A High-Fidelity Multiphysics Analysis Method for the MSFR Reactor Using CUPID–PRAGMA Coupling

Seongju Do and Jaeuk Im
Korea Atomic Energy Research Institute (KAERI), Republic of Korea.
sjdo@kaeri.re.kr

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1. Introduction

The Molten Salt Fast Reactor (MSFR) is a Generation IV nuclear reactor concept distinguished by the circulation of liquid fuel within the reactor core. Such a configuration requires high-resolution multiphysics simulations because of the inherently strong feedback mechanisms between neutron transport and thermal-hydraulic behavior. This work presents a high-fidelity steady-state multiphysics coupling framework specifically developed for detailed MSFR analysis. The proposed methodology couples large-eddy simulation (LES)-based thermal-hydraulics in CUPID with GPU-accelerated Monte Carlo neutron transport calculations in PRAGMA through the partitioned coupling library preCICE. CUPID, a multidimensional two-phase flow code developed at KAERI, enables detailed resolution of complex turbulent flow structures. This capability is essential for analyzing liquid-fueled reactor systems. PRAGMA employs massively parallel GPU acceleration to execute large-scale Monte Carlo neutron transport calculations, significantly reducing computational time while maintaining high statistical accuracy. The preCICE library offers a flexible and scalable partitioned coupling environment for multiphysics simulations. Steady-state coupled simulations were performed for the MSFR reference configuration. The coupled simulation results demonstrate that the proposed framework effectively captures key MSFR phenomena, including power–temperature feedback and flow recirculation.

2. Methodology

The coupling strategy adopts a partitioned scheme in which CUPID and PRAGMA independently solve their governing physics and exchange interface data via preCICE at every coupling iteration. The steady-state solution is achieved through iterative data exchange between the two solvers as follows:

- PRAGMA → CUPID: Volumetric power distribution (W/m³)
- CUPID → PRAGMA: Molten salt temperature field (K) and molten salt density field (kg/m³)

CUPID, developed at KAERI, is a high-fidelity multidimensional thermal–hydraulics code designed for transient two-phase flow analysis in reactor components. [1], [2]. CUPID, developed at KAERI, is a high-fidelity multidimensional thermal–hydraulics code designed for transient two-phase flow analysis in reactor components [3]. In contrast to traditional incompressible solvers, CUPID adopts the ICE scheme, which consistently accounts for density variations within the governing equations. Buoyancy forces resulting from thermally induced density gradients are directly evaluated without empirical approximations. The CUPID code is capable of accurately modeling the complex interaction of natural and forced convection flows within the MSFR.
The key features of the CUPID code can be summarized as follows:

- Geometric flexibility is achieved through the finite volume method on unstructured meshes.
- CUPID applies a two-fluid model for two-phase flow simulations.
- The WALE(Wall-Adapting Local Eddy-viscosity) LES turbulence model is incorporated for high-resolution turbulence simulation.
- Parallel computation is enabled through MPI-based domain decomposition.

PRAGMA is a graphics processing unit (GPU)-based continuous-energy Monte Carlo (MC) code developed at Seoul National University, initially designed for neutron transport analysis in conventional power reactor systems [4]. To facilitate simulations of advanced reactor systems, a new particle tracking algorithm leveraging NVIDIA’s OptiX GPU-based ray-tracing framework was implemented, and the geometry module was extended to accommodate unstructured mesh geometries.

preCICE is an open-source software library designed for partitioned multiphysics coupling between independently developed simulation codes, offering black-box integration, parallel data communication, various mapping algorithms, and convergence acceleration techniques. The library enables the coupling of standalone simulation codes without modification of their internal numerical algorithms, thereby improving modularity and extensibility of multiphysics simulation frameworks [5], [6].

The multiphysics coupling is implemented via customized preCICE adapter modules for the CUPID and PRAGMA codes. Through the CUPID adapter, the volumetric heat source distribution calculated by PRAGMA is received, while the corresponding molten salt density and temperature fields are transmitted to PRAGMA.

Within PRAGMA, the adapter utilizes the temperature and density information provided by CUPID to perform cross-section updates and then transmits the recalculated volumetric heat source distribution to CUPID.

The coupling procedure is fully configurable through XML input files, which provide detailed specification of coupling frequencies, spatial mapping techniques, convergence criteria, and relaxation or acceleration parameters.

Accurate information transfer across non-matching discretizations is achieved through the application of various spatial mapping algorithms. To maintain total reactor power conservation, a conservative mapping scheme is applied to the heat generation field, whereas temperature and density variables are transferred using a consistent mapping approach. In cases where the CUPID computational mesh and the PRAGMA tally mesh are non-aligned, radial basis function (RBF) interpolation is applied to achieve accurate spatial projection.

Through the integration of preCICE, a robust and scalable coupled simulation environment is achieved while preserving the original numerical structures of both CUPID and PRAGMA.

3. Numerical results

A detailed steady-state neutronic and thermal–hydraulic assessment of the Molten Salt Fast Reactor (MSFR) was conducted to characterize its nominal operating conditions. All modeling assumptions, boundary conditions, and reference parameters were adopted in accordance with the validated MSFR benchmark specification reported in [7]. The detailed physical properties and operating conditions are summarized in Table 1. In the present MSFR configuration, a KCl–UCl_3 molten chloride salt mixture is employed as both the circulating fuel and the primary coolant.

Table 1. Physical properties and operating conditions

Parameter	Symbol	Value
Power	Q	300 MW
Inlet Temperature	T_{in}	898.0 K
Mass flow rate	$\dot{M}$	1882.12 kg/s
Pressure	P	100.0 KPa

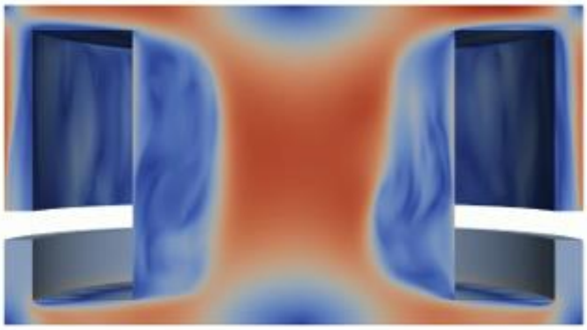

Figure 1. Flow analysis result using CUPID (without PRAGMA coupling)

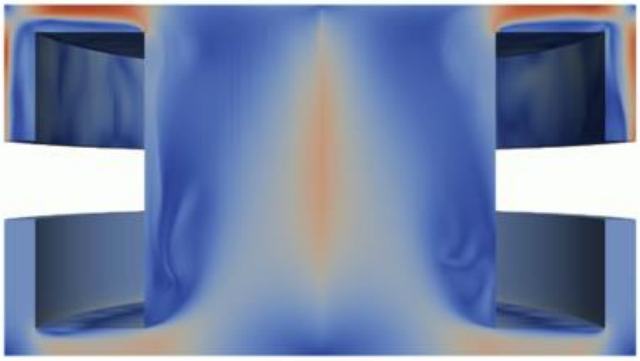

Figure 2. Flow analysis result using CUPID (with PRAGMA coupling)

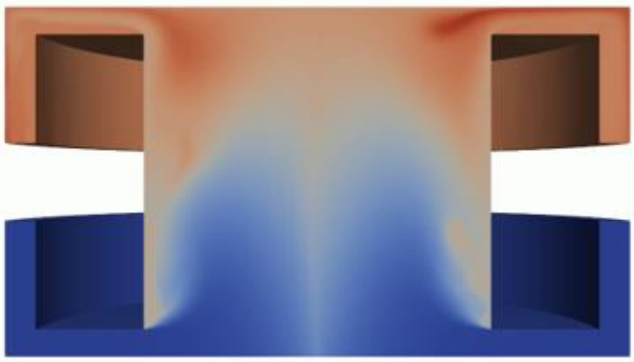

Figure 3. Temperature distribution (with PRAGMA coupling)

As shown in Figure 1, the standalone CUPID calculation employed a WALE-based large-eddy simulation (LES) model to resolve the turbulent flow field. The high-fidelity LES approach captures shear-driven near-wall turbulence features that were absent in earlier RANS-based studies.

As illustrated in Figure 2, the coupled simulation incorporates the PRAGMA-calculated heat generation profile into CUPID to determine the corresponding thermal–hydraulic responses. In contrast to the standalone case, the coupled results demonstrate a substantially modified flow-field distribution.

Figure 3 indicates that the observed differences stem from buoyancy-induced upward transport of hot fuel salt generated in regions of elevated power density.

In summary, the coupled analysis confirms that buoyancy-driven feedback mechanisms can strongly alter the hydrodynamic behavior, highlighting buoyancy as an essential physics phenomenon in predictive high-resolution simulations of fuel-salt reactor systems.

4. Conclusions

The implementation of customized preCICE adapters for the CUPID and PRAGMA codes results in a stable and scalable multiphysics coupling architecture for heterogeneous solver integration.

A principal advantage of the proposed framework is the advanced thermal–hydraulic modeling capability offered by CUPID. By employing the ICE scheme, CUPID naturally accounts for variable-density effects and buoyancy-induced flow behavior without supplementary empirical corrections. In addition, the incorporation of the WALE large-eddy simulation (LES) turbulence model enhances the resolution of shear-induced near-wall turbulence structures. On the neutronics side, PRAGMA efficiently evaluates core power distributions using a GPU-accelerated continuous-energy Monte Carlo method. The coupled multiphysics simulations exhibit significant deviations compared with standalone thermal–hydraulic analyses. These discrepancies primarily arise from localized high-power regions that generate buoyancy-driven high-temperature fuel plumes. Given its robust treatment of compressible and variable-density flow via the ICE scheme, CUPID is especially applicable to low-velocity Generation IV reactor systems.

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