Development and Verification of a General-Purpose Nuclear-Thermal Coupling Code Based on preCICE and Its OpenFOAM Adapter

Authors: Tan Liangkang, Deng Junjie, Zhao Pengcheng, Liu Zijing, Li Wei

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Abstract

To address the issues of low efficiency and insufficient accuracy in traditional programs for multi-physics coupling simulation of nuclear reactors, this study constructs a general three-dimensional neutronics-thermal coupling program based on the open-source coupling library preCICE and its adapter OpenFOAM-adapter. The neutronics module adopts a finite volume method neutron transport program developed by our research group, while the thermal-hydraulics module integrates three-dimensional solid heat conduction (laplacianFoam) and fluid convection heat transfer models (buoyantPimpleFoam). Through secondary development, the volume coupling functionality of the conjugate heat transfer module is extended to achieve cross-grid data exchange between the neutronics and thermal-hydraulics modules. A single-rod benchmark problem for pressurized water reactors is selected to conduct mesh independence analysis, comparing data transfer methods such as nearest-neighbor mapping, nearest-projection mapping, and radial basis function mapping. The results demonstrate that the program can accurately output three-dimensional power distribution, neutron flux density, temperature field, and velocity field, with the relative error of the coolant outlet average temperature being less than 0.1% and the relative error of the cladding maximum temperature being 0.14%. The calculated results agree well with the reference values in the literature. This program breaks through the traditional customized development mode, supporting heterogeneous mesh differential configuration and large-scale parallel computing, and can provide a reference tool for reactor safety analysis, optimization design, etc.

Full Text

Preamble

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Development and Validation of a General-Purpose Neutronics-Thermal-Hydraulic Coupling Code Based on preCICE and the OpenFOAM-adapter

Tan Liangkang[1], Deng Junjie[1], Zhao Pengcheng[1], Liu Zijing[1], Li Wei[2]

[1](School of Nuclear Science and Technology, University of South China, Hengyang, Hunan 421001, China)
[2](School of Resources, Environment and Safety Engineering, University of South China, Hengyang 421200, China)

Abstract

[**Background**] The safe operation of nuclear reactors relies on precise simulation of multi-physics couplings, including neutron transport, conjugate heat transfer, and fluid dynamics. Traditional customized coupling programs often suffer from low efficiency and insufficient accuracy, struggling to meet the demands of complex scenarios in advanced reactor designs such as high-resolution digital twin simulations. [**Purpose**] This study aims to develop a general-purpose three-dimensional neutronics-thermal-hydraulics coupling code with high precision, leveraging the open-source multi-physics coupling library preCICE and its OpenFOAM-adapter. The goal is to enable accurate prediction of safety parameters and in-depth analysis of multi-physics interactions within reactor cores. [**Methods**] The proposed framework integrates a neutron transport module and a thermal-hydraulic module. The neutron physics module employs a self-developed neutron transport solver based on the finite volume method, validated against benchmark problems. The thermal-hydraulics module combines a 3D solid heat conduction model (laplacianFoam) and a buoyant turbulent flow model (buoyantPimpleFoam) for detailed analysis of temperature and velocity fields. Through secondary development of the preCICE adapter, the conjugate heat transfer (CHT) module is enhanced to support volume coupling and bidirectional data exchange between neutron and thermal-hydraulics solvers. A typical pressurized water reactor (PWR) single-rod benchmark is used for validation, involving grid independence analysis and comparison of three data mapping methods: nearest-neighbor, nearest-projection, and radial basis function (RBF) interpolation. [**Results**] The program accurately outputs key parameters, including 3D power distribution, neutron flux density, velocity fields, and temperature fields. Quantitative verification shows a relative error of less than 0.1% for the coolant outlet temperature and 0.14% for the maximum cladding temperature, satisfying the precision requirements of reactor design codes. Grid independence analysis confirms that a medium-fidelity thermal-hydraulic grid combined with a coarse neutron grid balances accuracy and computational efficiency. Among data mapping methods, nearest-neighbor mapping provides acceptable precision with the lowest computational cost, while RBF interpolation, though more accurate, incurs higher computational overhead. [**Conclusions**] The developed program breaks through the limitations of traditional customized coupling approaches, supporting heterogeneous grid configurations and large-scale parallel computing. It offers a robust tool for high-resolution neutronics-thermal-hydraulics coupling simulations, facilitating safety analysis, design optimization, and digital twin modeling of reactor cores.

Keywords: preCICE; OpenFOAM-adapter; reactor neutronics; thermal-hydraulics; neutronics-thermal-hydraulic coupling

Chinese Library Classification: TL99

CSTR: (to be assigned)

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1. Introduction

During nuclear reactor operation, strong nonlinear couplings among multiple physical fields—including neutron transport, conjugate heat transfer, and fluid dynamics—directly affect core power distribution and safety characteristics. Multi-physics coupling simulation is crucial for revealing complex physical mechanisms within reactors and predicting key safety parameters. However, traditional single-physics coupling programs suffer from low efficiency and insufficient accuracy, making it difficult to meet the demands of complex scenarios. Therefore, there is an urgent need to develop general-purpose, efficient, and accurate multi-physics coupling programs to support reactor safety analysis and design optimization [**?**].

In recent years, numerous studies on neutronics-thermal-hydraulic coupling analysis for different reactor types have been conducted both domestically and internationally. Ferraro et al. [**?**] developed the Serpent2/SUBCHANFLOW coupling system using external coupling with input-output file exchange for internal field transfer, performing pin-by-pin calculations for the OECD/NRC PWR MOX/UO2 core transient benchmark. Wenpei Feng et al. [**?**] coupled CORTH with CORCA-K based on the typical server-client coupling system ICoCo interface, employing the third-party library MEDCoupling to handle mesh interpolation and field mapping between CORTH and CORCA-K programs. Yang Dongmei [**?**] from Shanghai Jiao Tong University developed a tool for lead-cooled fast reactor physics-thermal coupling characteristic research and transient analysis based on the subchannel program COBRA-LM and neutron physics program SKETCH-N using the parallel virtual machine PVM function library. Luo Yantao [**?**] studied the neutronics-thermal coupling characteristics of the novel deployable LOTUS reactor during dynamic deployment by coupling SERPENT and STAR-CCM+ based on external explicit coupling methods with regional mapping for data transfer. Wang et al. [?] established a point reactor kinetics model using FLUENT' s UDF (User-Defined Function) capability and coupled it with FLUENT' s own thermal-hydraulic solver to analyze transient neutronics-thermal coupling characteristics for a blockage accident in a lead-based reactor single fuel assembly. Meanwhile, with the deepening development of digital reactors in recent years, many general-purpose multi-physics coupling platforms have emerged, such as MOOSE [?], SALOME [?], preCICE [?], and MORE [?]. Hu Tianliang et al. [?] coupled three-dimensional neutron diffusion spatiotemporal kinetics, three-dimensional solid heat conduction, and one-dimensional fluid flow heat transfer based on the multi-physics coupling platform MOOSE to achieve steady-state and transient multi-physics coupling calculations for the Xi' an pulsed reactor. In 2005, the European NURESAFE project aimed to develop an integrated multi-physics simulation platform for light water reactor safety analysis and innovative light water reactor design [?, ?]. This platform' s multi-physics coupling involved core physics, thermal-hydraulics, and fuel thermomechanics, integrating all programs into the SALOME open-source platform for user convenience. Li Zhigang et al. [?] developed a core cell-level neutronics-thermal coupling calculation system based on the multi-module reactor coupling framework MORE, integrating modules such as CORCA-SPn, CORTH, CORTH-R, and TH1D to accurately solve three-dimensional SP3 equations, channel flow heat transfer, and fuel heat conduction equations. Most current neutronics-thermal coupling programs are built relying on traditional customized development modes, employing explicit coupling strategies and one-to-one mesh mapping methods. However, with advanced reactors' increasing demands for multi-physics coupling with rich hierarchies, wide spans, and multiple combinations, flexible and general-purpose high-order multi-physics coupling analysis tools with secondary development capabilities are urgently needed.

To address the multi-physics coupling simulation requirements of advanced nuclear energy systems, this study constructs a neutronics-thermal coupling computational framework based on the open-source multi-physics coupling library preCICE and its official adapter OpenFOAM-adapter. The neutronics module employs a three-dimensional neutron transport program based on the finite volume method previously developed by our team [?]. The thermal-hydraulic module integrates a three-dimensional solid heat conduction model (laplacianFoam) and a buoyancy-driven turbulent flow model (buoyantSimpleFoam) to accurately resolve the flow and temperature fields within the reactor core. Furthermore, through secondary development of the preCICE official adapter OpenFOAM-adapter, the data read-write functionality and mesh interface dimensions of the conjugate heat transfer (CHT) module are expanded to enable efficient data interaction between neutronics and thermal-hydraulic modules. Finally, mesh independence analysis and result validation are performed on typical cases, and the effects of three data mapping methods supported by preCICE are compared.

1.1 Three-Dimensional Neutron Transport Spatiotemporal Dynamics Model

The Boltzmann transport equation describes the neutron transport balance process within a system, with each term representing neutron production, transport, and loss mechanisms. The mathematical expression of the three-dimensional Boltzmann equation within unit volume, unit solid angle, and unit energy interval is:

$$\frac{1}{v}\frac{\partial \phi}{\partial t}+\Omega\cdot\nabla\phi+\Sigma_t(\mathbf{r},E,t)\phi(\mathbf{r},\Omega,E,t)=\int_0^\infty dE'\int_{4\pi}d\Omega'\Sigma_s(\mathbf{r},E'\to E,\Omega'\to\Omega,t)\phi(\mathbf{r},\Omega',E',t)+\frac{\chi(E)}{4\pi}\int_0^\infty dE'\nu$$

where t is the time variable, $\mathbf{r}$ represents the neutron position vector, Ω is the neutron direction vector, $\phi(\mathbf{r},\Omega,E,t)$ is the neutron angular flux density per unit energy interval, unit solid angle, and unit volume; $\Sigma_t(\mathbf{r},E,t)$ is the total neutron cross-section, $\Sigma_s(\mathbf{r},E'\to E,\Omega'\to\Omega,t)$ represents the scattering cross-section from initial energy E' and initial direction Ω' to energy E and direction Ω, and $\chi(E)$ is the fission neutron energy spectrum.

The discrete ordinates method (S_N) is employed for spatial direction discretization. This method offers high numerical computational efficiency and flexible controllability of direction discretization order. Spatial discretization is based on the finite volume method, consistent with the numerical solution framework of the OpenFOAM platform. Energy discretization adopts the multi-group approximation method, which divides neutron energy into several energy groups and performs weighted averaging of material properties (such as reaction cross-sections, neutron velocity, etc.) within each group to obtain multi-group parameters. Detailed calculation procedures for the neutron transport program can be found in reference [**?**].

1.2 Three-Dimensional Solid Heat Conduction Model

The solid heat conduction process in fuel and cladding regions can be described by the three-dimensional heat conduction equation:

$$\rho c_p\frac{\partial T}{\partial t}=\nabla\cdot(k\nabla T)+Q$$

where ρ is material density, c_p is specific heat capacity at constant pressure, T is the temperature field distribution, k is thermal conductivity, and Q is the volumetric heat source term.

The heat source term in the fuel region is obtained through neutron transport calculations, with the expression:

$$Q=\sum_g \kappa_g\Sigma_{f,g}\phi_g$$

where κ_g is the neutron energy generation cross-section for group g, and ϕ_g is the neutron flux density for the corresponding energy group.

1.3 Three-Dimensional Fluid Convection Heat Transfer Model

The energy released by nuclear fuel fission reactions in the core causes fuel temperature elevation, and heat is transferred to the coolant through conduction and convection, with the coolant transporting heat as it flows through the core. The coolant flow and heat transfer process are described by the following governing equations:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Momentum equation:

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \tau$$

Energy equation:

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{U} h) = \nabla \cdot (k_{eff} \nabla T) + Q_s$$

where ρ is fluid density, $\mathbf{U}$ is velocity vector, p is static pressure, τ is stress tensor, μ_{eff} is effective viscosity (including laminar viscosity μ_l and turbulent viscosity μ_t), h is specific enthalpy ($\mathrm{J \cdot kg^{-1}}$), and Q_s is the radiation source term ($\mathrm{W \cdot m^{-3}}$).

2. preCICE Open-Source Coupling Library and Its Secondary Development

2.1 preCICE Core Framework and Adapter Principle

preCICE (Precise Code Interaction Coupling Environment) is an open-source multi-physics coupling library jointly developed by the Technical University of Munich and the University of Stuttgart. Its core design philosophy is modular decoupling, aiming to construct a general-purpose multi-physics coupling paradigm for complex engineering scenarios. Its technical framework is implemented through a two-stage collaborative mechanism: preprocessing and solution coupling. In the preprocessing stage, geometric matching and data synchronization at coupling boundaries are completed based on various data mapping algorithms [**?**] (such as nearest-neighbor mapping, nearest-projection mapping, radial basis function mapping, etc.), establishing interface boundary consistency between heterogeneous solvers. The solution coupling stage employs iterative convergence strategies to dynamically update cross-field data.

For coupling scheme design and implementation, preCICE provides multiple combinations of serial/parallel and explicit/implicit coupling methods. The parallel coupling approach enables independent solving of each physics solver through a unified time window. Within the time window, each solver performs sub-cycling calculations based on its own time step, and data matching and transfer at each time point are completed through interpolation methods. Specifically, the following principles guide coupling scheme selection: for numerical reasons, explicit coupling should always be used for unidirectional data transfer; for strongly coupled problems with bidirectional data interaction (such as conjugate heat transfer modules), implicit coupling can be employed with various convergence acceleration schemes [?] (constant under-relaxation, Aitken adaptive under-relaxation, and various quasi-Newton variants such as IQN-ILS and IQN-IMVJ) to ensure numerical stability. When coupling more than two solvers, there are two options: configuring coupling schemes individually for each solver pair, or constructing them as a whole into a single coupling scheme. Particularly, for multi-solver strong coupling scenarios in thermal-hydraulic modules, a fully implicit multi-coupling scheme [?] can be adopted to achieve dynamic equilibrium among various physical fields through iterative solving. This hierarchical coupling strategy significantly improves solution efficiency for large-scale multi-field coupling problems while ensuring computational accuracy.

[Figure 1: see original paper] preCICE functional description [?]

As shown in Figure 2 [Figure 2: see original paper], preCICE provides official adapters for various mainstream solvers (such as OpenFOAM, CalculiX) [?] and supports API bindings for C, Fortran, Python, and other languages. Adapters serve as "glue" between each solver and the preCICE library. Depending on the coupling program, an adapter can be a module or class of solver code or a complete standalone software using certain callback interfaces of the solver. preCICE achieves collaborative simulation of heterogeneous solvers through efficient data exchange and iterative algorithms. This design not only supports coupling among multiple solvers but also significantly reduces code invasiveness in multi-physics collaboration and lowers development complexity, allowing developers to focus on single-field solver optimization without reconstructing underlying communication logic.

[Figure 2: see original paper] Adapter functional description [?]

2.2 Functional Expansion of the Conjugate Heat Transfer Module

In coupling simulations, data exchange occurs through coupling meshes between solvers. The coupling mesh for each solver pair can be either a common coupling interface (surface coupling) or a common coupling overlapping volume (volume coupling). This study performs secondary development on the conjugate heat transfer (CHT) module of preCICE's official OpenFOAM adapter by first adding read-write support for heat source terms in the CHT module. Second, surface coupling at mesh interfaces is expanded to volume coupling for data exchange (temperature and heat source terms) within specified overlapping regions, providing tool support for coupling calculations between thermal-hydraulic and neutronics modules.

Typically, preCICE handles data transfer between interfaces of two solvers, with coupling interfaces specified through the `patches` field in the adapter configuration file `preciceDict`. Building upon this, the secondary-developed adapter supports not only surface coupling on domain boundaries but also volume coupling overlapping domains, which can be either complete domains or partial regions. For coupling the entire solution domain, the `locations` field in the adapter configuration file is specified as `volumeCenters` for data transfer of volume-coupled quantities (temperature, heat source terms). For coupling only certain regions of the domain, the OpenFOAM `cellSet` class is used to define one or more volume coupling regions using the specialized tool `topoSet` in OpenFOAM for managing "designated regions" to define one or more `cellSet`, which are then listed in `preciceDict`.

3. Unified Computing Platform Architecture Design

3.1 Unified Computing Platform Architecture

This study proposes a heterogeneous mesh coupling architecture based on a unified computing platform. This architecture integrates the neutron transport solver, three-dimensional solid heat conduction solver, and three-dimensional fluid convection solver within the OpenFOAM framework to construct a multi-physics collaborative computing platform. This single-platform architecture effectively avoids redundant computations caused by cross-platform data conversion and achieves high-precision data transfer between heterogeneous meshes through the preCICE library, while simultaneously leveraging the parallel architectures of both preCICE and OpenFOAM to enhance overall computational efficiency. Compared with traditional single-mesh coupling methods, a typical heterogeneous mesh mapping strategy is adopted where each physics solver employs an independent mesh system with resolution differentiated according to physical characteristics. The data transfer process follows physical conservation principles, with cross-mesh data achieved through various data mapping methods provided by preCICE.

3.2 Multi-Solver Coupling Mechanism

The bidirectional feedback mechanism of neutronics-thermal-hydraulic coupling is the core of reactor multi-physics analysis. Before calculation, the Monte Carlo program OpenMC [?] generates few-group macroscopic cross-sections at different temperature and density points in the form of polynomial functions fitted to temperature and density. The thermal-hydraulic module outputs temperature fields T and density fields ρ of fuel, cladding, and coolant through conjugate heat transfer calculations. Based on these field distributions, multi-group macroscopic cross-sections $\Sigma_{x,g}(\rho, T)$ (such as fission cross-section Σ_f, scattering cross-section Σ_s) in the neutronics model are updated to reflect dynamic changes in material properties with operating conditions. The neutronics module solves for neutron flux $\phi_g(\mathbf{r}, t)$ using updated cross-section parameters and calculates the fission heat source term Q, which is fed back as an input boundary condition to the thermal-hydraulic module to drive a new round of heat transfer and flow calculations. Coupling strength (such as data exchange frequency and convergence tolerance) directly affects key parameters including core power peaking factors and coolant temperature field gradients, and determines the spatiotemporal evolution characteristics of reactivity feedback (Doppler effect and moderator temperature effect). Explicit coupling strategies may lead to numerical oscillations, while implicit coupling improves stability through iterative correction but requires trade-offs in computational cost.

The neutronics-thermal-hydraulic coupling control equation system consists of equations (1)-(8) and corresponding initial and boundary conditions. The solution flow is shown in Figure 3 [Figure 3: see original paper], where ST represents sink temperature and HTC represents heat transfer coefficient.

[Figure 3: see original paper] Neutronics and thermal-hydraulics coupling flow chart

4. Coupling Program Validation and Results Analysis

The neutron transport solver employed in this study has been developed and validated in previous work [?], with its computational accuracy and reliability confirmed. The thermal-hydraulic solver module integrates mature official OpenFOAM solvers, including verified heat conduction and flow heat transfer calculation modules. Given that each single-physics solver already possesses independent reliability, the validation focus of this study concentrates on verifying the logical correctness of the adapter-based coupling framework and assessing the reliability of multi-physics data transfer.

4.1 Benchmark Geometry, Material Properties, and Boundary Conditions

A typical PWR single-rod model is selected as the validation case, which is referenced from literature [?]. The authors constructed a high-fidelity coupling tool MULTINUKE for PWR steady-state analysis by coupling the MCNP5 Monte Carlo particle transport program with the STAR-CCM+ computational fluid dynamics software. The fuel rod has a diameter of 1.0 cm, Zircaloy-4 cladding thickness of 0.1 cm, and water channel pitch of 1.5 cm. To optimize computational efficiency, the axial height of the benchmark model is compressed to 20 cm to control mesh scale. The specific model geometry is shown in Figure 4 [Figure 4: see original paper].

[Figure 4: see original paper] Geometry of PWR cell model

The fuel uses 5% enriched UO_2, and the moderator is liquid water. Detailed geometric parameters and material configurations are listed in Table 1 , and thermal property parameters for each material are provided in Table 2 .

Geometric dimensions and materials

Thermal properties

The boundary condition system covers both neutronics and thermal-hydraulic dimensions, with Robin mixed boundary conditions [?] applied at coupling interfaces. Detailed configurations are provided in Table 3 . Neutronics calculations adopt a two-group energy structure (0.625 eV threshold).

Boundary conditions

4.2 Mesh Independence Analysis and Parameter Sensitivity Study

To evaluate the impact of mesh discretization on computational results, a multi-resolution mesh study is conducted. Both coolant and neutronics modules are configured with coarse, medium, and fine mesh levels (Table 4), with the fuel cell axially divided into 20 layers. Computations are performed on a computer with an Intel Core i9-14900KF CPU (32 physical cores). To improve computational efficiency, fuel/cladding heat conduction calculations are assigned a single core, coolant convection heat transfer calculations are parallelized across 20 cores, and neutron transport calculations are parallelized across 4 cores.

Number of meshes

Figure 4 [Figure 4: see original paper] shows the mesh sensitivity analysis results. The coolant temperature remains relatively stable under different mesh combinations, with a maximum deviation of 0.0024%. As the coolant mesh is refined, solution time increases stepwise, and the maximum cladding temperature stabilizes under medium mesh (maximum deviation 0.173%). Each neutronics mesh refinement increases solution time by approximately 2× but has relatively minor impact on computational results (maximum data deviation 0.347%). Considering both computational efficiency and accuracy, the medium coolant mesh combined with coarse neutronics mesh is selected as the optimal configuration.

[Figure 4: see original paper] Mesh independence validation

4.3 Key Physical Parameter Comparison and Validation

The literature provides coupling calculation results from MCNP5 and STAR-CCM+, including fuel rod axial power distribution, fuel rod axial centerline temperature, maximum cladding temperature, coolant outlet temperature, and coolant velocity distribution. As shown in Figure 5 [Figure 5: see original paper], the fuel rod axial power distribution and temperature field distribution calculated by our coupling program agree well with literature values. The normalized power is slightly lower than literature values in the middle section of the fuel cell and shows larger deviations near the inlet and outlet. This discrepancy may arise because the literature used continuous-energy cross-section libraries in MCNP5 calculations, while our deterministic program performs transport calculations using multi-group cross-sections output from OpenMC with temperature interpolation fitting. Additionally, the literature employed relatively coarse meshes, whereas our mesh division is more refined, which is another source of error. Regarding temperature distribution, the first half of the fuel rod shows good consistency, while the second half exhibits some deviation with an absolute deviation of approximately 10 K. Besides differences in neutronics calculations and mesh division, this deviation may also be caused by flow heat transfer models—the literature used the two-layer k-epsilon model in STAR-CCM+, while our study employs the standard k-epsilon model.

[Figure 5: see original paper] Axial power (a) and temperature (b) distribution of fuel rods

Table 5 presents quantitative comparisons of important parameters such as coolant outlet average temperature with our calculated values. The coolant outlet temperature shows only 0.03% error compared to the reference value, while the maximum cladding temperature is lower than the reference value by 0.14% deviation. These results indicate that our developed coupling program achieves computational accuracy close to literature results, and the correctness of the coupling process and reliability of computational results are preliminarily confirmed.

Quantitative temperature comparison

4.4 Performance Comparison of Data Mapping Methods

This section employs three data mapping methods officially provided by preCICE—nearest-neighbor mapping, nearest-projection mapping, and radial basis function mapping—to calculate the benchmark case. preCICE requires each mapping to provide constraint conditions ensuring that data interaction between different solvers satisfies physical laws and numerical stability, including conservative constraint and consistent constraint. The former ensures global conservation of physical quantities (such as mass, energy, momentum) during transfer across coupling interfaces, while the latter requires data mapping at coupling interfaces to satisfy geometric and field continuity.

The nearest-neighbor mapping method calculates distances using Euclidean norms at nodes of the output mesh and copies values from the geometrically nearest vertex nodes. This method is computationally fast and simple to implement but has numerical defects. Under consistent constraint conditions, some values in the input mesh may not participate in mapping operations, while others may be reused multiple times. Under conservative constraint conditions, vertices on the output mesh may fail to receive values or may receive multiple values from the input mesh that are accumulated.

The nearest-projection mapping method extends nearest-neighbor mapping by performing orthogonal projection of output nodes onto the nearest-neighbor nodes of the input mesh, using barycentric coordinates as interpolation weights to calculate output values at projection points. Although its computational speed is relatively fast and preCICE official documentation indicates its numerical performance is significantly better than nearest-neighbor mapping, it requires explicit mesh connectivity information, meaning the adapter must inform preCICE about connections between vertices.

Radial basis function mapping assembles and computes a global (potentially sparse) linear system constructed on one mesh and evaluated on another. The global interpolation consists of a linear combination of radially symmetric basis functions centered at each vertex, supplemented by linear polynomials. This method is typically more accurate and can provide higher-order convergence rates but has higher computational requirements. The paper provides an in-depth introduction to the principles of radial basis function mapping methods [**?**].

Figure 5 [Figure 5: see original paper] shows the impact of different data mapping methods on computational results. Compared with nearest-neighbor mapping, the time overhead of nearest-projection mapping and radial basis function (RBF) mapping increases significantly, with RBF mapping' s time overhead being approximately twice that of nearest-neighbor mapping. The current calculations do not demonstrate the advantage of nearest-projection mapping being faster than nearest-neighbor mapping. Regarding temperature calculations, the three mapping methods show negligible impact on coolant outlet average temperature. However, when predicting maximum cladding temperature, results from nearest-neighbor mapping and RBF mapping show high consistency, while nearest-projection mapping exhibits certain deviations with a maximum error of approximately 3%. This error may stem from geometric errors introduced by nearest-projection mapping when processing mesh connectivity information.

[Figure 5: see original paper] Comparison of different mapping methods

5. Conclusions and Outlook

In response to the scarcity of high-fidelity multi-physics analysis tools for current numerical reactors, the difficulty of development, and the demands for generality, breadth, and multi-combination in coupling calculations, traditional low-order multi-physics coupling analysis tools and customized development can no longer meet the requirements for flexible, convenient, high-development-efficiency, and high-resolution full-core multi-physics coupling simulations. This paper develops and validates a general-purpose neutronics-thermal coupling program based on preCICE and OpenFOAM-adapter.

1. First, secondary development was performed on the official OpenFOAM-adapter provided by the multi-physics coupling library preCICE. Heat source term read-write functionality was added to the conjugate heat transfer module. A volume coupling interface was developed to support

multi-physics data exchange in designated overlapping regions in addition to surface coupling. A surface-volume coupling hybrid architecture was constructed to provide technical support for neutronics-thermal coupling.

2. Second, based on the functionally expanded OpenFOAM-adapter, a triple coupling system of fuel-cladding-coolant was established to achieve conjugate heat transfer calculations based on surface coupling. Furthermore, coupling with the previously developed neutron transport solver enabled heterogeneous mesh neutronics-thermal coupling solutions based on volume coupling. Due to the adopted partitioned solution strategy, the program supports differentiated coarse/fine mesh configurations between different solvers.

3. To verify the correctness and reliability of the neutron transport-conjugate heat transfer solver, mesh independence analysis was conducted to determine the optimal mesh configuration for the case (coarse neutron mesh + medium thermal-hydraulic mesh), and key parameters were compared. Results show a relative error of 0.03% for coolant outlet temperature and 0.14% deviation for maximum cladding temperature.

4. Finally, a systematic evaluation of three data mapping methods supported by preCICE (nearest-neighbor/nearest-projection/radial basis function) was performed, with quantitative analysis demonstrating that nearest-neighbor mapping offers superior solution accuracy and computational overhead for current neutronics-thermal calculations.

Future research will expand multi-physics functionality and uncertainty analysis, introduce thermomechanical deformation modules to construct refined neutronics-thermal-mechanical coupling analysis frameworks, and conduct multi-physics coupling uncertainty analysis to further improve program reliability.

Author Contributions

Tan Liangkang: Program development, validation, data analysis, and manuscript writing
Deng Junjie: Data collection
Li Wei: Guidance throughout program development, validation, and data analysis
Zhao Pengcheng: Research funding acquisition, manuscript review and revision
Liu Zijing: Manuscript modification and theoretical guidance

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Note: Figure translations are in progress. See original paper for figures.