CUPID-PRAGMA Coupling Method using preCICE library

Seongju Do [a*]

[a]*Korea Atomic Energy Research Institute, Daedeok - daero 989 beon - gil, Yuseong - gu, Daejeon 34057, Republic of Korea*

[*]*Corresponding author: sjdo@kaeri.re.kr*

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1. Introduction

The accurate analysis of nuclear reactor systems requires a multi-physics approach that integrates thermal-hydraulics, neutron transport, and structural mechanics. CUPID[1], developed by KAERI, is a component-scale thermal-hydraulic code specialized for two-phase flow simulations in reactor components, offering high-fidelity modeling of coolant behavior. On the other hand, PRAGMA[2] is a neutron transport code capable of precise particle tracking and collision physics, suitable for reactor core neutronics analysis.

The strong interdependence between coolant flow and power distribution necessitates a coupling strategy that ensures accurate information exchange among solvers. In this context, the preCICE[3] library provides a flexible and scalable framework for coupling heterogeneous codes. This study presents the development and application of a CUPID–PRAGMA coupled simulation environment using preCICE, focusing on iSMR (integral Small Modular Reactor) steady-state conditions.

2. Coupling Methodology

The coupling framework employs the preCICE library, which enables robust data exchange without altering the core algorithms of individual solvers. Several advanced features of preCICE are utilized:

Coordinate-based data mapping ensures flexible transfer between structured and unstructured meshes, avoiding the need for predefined index tables. This is particularly advantageous for reactor types such as MSR where mesh structures may be highly irregular. Direct MPI peer-to-peer communication reduces latency and eliminates middleware overhead, supporting scalability for large-scale HPC environments.

To guarantee reproducibility and portability across diverse computing environments, the entire coupling setup—including CUPID, PRAGMA, and preCICE—is containerized using Apptainer. This strategy encapsulates software dependencies and eliminates environment-related inconsistencies, a common challenge in collaborative code development.

The data exchange process was designed to handle interactions between coolant subchannels modeled in CUPID and neutron flux or power distributions calculated by PRAGMA. Interpolation strategies were applied to maintain accuracy when mapping between meshes of different resolution and geometry.

3. Numerical Results

The coupled simulation was tested for an iSMR reactor core operating at a thermal power of 520 MWth. The thermal-hydraulic model contained approximately 600,000 computational cells with boundary conditions defined as inlet temperature 295 °C, outlet temperature 325 °C, and system pressure of 15 MPa. For neutron transport, PRAGMA tracked approximately 100 million particles, ensuring statistically reliable power distribution data.

The coupled results demonstrated stable convergence under steady-state conditions. Real-time power feedback from PRAGMA successfully influenced coolant temperature and density distribution in CUPID, highlighting the importance of bidirectional interaction.

The preCICE framework minimized coupling overhead, and strong scalability was observed with increasing computational resources. Furthermore, memory usage was optimized due to efficient data exchange strategies, enabling simulations on both workstation and HPC cluster environments.

One-step calculation time versus the number of cores was also analyzed to demonstrate the strong scalability of the coupled framework. The simulation was performed with a fixed problem size (600,000 thermal-hydraulic cells and 100 million particles) while the number of cores was varied from 10 to 300. The results showed that the one-step time decreased reasonably with the increasing number of cores, indicating that the parallel efficiency was high and the communication overhead was minimal. This indicates that our coupling approach is highly efficient for large-scale simulations on high-performance computing (HPC) environments where a large number of cores are utilized to solve a single problem.

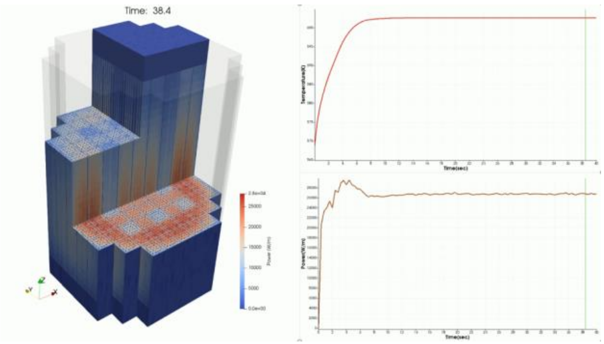
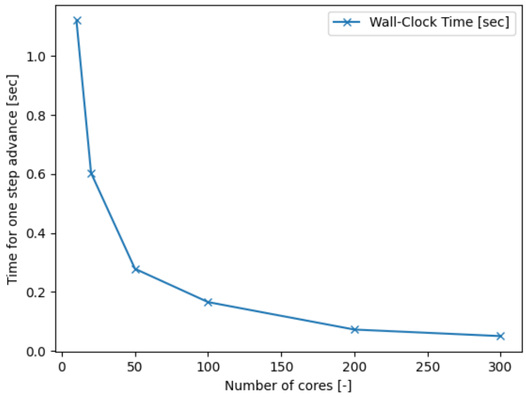


Fig. 1. Coupled simulation results of CUPID-PRAGMA: Steady-state calculation results for iSMR



Number of cores	Time / step [sec]
10	1.1213
20	0.6037
50	0.2788
100	0.1657
200	0.0726
300	0.0504

4. Conclusions

This work successfully implemented a multi-physics coupling between CUPID and PRAGMA using the preCICE library. The results confirm the robustness of the framework in terms of convergence stability, parallel scalability, and memory efficiency. The containerized deployment with Apptainer further ensures reproducibility across heterogeneous computing environments, addressing one of the key challenges in modern collaborative nuclear simulation research.

This study successfully established a robust and scalable thermal-hydraulics–neutronics interface. It also demonstrated efficient parallel coupling with negligible overhead, evidenced by the strong scalability analysis, which showed a near-linear reduction in one-step calculation time with an increasing number of cores. Furthermore, the work validated the potential of containerization for production-level nuclear analysis.

Future work will extend the framework to include structural mechanics modules for fuel and reactor vessel stress analysis, as well as transient simulations that capture dynamic reactivity feedback. Ultimately, this approach provides a solid foundation for the development of a virtual nuclear reactor platform capable of comprehensive multi-physics simulations.

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