Research on preCICE-Based Multiscale Coupling Uncertainty Analysis Methods

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Abstract

Current research on reactor thermal-hydraulic multi-scale coupling primarily focuses on multi-scale coupling code development and verification, while systematic studies regarding coupling code uncertainties remain relatively scarce. This study constructs a multi-scale coupling uncertainty analysis code by integrating the CFD code FLUENT, the subchannel code SUBCHANFLOW, and the DAKOTA uncertainty quantification module based on the preCICE open-source framework. By establishing a 3$×$3 rod bundle model, numerical verification is performed under steady-state and transient conditions, and uncertainty quantification and sensitivity analysis are conducted. Experimental data demonstrate: (1) Under steady-state conditions, the axial temperature distribution of the coupled system exhibits high consistency with results from standalone codes; (2) In transient verification, under sinusoidal perturbation of inlet flow rate, outlet flow rate fluctuations are completely synchronized in period and phase; (3) Uncertainty quantification reveals that parameters such as coolant temperature and peak cladding temperature display normal distribution characteristics; (4) Sensitivity analysis identifies inlet mass flow rate, outlet pressure, inlet temperature, and fuel rod heat flux as the dominant factors of system response, and the research results validate the response reliability of the multi-scale coupling system under dynamic conditions.

Full Text

Study on Multi-Scale Coupled Uncertainty Analysis Method Based on preCICE

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Abstract

Current research on reactor thermal-hydraulic multi-scale coupling primarily focuses on the development and verification of coupling programs, while systematic studies addressing uncertainties in coupled codes remain scarce. This study constructs a multi-scale coupled uncertainty analysis program based on the open-source coupling framework preCICE, integrating the CFD code FLUENT, subchannel code SUBCHANFLOW, and the DAKOTA uncertainty quantification module. Numerical verification is conducted under steady-state and transient conditions through establishing a 3$×$3 rod bundle model, and uncertainty quantification and sensitivity analysis are implemented. Experimental data demonstrate: (1) Under steady-state conditions, the maximum relative error of axial temperature distribution between the coupled system and single-code simulation results is 1.65%, indicating small errors; (2) In transient verification, under sinusoidal perturbation of inlet flow rate, outlet flow fluctuations are completely synchronized in period and phase; (3) Uncertainty quantification shows that parameters such as coolant temperature and peak cladding temperature have mean values within 95% confidence intervals with small standard deviations, indicating high computational credibility; (4) Sensitivity analysis reveals that outlet pressure and fuel rod heat flux have significant influence on system response, while inlet mass flow rate and cladding thermal conductivity produce significant negative effects on different response variables. The results validate the response reliability of the multi-scale coupled system under dynamic conditions.

Keywords: preCICE open-source coupling library; Multi-scale coupling; Uncertainty analysis; Subchannel code; Computational Fluid Dynamics code

Introduction

In reactor design and safety analysis, thermal-hydraulic characterization is a critical support for ensuring safe and stable reactor operation. With continuous advancement in numerical simulation technology, current thermal-hydraulic calculation programs can be categorized into three types based on modeling scale: system analysis codes, subchannel analysis codes, and CFD codes. System codes developed based on extensive experimental data exhibit significant computational deviations under conditions dominated by strong three-dimensional effects due to their lumped-parameter theoretical framework [1]. Subchannel codes can only be used for core region calculations, and their large control volume grids make it difficult to simulate complex three-dimensional flow characteristics such as secondary flows and mixing between core components. CFD codes can capture detailed flow phenomena through refined meshes, but high-fidelity simulations impose enormous computational resource demands [2]. Therefore, when conducting large-scale core thermal-hydraulic calculations, it is necessary to balance computational accuracy with simulation efficiency, making multi-scale coupled thermal-hydraulic computation a development trend in numerical simulation.

Numerous multi-scale coupling studies have been conducted both domestically and internationally, primarily focusing on coupling between system codes and subchannel codes, as well as between system/subchannel codes and CFD codes, resulting in the development of various multi-scale coupling programs. Lu Daogang et al. [3] coupled the system code SAC and CFD code FLUENT through an interface program, conducting verification based on the natural circulation mode of the DRACS passive residual heat removal system in the Japanese PLANDTL large-scale sodium loop test facility. Results showed that the coupled program agreed well with experimental values for key parameters during transients and could reveal temperature stratification and inter-wrapper flow phenomena in the pool. Liu Luguo et al. [4] used dynamic link libraries to implement a subchannel-CFD (CORTH/FLUENT) coupling program, simulating and analyzing the PNI 2-6 benchmark experimental conditions. Simulation results showed good agreement with experimental data, and the coupled program successfully predicted flow distribution and fluid temperature changes during flow reduction transients. Zhao Pengcheng et al. [5] employed an explicit overlapping domain method to couple the one-dimensional system code RELAP5_{LEAD} with CFD code FLUENT based on dynamic link library technology, conducting transient flow simulations for lead-cooled series and closed-loop pipelines and performing Code-to-Code comparative analysis. Results demonstrated that the coupled program could effectively simulate flow transients and pressure variations in closed loops. Luo Xiao et al. [6] built a multi-scale, multi-physics coupling program (NDK/KMC-SUB/Trio CFD) based on the unified coupling framework using the SALOME platform's generic program interface ICoCo, analyzing reactor shutdown conditions and asymmetric unprotected loss-of-flow accidents. Results indicated that the unified framework-based coupled program could better capture three-dimensional phenomena in the reactor, including axial thermal stratification in the upper plenum during shutdown conditions and significant thermal-hydraulic parameter oscillations caused by recirculation flow and thermal stratification in the lead pool during asymmetric unprotected loss-of-flow accidents. The Karlsruhe Institute of Technology (KIT) [7][8][9] conducted multi-scale coupling work for system/subchannel/CFD codes based on the SALOME platform, demonstrating that multi-scale coupling programs can improve local simulation accuracy and accurately describe local flow and heat transfer behaviors. Qiu et al. [10] coupled the subchannel code SACOS-PB and CFD code FLUENT using an explicit partitioned coupling method, analyzing flow blockage accidents in MYRRHA. Results showed that the multi-scale coupling program could effectively simulate three-dimensional flow and local physical phenomena in the upper plenum, providing significant value for

LFR core design and safety assessment. Ye et al. [11] established a CFD-RMD multi-scale coupling framework based on CFD and RMD (Reactive Molecular Dynamics) methods, analyzing pyrolysis gas injection effects in phenolic resin composites. Results showed that compared with full-scale RMD simulation, the multi-scale coupling program significantly improved computational efficiency at the same spatial-temporal resolution.

Current domestic research primarily focuses on the development and verification of multi-scale coupling programs, with limited work on uncertainty analysis for multi-scale coupled systems. Uncertainty analysis can quantify the propagation effects of multi-source uncertainties from neutron physics, thermal-hydraulics, fluid dynamics, and coupling interfaces, comprehensively evaluate system safety margins, identify and optimize key parameters with the greatest impact on simulation results, and improve model accuracy and reliability. This plays a critical role in reactor multi-scale coupling and necessitates the integration of uncertainty analysis modules into multi-scale coupling programs.

This study employs an explicit weak coupling method. First, FLUENT (CFD code) and SUBCHANFLOW (subchannel code) are redeveloped and coupled based on the open-source coupling library preCICE. Second, DAKOTA uncertainty analysis program is linked through external coupling methods using bash scripts and scheme scripts to develop a multi-scale coupled uncertainty analysis program. A 3\$×\$3 rod bundle model is then established to verify the correctness and reliability of data transfer between coupled programs. Finally, five input parameters are selected for uncertainty quantification and sensitivity analysis.

1. Introduction to preCICE

preCICE is an open-source coupling library jointly developed by the Technical University of Munich and the University of Stuttgart [12]. It provides MPI or TCP/IP communication channels, various mapping methods between unstructured grids, and explicit, implicit, and quasi-Newton coupling schemes for stability and convergence control, primarily used for partitioned multi-physics coupling. Figure 1 [Figure 1: see original paper] presents the basic introduction to preCICE, which has three main characteristics:

1.1 Partitioned Solving

Unlike strong coupling which requires constructing and solving equation systems for the entire solution domain, partitioned solving divides the entire physical field into several independent physical subdomains for separate solution [13]. This approach can utilize existing software or algorithm modules to calculate each physical field individually, with data correction through mutual boundary condition transfer. Partitioned solving avoids duplicating mature work, and preCICE can achieve accurate overall simulation results by combining individual subdomain solvers with less time cost.

1.2 Library Approach

preCICE uses a library approach, meaning preCICE is inserted into each solver as a function library, with each solver calling preCICE at runtime and running in the same thread. In contrast, framework coupling methods, such as the ADPRES-RELAP5 coupling program developed by Qian Guanhua et al. [14] based on the Salome-ICoCo upper-level monitoring architecture, require SALOME to act as a monitor calling ADPRES and RELAP5 through the ICoCo interface. To adapt to the modular standards of the ICoCo interface, the source code of ADPRES and RELAP5 must be modularly reconstructed. preCICE's high-level API only requires inserting functions into corresponding positions in the solver, easily avoiding 破坏求解器自身的结构和运算逻辑 (disruption of the solver's own structure and computational logic). Integrating new solution programs into existing programs requires minimal cost and offers high runtime flexibility. Schematic diagrams of the upper-level monitoring architecture and library approach are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper].

1.3 Black-Box Coupling

preCICE employs a black-box coupling approach to construct multi-physics collaborative simulation systems, treating each solver as an independent functional module. From a numerical method perspective, the framework only requires three basic characteristics from solvers: (1) input/output data interfaces; (2) time-step advancement mechanisms; (3) single-step iteration recalculation capability. Although this design theoretically faces coupling stability issues due to information loss, preCICE effectively overcomes these problems by integrating adaptive implicit coupling algorithms, convergence accelerators, and stability enhancement modules.

This architectural design provides significant advantages for expanding and optimizing multi-physics simulation systems. In terms of system scalability, new physical field solution modules can be quickly integrated through standardized interfaces without requiring deep understanding of internal algorithm implementation details of coupling participants. The black-box coupling process is illustrated in Figure 4 [Figure 4: see original paper]. In the algorithm optimization dimension, solvers for similar physical fields using different numerical methods (such as finite element methods and finite volume methods) can achieve performance comparison through module replacement. This flexible framework characteristic not only accelerates the development process of coupled systems but also provides an efficient experimental platform for innovative validation of numerical methods. preCICE operation schematic is shown in Figure 5 [Figure 5: see original paper].

2. Multi-Scale Coupling Methodology

2.1 Introduction to Multi-Scale Coupling Methods

From a numerical computation perspective, multi-scale coupling can be divided into strong coupling and weak coupling [15]. Strong coupling combines equation systems of different scales to solve complex nonlinear equation systems, which can significantly improve coupled code performance and is the most effective coupling method. However, strong coupling requires extensive source code modifications, presents high coupling difficulty, and has poor feasibility. Weak coupling solves each physical field individually at each scale, exchanging boundary condition data at specific times. Weak coupling fully utilizes existing programs for accurate simulation of each physical field scale. Compared with strong coupling, it can ensure coupling effectiveness without requiring extensive secondary development of source code, demonstrating strong applicability. Most domestic and international multi-scale coupling research is based on weak coupling, and this study also employs weak coupling methods.

From the perspective of data transfer methods, coupling can be divided into internal coupling and external coupling [16]. Internal coupling integrates different programs through overall compilation or compilation into dynamic link libraries completely integrated into other programs. External coupling has three implementation methods: (1) boundary condition transfer through input/output files; (2) direct data communication between programs; (3) coordination using control programs. Internal coupling has the highest computational efficiency but requires high-quality source code and significant resource investment. Among external coupling methods, file-based coupling is the simplest but faces massive I/O operations, consuming substantial memory resources during long transient simulations. Direct coupling between programs is challenging due to different programming languages and non-unified data formats. Using an intermediate control program for coordination can ensure program integrity while maximizing computational efficiency. This study adopts the intermediate program coordination method for coupling research.

2.2 Coupling Flow

The coupled program includes two main components: multi-scale coupling computation and uncertainty analysis. The multi-scale coupling computation serves as the core calculation component. To reduce communication resource consumption and better control coupled program calculations, the preCICE coupling library is used. The uncertainty analysis component primarily uses DAKOTA to repeatedly call the coupled computation program, with core operations focused on input/output, using bash scripts and scheme scripts to link the multi-scale computation program and DAKOTA uncertainty analysis program. Due to different coupling principles, the coupled program is divided into two parts for introduction.

2.2.1 Multi-Scale Coupled Computation Program Based on preCICE

To maintain numerical stability in coupled calculations and better leverage preCICE's black-box coupling advantages, the development principle in this study is to minimize modifications to programs due to coupling. Main operations include:

(1) Insert preCICE function library files into the subchannel code SUBCHANFLOW and CFD code FLUENT's UDF, and add variable modules for preCICE.

(2) Construct virtual grids as buffer zones in both SUBCHANFLOW and FLUENT. Boundary condition data obtained from coupling is first written into virtual grids, with the next operation determined by the computation mode.

(3) Insert preCICE functions into the subchannel program and reconstruct the calculation termination module of the subchannel program.

(4) Insert preCICE-related functions into UDF [17], with main UDF macro functions shown in Table 1 :

Table 1 UDF Macro Functions

UDF Macro Function Name	Function
DEFINE_{INIT}	Initialize preCICE
DEFINE_{{{EXECUTE}}*{{AT}}}*{END}	Transient data writing
DEFINE_{PROFILE}	Transient data reading
DEFINE_{PROPERTY}	Modify fluid properties
DEFINE_{{{EXECUTE}}*{{AT}}}*{EXIT}	Terminate preCICE
DEFINE_{{{ON}}_{{DEMAND}}}	Steady-state data writing, manual initialization

The DEFINE_{INIT} macro is primarily used for computational domain initialization, completing preCICE initialization including solver participant creation and mapping grid establishment. Additionally, a manual initialization function is set up using the DEFINE_{{{ON}}*{{DEMAND}}} macro for convenience. Since material properties in FLUENT default to fixed values, the constant property assumption significantly impacts results under high temperature and pressure conditions. This study uses DEFINE*{PROPERTY} to modify coolant fluid properties, primarily including fluid density, viscosity, specific heat capacity at constant pressure, and thermal conductivity. Coupled data reading uses DEFINE_{PROFILE}, which can modify boundary conditions such as temperature and pressure. Coupled data writing is divided into steady-state and transient calculations: steady-state data writing uses the DEFINE_{{{ON}}*{{DEMAND}}} macro, manually called by users; transient data writing uses DEFINE*{{{EXECUTE}}*{{AT}}}*{END}, called after transient calculation time step iterations. Finally, the DEFINE_{{{EXECUTE}}*{{AT}}}*{EXIT} macro closes preCICE communication channels after calculation completion.

(5) SUBCHANFLOW is compiled using the gfortran command, while FLUENT's UDF is externally compiled into dynamic link library files using

GCC and then loaded by FLUENT.

(6) Write preCICE configuration files to construct coupled program data flow.

(7) Start FLUENT and SUBCHANFLOW individually to achieve peer-to-peer startup of sub-physical fields.

In addition to these main modifications, other parts require fine-tuning to avoid conflicts between the two programs during computation. The FLUENT-SUBCHANFLOW multi-scale coupled program computation flow is shown in Figure 6 [Figure 6: see original paper].

2.2.2 Multi-Scale Coupled Data Flow Assuming both FLUENT and SUBCHANFLOW use mass flow inlet and pressure outlet boundary conditions. In steady-state coupled calculations, FLUENT acts as the upstream program, calculating the first 2 m of the model. After convergence, it passes two boundary condition distribution parameters (outlet temperature and mass flow rate) to SUBCHANFLOW through nearest-neighbor mapping via preCICE at the 2 m location for SUBCHANFLOW to complete the remaining model calculation. The data flow is shown in Figure 7 [Figure 7: see original paper].

In transient coupling, to ensure numerical stability, FLUENT first performs steady-state calculation. After convergence, it enters transient calculation mode, passing mass flow rate and outlet temperature to SUBCHANFLOW at each time window. After SUBCHANFLOW completes calculation, FLUENT reads SUBCHANFLOW's inlet pressure to update FLUENT's outlet pressure boundary condition. The specific data flow is shown in Figure 8 [Figure 8: see original paper].

2.3 Uncertainty Analysis Flow

The external coupling method based on DAKOTA links the multi-scale coupling component through bash scripts. First, parameters of interest are selected, and their probability distributions and uncertainties are determined through literature review. Then, sampling algorithms and sample sizes are determined. DAKOTA performs sampling and generates corresponding input parameter cards. Next, DAKOTA calls the multi-scale coupled program using these input parameter cards for calculation. After obtaining result files, the post-processing module in bash scripts extracts response variables and returns them to DAKOTA for processing and analysis. Finally, uncertainty analysis results are obtained. The specific flow is shown in Figure 9 [Figure 9: see original paper].

3. Multi-Scale Coupled Computation Program Verification

To verify the coupling results between FLUENT and SUBCHANFLOW, a 3$×$3 bare rod assembly model [18] is assumed and analyzed computationally.

3.1 Component Model Introduction

Model geometric parameters are shown in Figure 10 [Figure 10: see original paper]. The model height is 400 mm, assembly side length is 60 mm, fuel rod diameter is 10 mm, pitch is 20 mm; inlet temperature is 553.15 K, inlet mass flow rate is 4.12 kg/s, fuel rod heat flux is 60000 W/m^2, outlet pressure is 15.5 MPa. The rod bundle channel radial division is shown in Figure 11 [Figure 11: see original paper], with 16 subchannels divided.

**Table 2 3$\times 3 Component Model Parameters * *|Parameter|Value|| - - - - - - - - - - - - |- - - - - - - - ||Rod diameter(mm)|10||Pitch(mm)|20||Rod-to-wall distance(mm)|15||Assembly side length(mm)|60||Model height(mm)|400||Inlet temperature(K)|553.15||In
| 600 |

Boundary conditions include mass flow inlet and pressure outlet. In FLUENT, fuel rod modeling is simplified by only considering fuel rod heat flux. At the coupling interface, FLUENT's unstructured grid is marked according to subchannel division, and data exchange between SUBCHANFLOW and FLUENT is transferred one-to-one according to channel numbers.

3.2 Steady-State Calculation Verification

SUBCHANFLOW and FLUENT are used to calculate the model individually as benchmarks. In coupled calculation, FLUENT serves as the upstream program calculating the first 2 m of the model, passing mass flow rate and temperature boundary conditions to SUBCHANFLOW at 2 m via preCICE for SUBCHANFLOW to complete the remaining model calculation. The comparison of coupled calculation results is shown in Figure 12 [Figure 12: see original paper].

Channels 1, 2, and 6 represent corner channels, edge channels, and center channels, respectively. In corner channels, the maximum error between coupled program results and FLUENT is 1.65%, and with SUBCHANFLOW is 1.24%. In edge channels, the maximum error with FLUENT is 0.39%, and with SUBCHANFLOW is 0.28%. In center channels, the maximum error with FLUENT is 0.79%, and with SUBCHANFLOW is 0.32%. These results indicate small computational errors relative to benchmark programs.

The figure shows that axial temperature distributions from FLUENT and SUBCHANFLOW calculations for edge and center channels almost coincide. In corner channels, significant differences exist between FLUENT and SUBCHANFLOW results because subchannel software based on quasi-one-dimensional models and empirical formulas for lateral flow and heat transfer cannot capture three-dimensional secondary flows and turbulence anisotropy caused by geometric asymmetry. In contrast, Fluent solves the full three-dimensional Navier-Stokes equations directly, naturally resolving momentum and energy exchange through turbulence models, enabling more accurate characterization of local flow separation and three-dimensional thermal-hydraulic coupling characteristics in corner channels.

The temperature distribution curve for 0-2 m from the coupled program differs from FLUENT's standalone calculation because the outlet pressure setting in FLUENT's standalone complete model calculation is 15.5 MPa, and this outlet pressure setting remains 15.5 MPa in FLUENT's portion of the coupled model, causing some error between coupled model calculations and FLUENT results. However, the maximum relative error is less than 0.6%, which is considered acceptable.

The temperature distribution curves show ideal coupling effects in edge and center channels, with larger fluctuations in corner channels due to differences in solution methods between the two software packages, but the overall trend remains consistent. These results demonstrate that FLUENT can correctly transfer boundary conditions to the subchannel code SUBCHANFLOW through preCICE's communication channel.

3.3 Transient Calculation Verification

Transient testing is based on steady-state calculations, using fluctuating inlet mass flow rate as a boundary condition to test the coupled program's sensitivity to fluctuating boundary conditions. Transient calculations use fluctuating mass flow rate as FLUENT's inlet boundary condition with a fluctuation period of 1 s. FLUENT first undergoes steady-state calculation, then begins sinusoidal fluctuation calculation after convergence. The fluctuation expression is:

$$= 0.5 \sin 2\pi + 4.12$$

The total transient calculation time is 5 s with a time step of 0.01 s. After calculation, the inlet mass flow rate and subchannel program outlet surface mass flow rate over time are shown in Figure 13 [Figure 13: see original paper], demonstrating that subchannel outlet flow also exhibits sinusoidal fluctuation with frequency and phase consistent with inlet flow. Figure 14 [Figure 14: see original paper] shows the outlet flow variation trends for channels 1, 2, and 6 (representing corner, edge, and center channels) with FLUENT inlet flow fluctuations. Corner channels show the most pronounced fluctuation trend, followed by edge channels, while center channels exhibit the most stable flow variation. All three channel types show sinusoidal outlet flow fluctuations with frequency and phase synchronized with inlet flow. These results prove that the FLUENT/SUBCHANFLOW multi-scale coupling program can correctly respond to boundary condition changes with accurate and timely parameter calculations.

4. Uncertainty Analysis

4.1 Uncertainty Analysis Methodology

Key steps in uncertainty analysis include selection and quantification of uncertainty sources. Selection generally involves expert judgment such as Phenomena Identification and Ranking Table (PIRT) or sensitivity analysis confirmation.

Quantification requires providing probability distributions or distribution intervals for selected uncertain parameters.

Uncertainty quantification analysis evaluates the impact of input uncertainties on model outputs. Based on different mathematical theories, methods can be categorized into statistical and deterministic approaches. For reactor thermal-hydraulic analysis, statistical methods are typically used: first conducting uncertainty calculations, then performing sensitivity calculations. Statistical methods can be divided into input parameter uncertainty propagation methods and output parameter uncertainty extrapolation methods based on different uncertainty propagation pathways. This study employs the input parameter uncertainty propagation method [19].

4.2 Input Parameter Selection

This study conducts uncertainty analysis on a 3×3 fuel assembly. Through literature review [20], five boundary condition parameters are selected as input parameters: inlet coolant temperature, inlet mass flow rate, fuel rod heat flux, outlet pressure, and cladding thermal conductivity. Four parameters are selected as output parameters: DNB (Departure from Nucleate Boiling ratio), inner cladding temperature, coolant temperature, and fuel pellet temperature. Detailed information is shown in Table 3 .

Table 3 Input Parameter Uncertainty Information

Boundary Condition Parameter	Uncertainty (3σ)	Distribution Type
Inlet mass flow rate	±1.5%	Normal
Fuel rod heat flux	±5%	Normal
Cladding thermal conductivity	±5 W/(m·K)	Normal

4.3 Uncertainty Sampling Method and Sample Size Selection

Monte Carlo sampling and Latin Hypercube Sampling (LHS) are two common sampling methods. Simple Monte Carlo algorithms suffer from repetition and low efficiency. LHS divides the parameter range into n non-overlapping intervals with equal probability based on input parameter distribution types and uncertainties, randomly samples within each interval, then randomly combines sampling values from each parameter to create sample points that satisfy constraint conditions. This study employs LHS.

To reduce sampling times and save computational time for the multi-scale coupled system, this study uses the Wilks method to determine sample size. For two-sided tolerance intervals, the mathematical formula is:

$$1-\alpha^n-n(1-\alpha)\alpha^{n-1}=\beta$$

where n is sample size, α is tolerance probability, and β is confidence level. The U.S. Nuclear Regulatory Commission (NRC) recommends using 95% for both confidence level and probability in safety assessments. According to the formula, the minimum sample size is 93. For conservative estimation, the final sample size selected is 100 [21].

4.4 Uncertainty Quantification Analysis

Figure 15 [Figure 15: see original paper] shows the sampling calculation results for pellet and cladding maximum temperatures. The uncertainty bounds for both pellet and cladding maximum temperatures effectively envelope the nominal values, indicating reasonable uncertainty analysis results.

Figure 16 [Figure 16: see original paper] shows DAKOTA calculation result histograms, with curves representing probability density functions. Response parameters include DNB, inner cladding maximum temperature, fuel pellet maximum temperature, and coolant maximum temperature. The figure shows that DNB's probability density curve is left-skewed, with higher probability of low DNB values. All four response parameters have low kurtosis, indicating large data fluctuation ranges and low probability of extreme values. Mean values of all four response parameters fall within confidence intervals with small standard deviations, indicating high program calculation credibility.

Table 4 Uncertainty Quantification Results

Parameter	Confidence Interval Lower Bound	Confidence Interval Upper Bound
Cladding maximum temperature	322.097	331.245
Fuel maximum temperature	2153.421	2218.654
Coolant maximum temperature	584.321	598.765

4.5 Sensitivity Analysis

Rank correlation coefficient (Coefficient of Rank Correlation), also known as rank correlation coefficient, reflects the direction and strength of association between changing trends of two random variables. Spearman rank correlation analysis is used for global sensitivity analysis to analyze the influence of multiple input parameters on target parameters. The correlation coefficient ranges from -1 to +1, where positive signs indicate positive correlation, negative signs indicate negative correlation, and 0 indicates no correlation. The closer the absolute value is to 1, the stronger the sensitivity. Typically, | | > 0.7 is considered strong correlation, 0.5 < | | < 0.7 is moderate correlation, and 0.3 < | | < 0.5 is weak correlation.

This study conducts sensitivity analysis on response variables including inner cladding temperature, fuel maximum temperature, coolant temperature, and cladding thermal conductivity. To reduce mutual influence between input parameters, Spearman rank correlation analysis [22] is used, with results shown in Figure 17 [Figure 17: see original paper].

Results show that DNB is primarily strongly positively correlated with inlet temperature and strongly negatively correlated with outlet pressure, with cladding thermal conductivity having some influence. Inner cladding maximum temperature is strongly positively correlated with outlet pressure, moderately positively correlated with fuel rod heat flux, and negatively correlated with cladding thermal conductivity and inlet temperature. Coolant maximum temperature is strongly negatively correlated with mass flow rate, strongly positively correlated with inlet temperature and power density, and negatively correlated with cladding thermal conductivity. Fuel pellet maximum temperature is strongly positively correlated with fuel rod heat flux and outlet pressure, negatively correlated with cladding thermal conductivity, and shows no obvious relationship with other input parameters.

Conclusions

This study developed CFD code FLUENT, subchannel code SUBCHANFLOW, and uncertainty analysis program DAKOTA based on the preCICE open-source coupling library. Using explicit weak coupling and external program coordination methods, a reactor multi-scale coupled uncertainty analysis program was developed. A 3$×$3 rod bundle model was established to validate the multi-scale coupling program, and key response values were selected for uncertainty quantification and sensitivity analysis. The main conclusions are:

1) This study developed a "FLUENT-SUBCHANFLOW-DAKOTA" multi-scale coupled uncertainty analysis program based on the preCICE open-source coupling library. The program is primarily applicable for multi-scale coupling and uncertainty analysis research at the core local level, core assembly level, and primary loop system level for reactors with coolant types including water, liquid metals (sodium and lead), and gases (helium, air, etc.).

2) A 3$×$3 rod bundle model was established for Code-to-Code steady-state and transient calculation verification. Steady-state calculation results validated the accuracy of data transfer at coupling interfaces. Transient calculation results showed that the coupled program can correctly respond to boundary condition changes. Under sinusoidal inlet flow perturbation conditions, outlet total flow variations remained consistent, and outlet flows from three typical channel types were synchronized in period and phase with inlet flow fluctuations.

3) Uncertainty quantification analysis yielded probability distributions for response values, showing that all key parameters fall within 95% confidence intervals with normal or approximately normal distributions and small standard deviations, indicating high credibility of coupled program calculation results. Sensitivity analysis results showed that outlet pressure and fuel rod heat flux have significant influence on system response, inlet mass flow rate and cladding thermal conductivity produce significant negative effects on different response variables, and inlet temperature changes have complex effects on different response variables.

Author Contributions

DONG Shihao: Drafted the manuscript, analyzed/interpreted data; **DENG Junjie:** Collected data; **HUANG Zhe:** Visualized data; **LIU Zijing:** Proposed research ideas, theoretical guidance; **LI Wei:** Technical guidance and manuscript review; **ZHAO Pengcheng:** Manuscript review, revision, and funding support.

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

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