONA.

2. PIN-LEVEL COUPLED CODE SYSTEM

2.1. CAPP Code

The CAPP code has been developed for reactor core analysis of HTGRs. In order to find the effective multiplication factor, neutron flux distribution, and power distribution of the reactor core, the three-dimensional multi-group neutron diffusion equation should be solved. CAPP solves this equation using the finite element method (FEM). It has its own thermal-fluid analysis solver to consider the thermal feedback effect. The depletion calculation can be performed using arbitrary decay chains of nuclides.

Fig. 1 shows the hierarchical mesh structure of a block-type HTGR core in CAPP. The reactor core consists of a lot of hexagonal prisms called “blocks” that correspond to actual fuel and reflector blocks in HTGR. Each block also consists of several triangular prisms. These triangular prisms correspond to finite elements, which are the unit computational cells in CAPP. Each triangular prism has neutron flux, power, fuel temperature, moderator temperature, and nuclide densities.

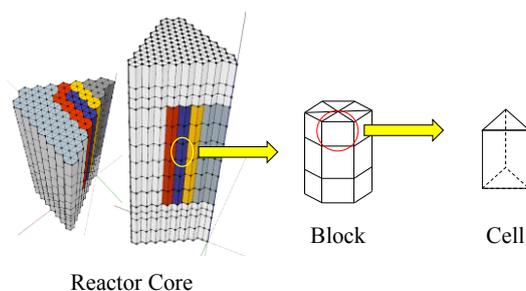


Figure 1. Hierarchy of Mesh Structure in CAPP.

As mentioned earlier, CAPP uses the FEM to calculate the neutron flux and power distribution. Therefore, not only one averaged power density value for each computational cell but also the internal power distribution can be represented as a linear combination of shape functions of the finite element. On the other hand, the homogenized nuclear cross sections for each block used in CAPP are provided by the two-dimensional transport analysis code DeCART2D [12]. At this time, the pin power form function for each fuel block is also made by DeCART2D and provided to CAPP. CAPP synthesizes the power distribution inside the computational cells and the provided pin power form functions, so that the pin power distribution of the reactor core is reconstructed.

2.2. CORONA Code

The CORONA code has been developed for high-fidelity thermal-fluid analysis of block-type HTGR cores. To illustrate what CORONA is aiming for, Fig. 2 summarizes the application areas of thermal-fluid analysis codes of a block-type HTGR core [7]. The position of CORONA is between the computational fluid dynamics (CFD) code and the system safety analysis code. The GAMMA+ code is a thermal-fluid system safety analysis code that can simulate the general thermal-fluid phenomena in a HTGR system. However, it is difficult to accurately describe the interior of the reactor core. On the other hand, CFD codes (e.g. CFX [13]) can be used for high-fidelity thermal-fluid analysis because they can use micro-grids to perform precise analysis on local regions. However, they require enormous computational resources for solving a problem as large as a reactor core.

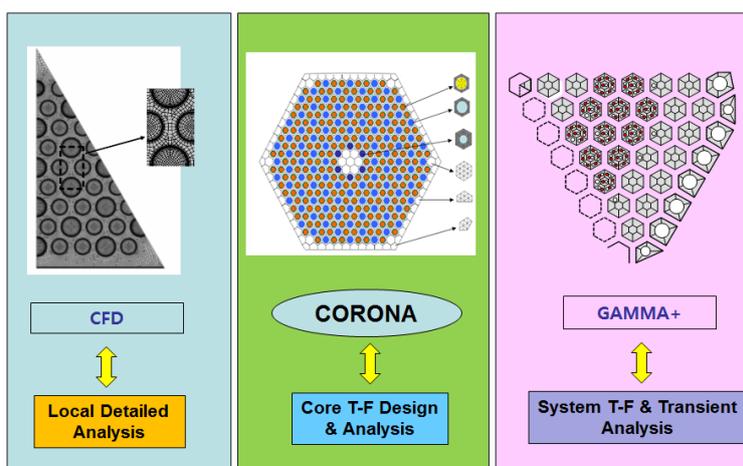


Figure 2. Thermal-Fluid Analysis Codes of a Block-type HTGR Core in KAERI [7].

The objective of CORONA development is to solve a block-type HTGR core faster than commercial CFD codes with CFD-level accuracy. For this purpose, CORONA analyzes fluid domain as the combination of one-dimensional problems. Each coolant channel (including bypass gap) is well approximated as the serially connected 1-D fluid problems. CORONA analyzes solid domain as a three-dimensional problem, such as CFD. However, as a result of balancing accuracy and computation speed, the mesh size used by CORONA is larger than that used by CFD (See Fig. 2). In addition, based on the regular structure of the block-type HTGR core, the basic unit cells are determined, and a combination of these cells is used to make a fuel block. This enables efficient grid generation. The parallel computation for each column can be also possible to increase the efficiency of the calculation.

In this study, two options of fluid analysis were considered for CORONA calculation. One is the channel model, which simply uses a fixed distribution of coolant channel flows and does not consider cross flow. These additional assumptions allow faster calculation. The other is a network model, in which a flow network consists of flow regions. The momentum balance and the energy balance of flow are calculated accurately.

CORONA can use power density as input for each fuel pin cell. Since CORONA cannot calculate power by itself, the power distribution given in the simple approximation or calculated from CAPP should be copied into the input file of CORONA. In both cases, it is different from the real one because the power distribution data does not consider precise thermal-fluid analysis.

2.3. Coupling Strategy

Fig. 3 is a schematic of the CORONA/CAPP coupled code system. This code system refers to the CAPP/GAMMA+ neutronics and thermal-fluid coupled code system developed by KAERI. The server program COTOCA (CORONA to CAPP) is placed between the two codes to control the communication of information between CAPP and CORONA. COTOCA sends and receives data directly to and from the client codes rather than exchanging files.

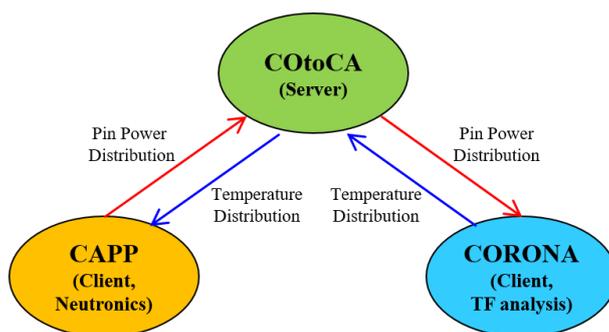


Figure 3. CORONA/CAPP Coupled Code System Scheme.

When synthesizing pin power distribution in CAPP, COTOCA receives it and sends it to CORONA. CORONA performs thermal-fluid analysis using the pin power distribution as the heat source. The result is a temperature distribution of fuel, moderator and coolant, which COTOCA receives and sends to CAPP. CAPP determines the nuclear cross sections by temperature distribution and uses the cross sections to calculate the power distribution. The above process does not proceed sequentially. Each code performs a calculation to update data, exchanges data with each other, and performs a calculation again under new conditions. Both codes check the convergence of data based on their own criteria and send it to COTOCA. COTOCA sends an end-of-computation message to both codes to end the iteration only when both codes have converged.

What is important in the CORONA/CAPP coupled code system is the mapping between the two codes. The shape and index of the computational grid in CAPP is different from those in CORONA. Moreover, there are several types of fuel and coolant hole arrangements in blocks of HTGRs, making it difficult to generalize. The COTOCA code takes the mapping information between the two codes as an input data and takes care of converting the information that each code carries to the other code.

Three-dimensional mapping through COTOCA is a synthesis of radial two-dimensional and axial one-dimensional mappings. A block-type HTGR consists of hexagonal block layers with regular axial structure. Therefore, the mapping to the axial direction can be performed simply. The difference between the grids of the two codes can be handled using the mapping matrix used in CAPP/GAMMA+ coupled code system [10].

In the case of two-dimensional mapping, fuel and reflector blocks can find corresponding blocks in CAPP and CORONA. When transferring pin power distribution from CAPP to CORONA, the index of the fuel pin in CAPP and the fuel pin in CORONA correspond one to one. Conversely, when sending the temperature distribution from CORONA to CAPP, since CAPP requires a temperature value in each triangular prism, CORONA divides a block into six triangular sectors and maps them to the triangular grids of CAPP.

Finally, the mapping from CORONA to CAPP is a composition of block-wise correspondence and triangular sector-wise correspondence within the block, and the mapping from CAPP to CORONA is a composition of block-wise correspondence and internal pin-wise correspondence within the block.

3. NUMERICAL RESULTS

In this section, a test problem is chosen to determine whether the CORONA/CAPP coupled code system works well. The test problem is a single column of a block-type HTGR core. It is one of the problems created by referring to the fuel block of the MHTGR-350 benchmark problem [14]. Fig. 4 shows the geometry of the single column problem and Table I shows the problem conditions. In addition, a control rod is inserted at the center of the block to control the excess reactivity.

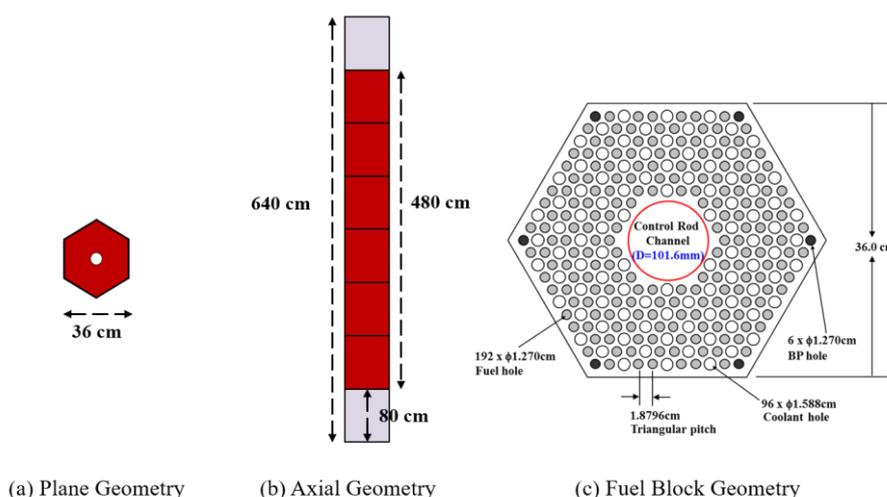


Figure 4. Geometry of Single Column Problem.

Table I. Problem conditions of the single column problem.

	Values
Thermal power (MWth)	3.1818
Coolant inlet temperature (°C)	259
Total coolant mass flow (kg/sec)	1.43
Number of fuel columns	1
Number of inner reflector columns	0
Number of outer reflector columns	0
Total height (cm)	640
Active core height (cm)	480
Bypass flow gap size (mm)	0
Crossflow gap size (mm)	0

In order to verify the results of analyzing the single column problem with the CORONA/CAPP coupled code system, CAPP stand-alone and CAPP/GAMMA+ coupled code system were used for the purpose of comparison. In addition, the channel model option (CORONA/CAPP-1) and the network model option (CORONA/CAPP-2) were also considered. At this time, the control rod position was fixed to maintain the critical state in the CAPP stand-alone calculation.

Table II shows the effective multiplication factor results for the single column problem. Since it is a simple model, CAPP stand-alone calculation and the CAPP/GAMMA+ coupled analysis, which use a similar grid for thermal fluid analysis, fit very well. In the case of CORONA/CAPP using a channel model, the flow into each coolant channel is constant, like the representative coolant channel used in CAPP or CAPP/GAMMA+. Therefore, there is no significant difference in the effective multiplication factor. In contrast, the network model solves the flow and temperature of each coolant region accurately, so all coolant channels have different status values. This results in a difference of about 100 to 160 pcm from the previous three calculations.

Table II. Multiplication factors for single column problem.

Code	CAPP	CAPP/GAMMA+	CORONA/CAPP-1	CORONA/CAPP-2
k_{eff}	1.00000	1.00022	0.99960	0.99864

Fig. 5 compares the power distribution and fuel temperature distribution in the axial direction. For the power distribution, the four calculations show nearly similar values. However, in the case of fuel temperature distribution, CORONA/CAPP-2 using the network model shows slightly higher values.

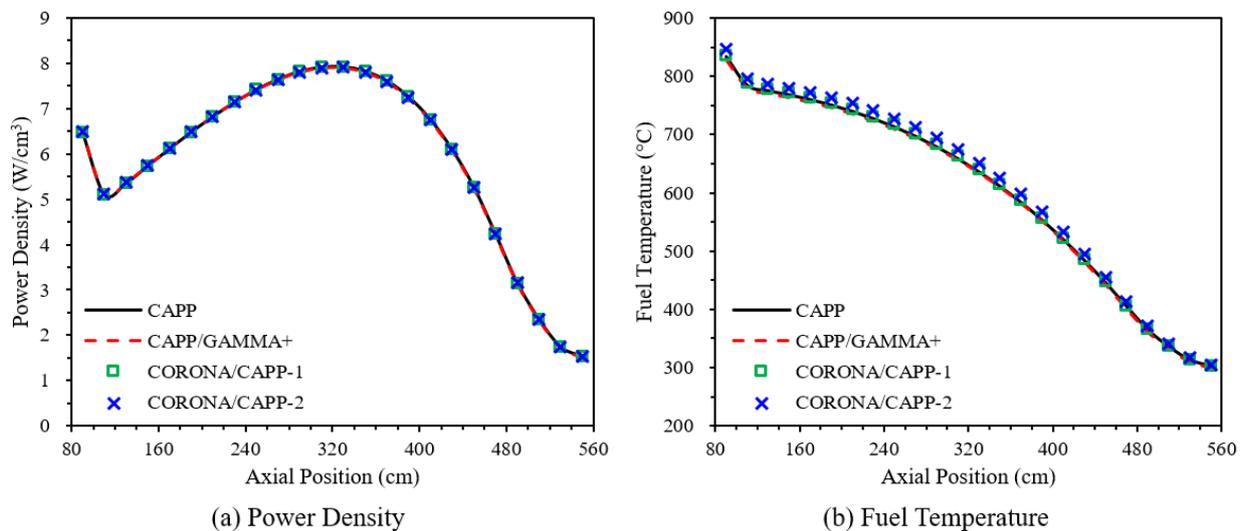


Figure 5. Axial Distribution for Single Column Problem.

Fig. 6 shows the radial temperature distribution in the lowest computational lattice layer (20 cm in height) in the CORONA/CAPP calculation. The temperature distribution varies depending on the analysis method for the fluid. At this time, the maximum fuel temperature can be found at the inner fuel compact. The maximum fuel temperature is 896.5 °C when the channel model is used and 910.9 °C when the network model is used. The maximum fuel temperature from the CAPP/GAMMA+ coupled code system is 846.8 °C. Therefore, the result of CORONA/CAPP coupled code system is about 50 ~ 64 °C higher.

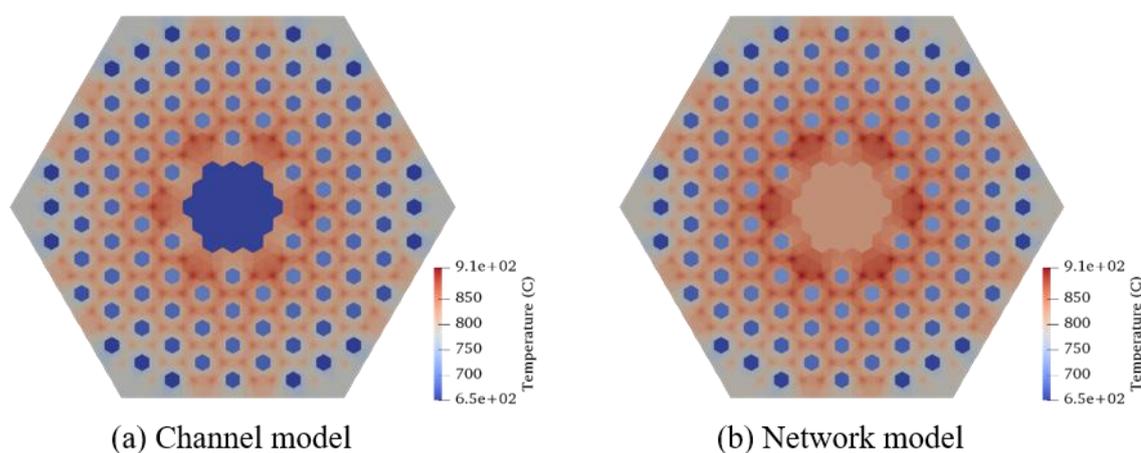


Figure 6. Radial Temperature Distribution at the Bottom of Active Region for Single Column Problem.

4. CONCLUSIONS

In this study, a reactor core analysis code CAPP and core high-fidelity thermal-fluid analysis code CORONA were used to perform more precise coupled code system than the previously developed CAPP/GAMMA + coupled code system. In order to test the CORONA/CAPP coupled code system, we analyzed the single HTGR column problem and confirmed the result. From the numerical results, the CORONA/CAPP coupled code system showed reasonable results for power distribution and temperature distribution. In addition, when using the accurate CORONA fluid analysis option, the calculation results were different due to the fluid analysis differences with other methods. Finally, it was found that the maximum fuel temperature calculated by CORONA/CAPP predicted a higher value than the conventional CAPP/GAMMA+ coupled code system. Therefore, CORONA/CAPP would be an enough option to predict more accurate fuel temperature values. Conversely, the difference between CORONA/CAPP and the existing codes can be helpful to determine the validity of the existing code calculation.

In this study, because of the single column problem, the power distribution, the temperature distribution, and the flow were relatively simple, so the difference between the codes was not very noticeable. It is necessary to compare the results between the codes for more complex problems in the future. In the case of the CORONA/CAPP coupled code system, core thermal-fluid analysis is performed with a different level of accuracy than the thermal-fluid analysis used by CAPP or GAMMA +. It needs to be verified through measurement data or benchmark problems.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2017M2A8A1014757).

REFERENCES

1. U. Rohde et al., "Development and Verification of the Coupled 3D Neutron Kinetics/Thermal-Hydraulics Code DYN3D-HTR for the Simulation of Transients in Block-Type HTGR," *Nuclear Engineering and Design*, **251**, pp. 412-422 (2012).
2. G. Strydom et al., "Comparison of the PHISICS/RELAP5-3D ring and blockmodel results for phase I of the OECD/NEA MHTGR-350 benchmark," *Nuclear Technology*, **193**, pp. 15-35 (2016).
3. H.C. Lee, C.K. Jo, and J.M. Noh, "Development of CAPP Code Based on the Finite Element Method for Analysis of VHTR Cores," *Proceedings of HTR2008*, Washington, DC, USA, September 28–October 1, 2008 (2008).
4. H.C. Lee, C.K. Jo, and J.M. Noh, "Development of the CAPP Code for the Analysis of Block Type VHTRs," *Transactions of the Korean Nuclear Society Spring Meeting*, Taebaek, Korea, May 26–27, 2011 (2011).
5. H.C. Lee, T.Y. Han, C.K. Jo, and J.M. Noh, "Development of the HELIOS/CAPP Code System for the Analysis of Pebble Type VHTR Cores," *Annals of Nuclear Energy*, **71**, pp. 130-144 (2014).
6. N.I. Tak et al., "A Practical Method for Whole Core Thermal Analysis of Prismatic Gas-Cooled Reactor," *Nuclear Technology*, **177**, pp. 352-365 (2012).
7. N.I. Tak et al., "Development of a Core Thermo-Fluid Analysis Code for Prismatic Gas Cooled Reactors," *Nuclear Engineering and Technology*, **46**, pp. 641-654 (2014).
8. H.S. Lim and H.C. No, "GAMMA Multidimensional Multi-Component Mixture Analysis to Predict Air Ingress Phenomena in an HTGR," *Nuclear Science and Engineering*, **152**, pp. 87-97 (2006).
9. H.S. Lim, *General Analyzer for Multi-component and Multi-dimensional Transient Application, GAMMA+ 1.0 Volume II: Theory Manual*, KAERI/TR-5728/2014, Korea Atomic Energy Research Institute (2014).
10. N. Tak, H.C. Lee, H.S. Lim, and T.Y. Han, "CAPP/GAMMA+ code system for coupled neutronics and thermo-fluid simulation of a prismatic VHTR core," *Annals of Nuclear Energy*, **92**, pp. 228-242 (2016).
11. S. Yuk et al., "CAPP/GAMMA+ Coupled Code System for Transient Analysis of a Block-Type HTGR Core," *Proceedings of M&C2019*, Portland, Oregon USA, August 25-29, 2019 pp. 1857-1863 (2019).
12. J. Y. Cho et al., *DeCART2D v1.1 User's Manual*, KAERI/UM-40/2016, Korea Atomic Energy Research Institute (2016).
13. "CFX version 19.0", www.ansys.com (2018).
14. J. Ortensi et al., *Benchmark of the MHTGR-350 MW Core Design. Volumes I and II*, NEA/NSC/R(2017)4, Nuclear Energy Agency (2017).