



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

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## Introduction

**CUPID** — Component Unstructured Program for Interfacial Dynamics [1, 2, 3]

CFD code developed at **KAERI** for thermal-hydraulic analysis of nuclear systems.

- ▶ 3D two-fluid, two-phase flow on unstructured meshes
- ▶ **LES** turbulence modeling with **WALE** (Wall-Adapting Local Eddy-viscosity) subgrid model
- ▶ Conjugate heat transfer for complex reactor geometries

**PRAGMA** — Power Reactor Analysis using GPU-based Monte Carlo Algorithm [4, 5]

Continuous-energy Monte Carlo neutronics code developed at **Seoul National University**.

- ▶ **Continuous-energy Monte Carlo** neutron transport
- ▶ **GPU-friendly** architecture for high-speed whole-core calculations
- ▶ Spatially resolved power distributions for T-H coupling

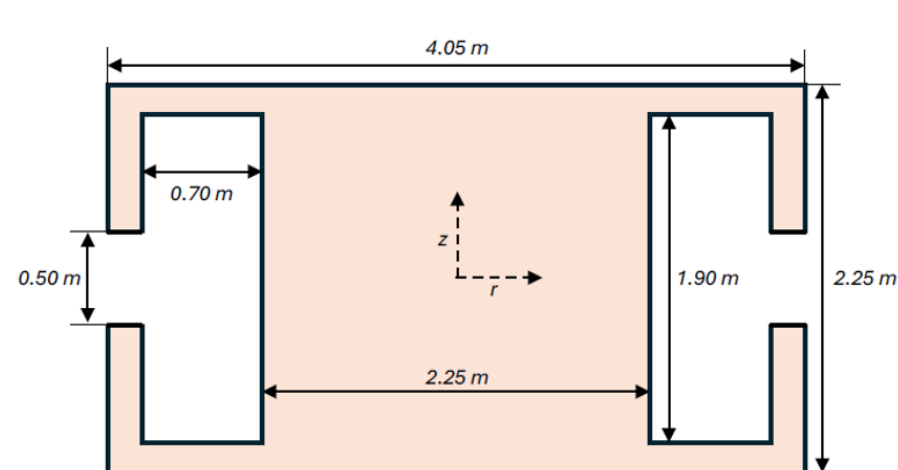
## MSFR

The **MSFR** (Molten Salt Fast Reactor) is a Gen-IV liquid-fueled reactor (SAMOFAR, 3,000 MWth). The fuel salt acts as both fuel and coolant, creating strong neutronics–thermal-hydraulics coupling [5].

### Simplified Computational Model [6]

Pumps & heat exchangers are omitted; a continuous inlet/outlet cylindrical geometry is adopted to reduce mesh and computational cost.

Parameter	Value
Fuel salt	LiF–ThF <sub>4</sub> – <sup>233</sup> UF <sub>4</sub> (77.5 mol% LiF)
Power	300 MWth
$T_{in} / T_{out}$	898 K / 998 K
Density	4,125 kg/m <sup>3</sup> at 973 K
$\dot{m}$	1,882 kg/s



### Why 3D Multiphysics Coupling?

- ▶ Fuel salt = neutron source + coolant ⇒ strong two-way feedback
- ▶ Non-uniform flow → non-uniform heating → Doppler & density reactivity feedback
- ▶ 1D/point-kinetics cannot capture spatial effects

## References

- [1] J.J. Jeong et al., The CUPID code development and assessment strategy, *Nucl. Eng. Tech.*, 42(6) (2010), 636–655.
- [2] H.Y. Yoon et al., Recent improvements in the CUPID code for multi-dimensional two-phase flow analysis, *Nucl. Eng. Tech.*, 46(5) (2014), 655–666.
- [3] I.K. Park et al., An implicit code coupling of 1-D system code and 3-D in-house CFD code for multi-scaled simulations, *Ann. Nucl. Energy*, 59 (2013), 80–91.
- [4] K.M. Kim et al., Practical methods for GPU-based whole-core Monte Carlo depletion calculation, *Nucl. Eng. Tech.*, 55(7) (2023), 2516–2533.
- [5] N. Choi et al., Optimization of neutron tracking algorithms for GPU-based continuous energy Monte Carlo calculation, *Ann. Nucl. Energy*, 162 (2021), 108508.
- [6] M. Dalinger et al., High-Fidelity Modelling of the Molten Salt Fast Reactor, *Proc. NURETH* (2024).
- [7] G. Chourdakis et al., preCICE v2: A sustainable and user-friendly coupling library, *Open Research Europe*, 2:51 (2022).

## Coupling Procedure

**preCICE** — Precise Code Interaction Coupling Environment [7]

Open-source multi-physics coupling library enabling partitioned coupling between arbitrary solvers on non-conforming meshes.

### Key Features

- ▶ Coordinate-based **RBF** data mapping between non-conforming meshes
- ▶ Direct peer-to-peer socket communication

### Coupling Scheme

- ▶ Partitioned **explicit (staggered)** coupling

### Assumption

- ▶ Steady-state only; DNP transport not considered

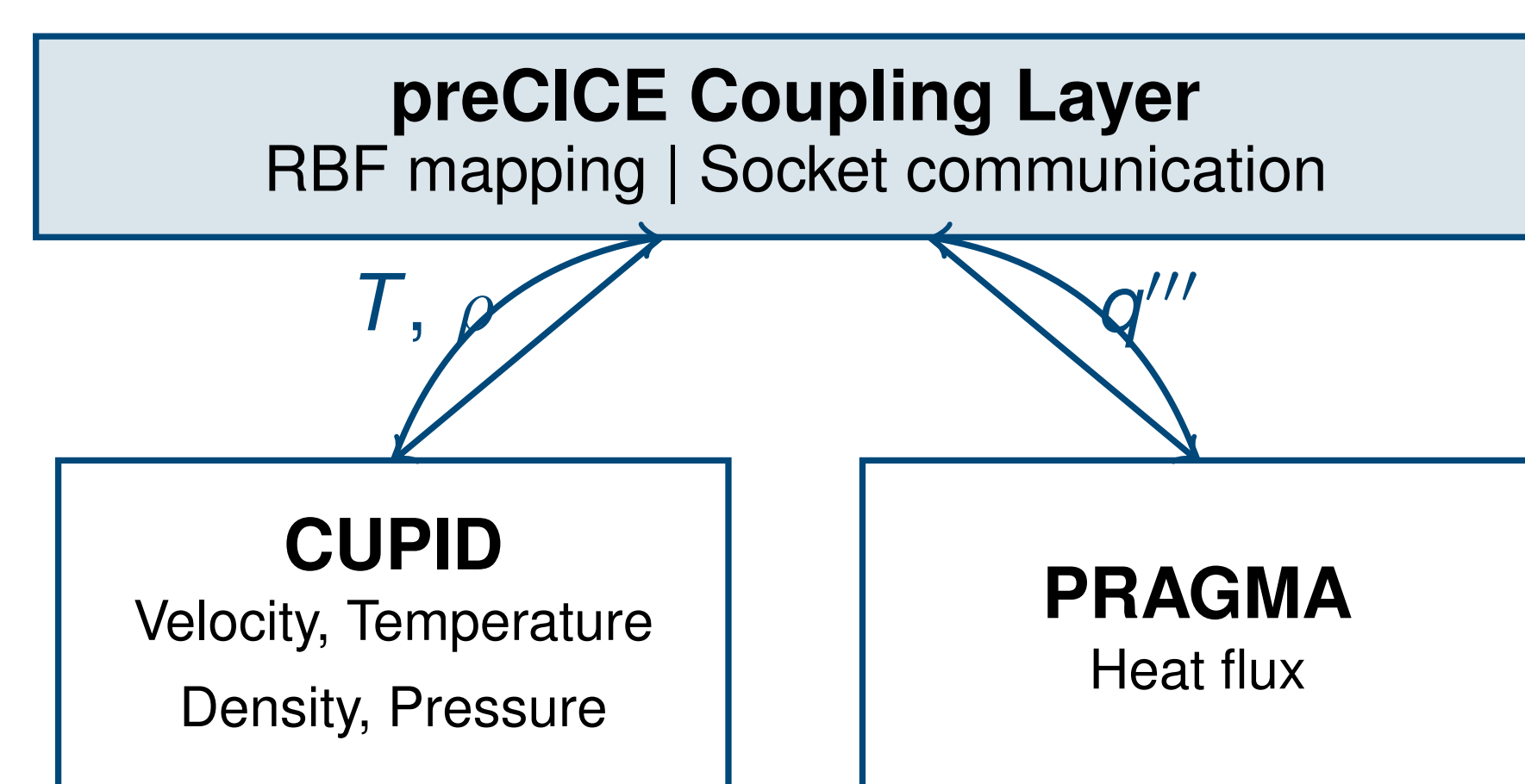


Fig. 1: CUPID–PRAGMA coupling architecture via preCICE

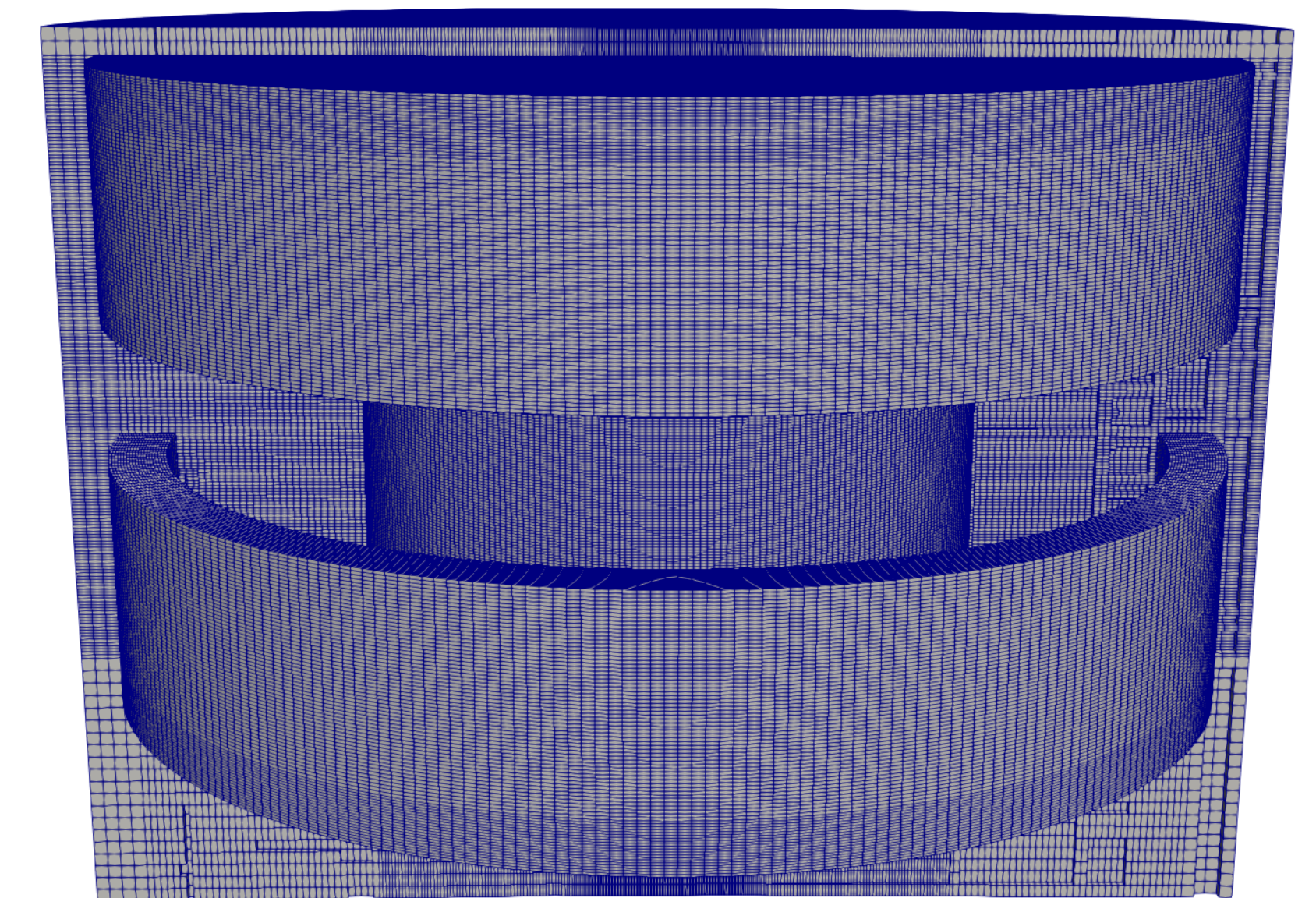


Fig. 2: Non-conforming meshes: CUPID (core only) and PRAGMA (core + reflector)

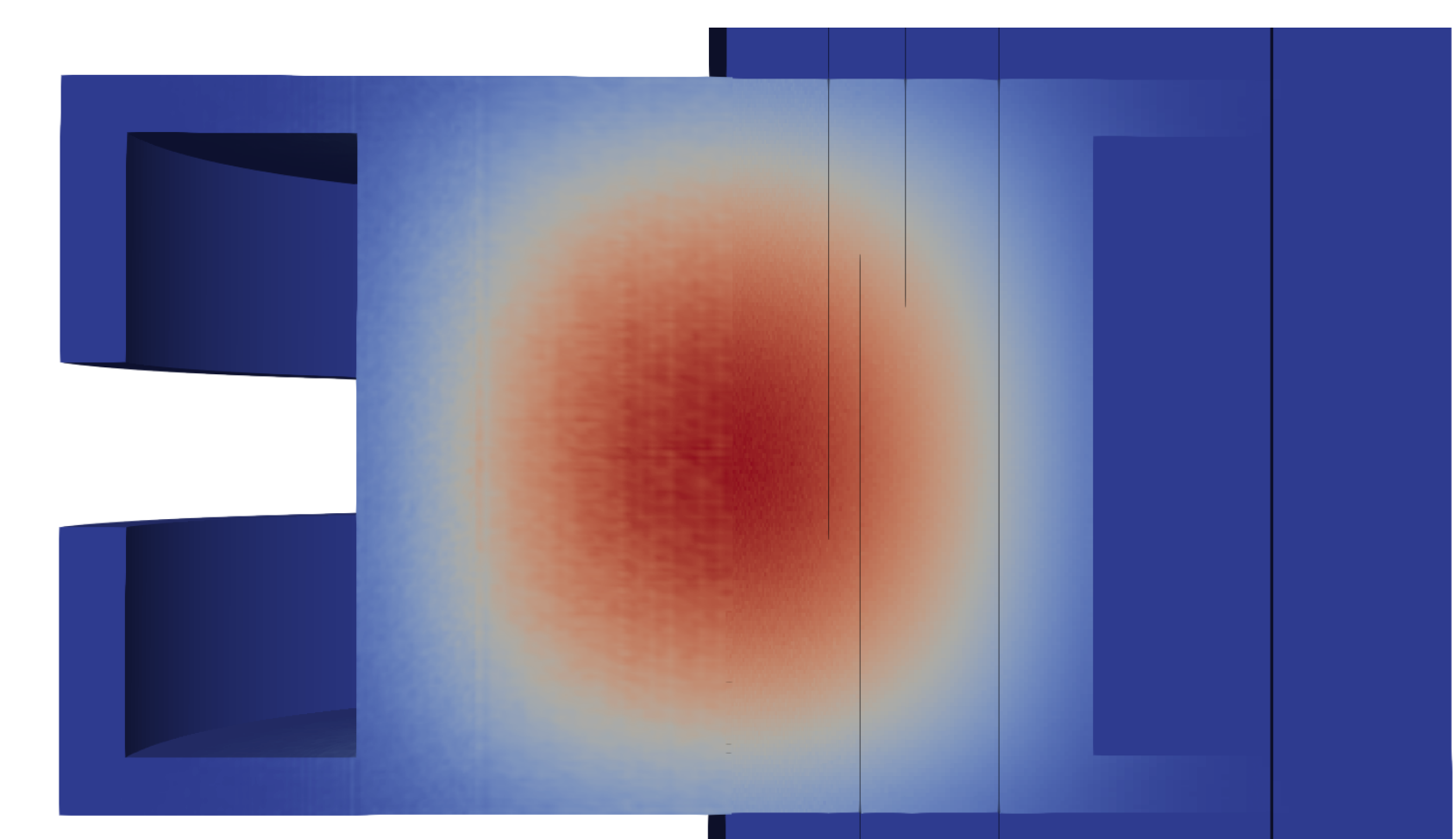


Fig. 3: Power distribution: PRAGMA result (right) mapped onto CUPID mesh via RBF mapping (left)

## Results

Steady-state analyses on the simplified MSFR geometry assess the impact of neutronics–thermal-hydraulics coupling.

	Case 1 (Standalone)	Case 2 (Coupled)
Setup	CUPID only	CUPID / PRAGMA coupling
Heat source	None (isothermal)	Spatially resolved $q'''$

### Temperature Distribution

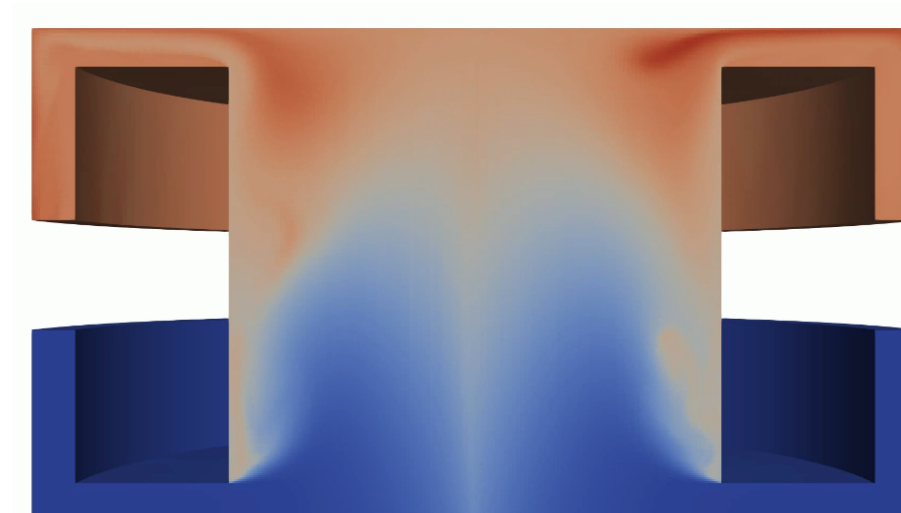


Fig. 4: Temperature field: (Case 2) Neutronics feedback produces a strong axial temperature gradient.

### Velocity Field Distribution

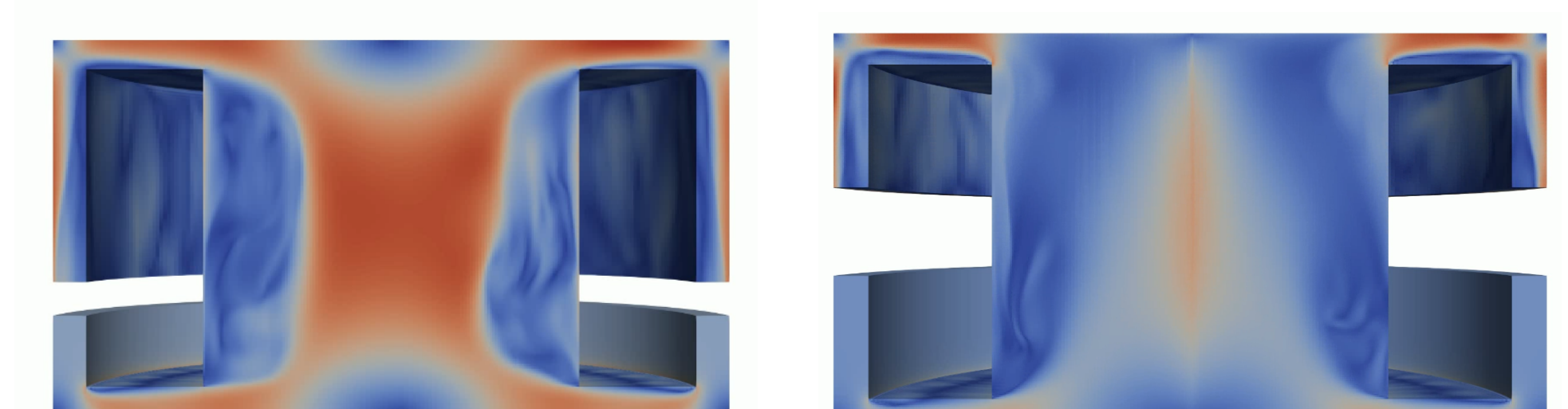


Fig. 5: Velocity field: Case 1 (left, isothermal) vs. Case 2 (right, coupled). Buoyancy effects from non-uniform heating modify the recirculation structure.

### Key Observations:

- ▶ **Temperature:** The spatially resolved  $q'''$  from PRAGMA produces a pronounced axial temperature gradient and a hot-spot migration toward the core center, which is absent in the isothermal Case 1.
- ▶ **Flow structure:** Non-uniform buoyancy forces in Case 2 intensify upper-core recirculation, substantially altering the velocity field from the isothermal baseline.
- ▶ **Coupling impact:** The standalone (isothermal) assumption underestimates peak temperature and overestimates flow symmetry, demonstrating the necessity of neutronics–T/H coupling for MSFR analysis.

## Conclusion

- ▶ A high-fidelity multiphysics framework for the MSFR was developed by coupling **CUPID** (LES/WALE) and **PRAGMA** (GPU Monte Carlo) via the **preCICE** library.
- ▶ Partitioned **explicit (staggered) coupling** with RBF mapping achieves consistent data exchange between non-conforming meshes.
- ▶ Steady-state results confirm significant differences between the coupled and standalone cases:
  - ▶ Asymmetric temperature structure driven by spatially resolved power distribution
  - ▶ Modified buoyancy-driven flow structure in the coupled case
- ▶ **3D multiphysics coupling is essential** for accurate MSFR safety analysis.

**Future Work:** DNP transport coupling; transient analysis (pump trip, reactivity insertion accidents)