

CORONA/CAPP Coupling Scheme for a Prismatic HTGR Core

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1. Introduction

As the physical phenomena within a reactor core—such as neutron transport, heat transfer, and fluid dynamics—are intrinsically coupled, a multi-physics simulation approach is favored for accurate analysis. This is especially critical for high temperature gas-cooled reactors (HTGRs), where significant temperature gradients within the reactor core exist.

To this end, KAERI previously developed a coupled neutronics/thermal-fluids system [1] by coupling the neutronics code CAPP [2] and the system safety analysis code GAMMA+ [3]. This system improved analysis accuracy over standalone calculations by exchanging power and temperature distributions. However, the data exchange in the CAPP/GAMMA+ system occurs at a block or sub-block level. For a more precise evaluation of critical safety parameters like the maximum fuel temperature, a finer calculation mesh is required.

The core thermal-fluids code CORONA [4] is designed to perform thermal-fluid analysis on a mesh with CFD (Computational Fluid Dynamics) level fidelity, resolving down to the fuel compact scale. Meanwhile, CAPP, while performing core-level calculations on a coarser mesh, can reconstruct pin-level power distributions. Therefore, coupling CAPP and CORONA promises a significant improvement in the fidelity of both power and temperature results.

Based on these considerations, a method for coupling CAPP and CORONA was developed and successfully tested on a single fuel column problem [5]. This study extends that work by applying the CORONA/CAPP coupling scheme to a prismatic HTGR core problem. We perform a steady-state analysis and compare the results with conventional methods to demonstrate the impact and value of this high-fidelity approach.

2. CORONA/CAPP Coupling Scheme

2.1 CAPP and CORONA Codes

CAPP is a reactor core analysis code developed for HTGRs. It solves the 3D multi-group neutron diffusion equation using the finite element method to calculate the effective multiplication factor, neutron flux, and power distribution. It also includes a simplified internal thermal-fluids module and can perform depletion calculations. A key feature utilized in this work is its ability to synthesize pin-power distributions within each

computational mesh by combining the shape function from the finite element solution with pre-calculated pin-power form functions from the lattice transport calculation by DeCART2D_HTR [6].

CORONA is a specialized code for detailed thermal and fluid dynamics analysis of prismatic HTGR cores. It positions itself between system-level codes like GAMMA+ and full CFD codes. While GAMMA+ struggles to model the intricate details of the core, full CFD is computationally prohibitive for core-level problems. CORONA achieves CFD-level accuracy with significantly greater speed by modeling the fluid domain as a 1D network and the solid domain in 3D. It leverages the regular geometry of the block-type core for efficient mesh generation and employs column-wise parallelization to enhance computational performance. CORONA can use different fluid models, including a simplified 'Channel' model that can speed-up the calculations and a more rigorous 'Network' model that solves for energy and momentum balance across a connected flow network.

2.2 Coupling Methodology

The coupling of CAPP and CORONA is managed by a server program named COtoCA (CORONA to CAPP), which controls the data exchange and convergence checks between the two client codes, as illustrated in Figure 1.

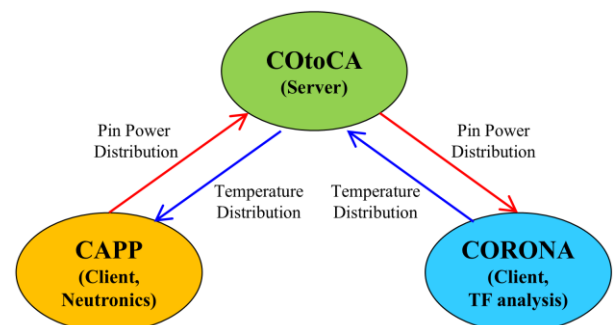


Fig. 1. Schematic of the CORONA/CAPP coupling scheme

The iterative calculation process is as follows:

1. CAPP calculates the core power distribution and synthesizes the pin-level power data.
2. COtoCA receives the pin power distribution from CAPP and maps it onto CORONA's mesh.

3. CORONA receives the pin power as a heat source and performs a detailed thermal-fluids analysis, calculating the temperature distributions for the fuel, moderator, and coolant.
4. COtoCA receives the temperature distributions from CORONA and maps them back onto CAPP's mesh.
5. CAPP uses the updated temperature data to re-evaluate temperature-dependent cross-sections and calculates a new power distribution.

This process is repeated until the solution converges. Both codes independently check for convergence based on their respective criteria and report their status to COtoCA. The server terminates the iteration only when both codes have converged.

A critical component of this scheme is the mapping of data between the disparate meshes of CAPP and CORONA. COtoCA handles this complex task based on a mapping file provided by the user. The 3D mapping is achieved by combining a 2D radial map and a 1D axial map. For CAPP-to-CORONA power mapping, a one-to-one correspondence is established between fuel compact indices. For CORONA-to-CAPP temperature mapping, each hexagonal block in CORONA is divided into six triangles, which are then mapped to the corresponding triangular prism meshes in CAPP.

3. Numerical Results

3.1 MHTGR-350 Type Core Problem

To test the CORONA/CAPP coupling system, a steady-state analysis was performed on the MHTGR-350 type core problem, which is part of a VHTR common benchmark problem set developed at KAERI [7]. This problem is based on the well-known MHTGR-350 benchmark [8] and represents a full-scale core. The main operating conditions are listed in Table I and the core geometry is shown in Figure 2.

Table I: Main Parameters of the MHTGR-350 Type Core Problem

	Value
Thermal power (MW_{th})	350
Coolant inlet temperature ($^{\circ}\text{C}$)	259
Total coolant mass flow (kg/sec)	157.1
Number of fuel columns	66
Number of inner reflector columns	19
Number of outer reflector columns	126
Total height (cm)	1120
Active core height (cm)	800

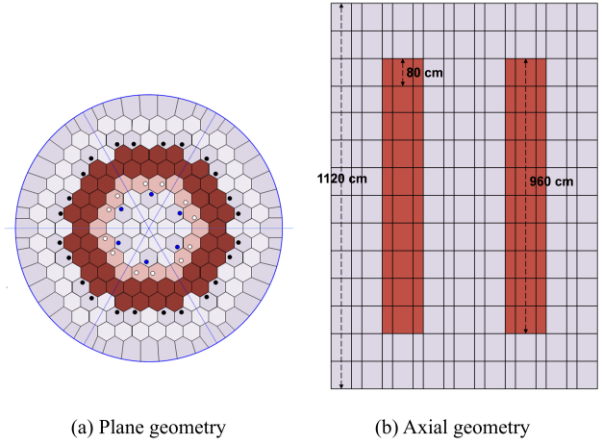


Fig. 2. Geometry of the MHTGR-350 type core problem.

3.2 Comparison of Results

The results from the CORONA/CAPP system were compared against CAPP standalone. For the CORONA/CAPP runs, both the 'Channel' and 'Network' fluid models in CORONA were tested.

Table II summarizes the key results for the effective multiplication factor (k_{eff}) and the maximum fuel temperature. The CORONA/CAPP calculations, which account for an 8% core bypass flow, result in lower k_{eff} values due to the corresponding increase in fuel and moderator temperatures. The CAPP standalone only provides simplified thermal analysis and does not consider bypass in detail. Considering the bypass flow fraction obtained by CORONA/CAPP calculation, when calculating with a reduced flow rate (Flow-reduced option) in CAPP, k_{eff} decreases as the core temperature rises, as in the CORONA/CAPP calculation.

A notable difference is observed between the Channel and Network models, which is attributed to different local coolant flow distributions even with the same total bypass flow fraction. The most significant difference is seen in the maximum fuel temperature. The Network model predicts a temperature of 1284.9°C , which is 234.4°C higher than the Channel model's prediction. This discrepancy is likely because the Network model calculates a lower local coolant flow rate in the vicinity of the hot spot, leading to less effective cooling and a higher peak temperature.

Figures 3 and 4 show the axial power density and fuel temperature distributions, respectively. While the power profiles are very similar across all cases, the fuel temperature profiles show clear differences. The CORONA/CAPP results are generally higher than the CAPP standalone result due to the inclusion of bypass flow. Considering the reduced flow rate in the CAPP calculation, the overall axial distribution becomes similar to CORONA/CAPP results.

Table II: Comparison of k_{eff} and Maximum Fuel Temperature

Code	Options	Keff	Diff. [pcm]	Maximum Fuel Temperature [°C]	Diff. [°C]	Bypass Flow Frac. [%]
CAPP		1.00132	--	1163.3	--	0
	Flow-reduced	0.99881	-251	1228.6	65.3	8.0
CORONA/CAPP	Channel	0.99774	-358	1050.5	-112.8	8.0
	Network	0.99561	-571	1284.9	121.6	8.0

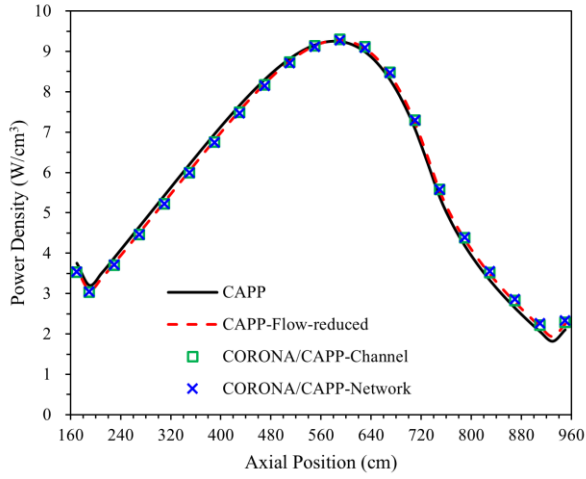


Fig. 3. Axial power density in the active core.

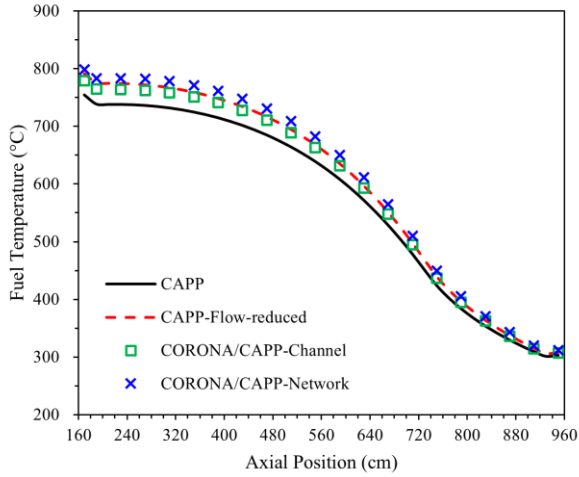


Fig. 4. Axial fuel temperature distribution in the active core.

Figures 5 and 6 show the radial temperature distribution at the bottom of the active core which are calculated by the CORONA/CAPP-Channel, and CORONA/CAPP-Network, respectively. It visually demonstrates the difference between the fluid models. The Network model predicts a more pronounced and widespread high-temperature region compared to the Channel model.

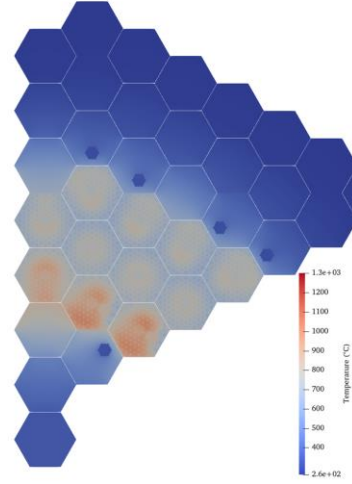


Fig. 5. Radial temperature distribution at the bottom of the active core (CORONA/CAPP-Channel).

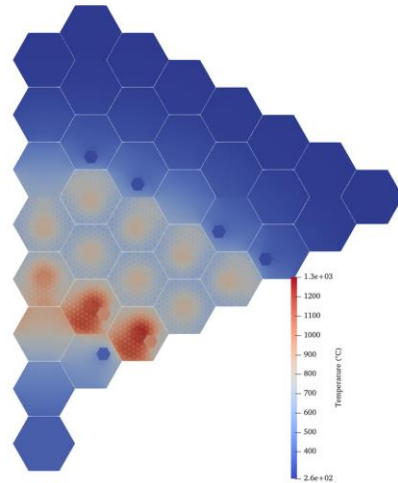


Fig. 6. Radial temperature distribution at the bottom of the active core (CORONA/CAPP-Network).

4. Conclusions

In this study, the CORONA/CAPP coupled code system for high-fidelity, pin-level neutronics and thermal-fluids analysis, was successfully extended and applied to a full-core block-type HTGR problem. The system produced reasonable and consistent results for power and temperature distributions.

The comparison with conventional methods demonstrated that the choice of the thermal-fluid model has a significant impact on the results, particularly on the maximum fuel temperature. The detailed Network model in CORONA predicted a higher peak fuel temperature than the CAPP standalone, suggesting that the more detailed flow physics captured by CORONA are crucial for accurate safety analysis.

This work confirms that the CORONA/CAPP system can serve as a powerful tool for obtaining more precise fuel temperature predictions. It can also be used to assess the validity and conservatism of results from lower-fidelity methods. Future work will involve applying the system to wider range of problems to further investigate the sources of discrepancies and comparing the results with one-way coupled calculations. Validation against experimental data or higher-fidelity simulation codes will also be necessary to fully qualify the system.

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REFERENCES

- [1] N. I. 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*, Vol.92, p.228, 2016.
- [2] 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*, Vol.71, p.130, 2014.
- [3] 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*, Vol.152, p.87, 2006.
- [4] N. I. Tak, S. N. Lee, M. H. Kim, H. S. Lim, and J. M. Noh, Development of a Core Thermo-Fluid Analysis Code for Prismatic Gas Cooled Reactors, *Nuclear Engineering and Technology*, Vol.46, p.641, 2014.
- [5] S. Yuk, N. Tak, and C.K. Jo, Development of Pin-Level Neutronics/Thermal-Fluid Analysis Coupled Code System for a Block-Type HTGR Core, *Proceedings of PHYSOR2020*, March 29–April 2, 2020, Cambridge, United Kingdom.
- [6] T. Y. Han et al., *DeCART2D_HTR v1.0 User's Manual*, KAERI/TR-8584/2021, Korea Atomic Energy Research Institute, 2021.
- [7] S. N. Lee et al., *CAPP/CORONA code Transient Analysis Verification Report for High Temperature Gas-Cooled Reactor Core Design*, KAERI/TR-7461/2018, Korea Atomic Energy Research Institute, 2018.

- [8] 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.