A Monolithic Immersed Boundary Framework for Thermal FSI with Surrogate Model-based Uncertainty Quantification

Tiantian XU [1]

1) *School of Mathematics and Computing (Computational Science and Engineering), Yonsei University, Seoul 03722, KOREA*

Corresponding Author : Tiantian XU, tian0917@yonsei.ac.kr

ABSTRACT

Thermal fluid-structure interaction (FSI) represents a complex multiphysics phenomenon widely encountered in aerospace, marine engineering, and biomedical applications. Accurate prediction of such problems remains challenging due to inherent uncertainties arising from material properties and model parameters. This study proposes an efficient monolithic immersed boundary projection method (MIBPM) for incompressible flows with heat transfer. By employing a staggered time discretization scheme and a two-step approximate LU decomposition, the method ensures both stability and accuracy for both forced and natural convection, as well as for particle-laden flows. The MIBPM is further extended to simulate buoyancy-driven convection in complex geometries, including particle sedimentation and cylinder arrays within enclosures. For particle sedimentation at density ratios near unity, we improve the original formulation through implicit coupling of fluid and solid motion, enabling stable simulations in regimes where traditional methods suffer from numerical instability. In simulations of natural convection within square enclosures containing multiple cylinders, we systematically investigate the effects of Rayleigh number, cylinder count, and volume fraction on flow regimes and heat transfer. To enable efficient uncertainty quantification (UQ), we integrate the MIBPM with a non-intrusive surrogate model based on tensor-train decomposition (TTD) and polynomial chaos expansion (PCE). The resulting TTD-PCE significantly accelerates UQ and parameter identification in complex FSI systems, such as flexible filament dynamics. This unified framework offers a reliable solution for modeling thermally coupled FSI systems under uncertainty.

REFERENCES

1. Xu, T. and Choi, J.-I., "Efficient monolithic immersed boundary projection method for incompressible flows with heat transfer", *Journal of Computational Physics*, 477, 2023, 111929.
2. Xu, T. and Choi, J.-I., "Stable monolithic immersed boundary projection method for particle sedimentation with heat transfer at density ratios near unity", *Physics of Fluids*, 35(10), 2023.
3. Xu, T. and Choi, J.-I., "Numerical investigation of flow and heat transfer characteristics in buoyancy-driven convection around cylinder arrays within an enclosure", *Physics of Fluids*, 37(2), 2023.