

## Research on a Multiscale Coupling 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 validation of multi-scale coupling programs, while systematic studies on uncertainties in coupling programs remain relatively scarce. This study constructs a multi-scale coupling uncertainty analysis program based on the preCICE open-source framework, integrating the CFD code FLUENT, the subchannel code SUBCHANFLOW, and the DAKOTA uncertainty quantification module. By establishing a  $3 \times 3$  rod bundle model, numerical verification is conducted under steady-state and transient conditions, and uncertainty quantification and sensitivity analysis are implemented. Experimental data demonstrate: (1) Under steady-state conditions, the axial temperature distribution of the coupled system shows high agreement with calculation results from standalone codes; (2) In transient verification, under inlet flow sinusoidal perturbation conditions, outlet flow fluctuations are completely synchronized in both period and phase; (3) Uncertainty quantification indicates that parameters such as coolant temperature and peak cladding temperature exhibit normal distribution characteristics; (4) Sensitivity analysis reveals that inlet mass flow rate, outlet pressure, inlet temperature, and fuel rod heat flux density are the dominant factors affecting 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 codes, while systematic studies addressing uncertainties in coupled codes remain scarce. This study constructs a multi-scale coupled uncertainty analysis code by integrating the CFD code FLUENT, the subchannel code SUBCHANFLOW, and the DAKOTA uncertainty quantification module within the open-source preCICE coupling framework. A  $3\times 3$  rod bundle model was established to conduct numerical verification under steady-state and transient conditions, followed by uncertainty quantification and sensitivity analysis. The results demonstrate that: (1) Under steady-state conditions, the axial temperature distribution from the coupled system shows a maximum relative error of 1.65% compared with single-code simulations, indicating good agreement; (2) In transient verification with sinusoidal inlet flow perturbations, outlet flow fluctuations exhibit perfect synchronization in both period and phase; (3) Uncertainty quantification reveals that parameter averages for coolant temperature, peak cladding temperature, and other key quantities fall within 95% confidence intervals with small standard deviations, confirming high computational reliability; (4) Sensitivity analysis identifies outlet pressure and fuel rod heat flux as dominant factors affecting system responses, while inlet mass flow rate and cladding thermal conductivity exert significant negative influences on different response variables. These findings 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; CFD code

## Introduction

In reactor design and safety analysis, thermal-hydraulic characterization provides critical support for ensuring safe and stable reactor operation. With continuous advances in numerical simulation technology, current thermal-hydraulic codes can be classified into three categories 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. Subchannel codes are limited to core region calculations, and their relatively coarse control volume grids cannot capture complex three-dimensional flow features such as inter-assembly crossflow and mixing. CFD codes can resolve detailed flow phenomena through fine meshes, but high-fidelity simulations impose enormous computational re-

source demands. Therefore, for large-scale core thermal-hydraulic calculations, multi-scale coupling approaches have become an essential trend in numerical simulation development, balancing computational accuracy with efficiency from the perspective of the research object.

Numerous multi-scale coupling studies have been conducted domestically and internationally, primarily focusing on coupling between system and subchannel codes, as well as between system/subchannel and CFD codes, resulting in the development of various multi-scale coupling programs. Lu Daogang et al. [1] coupled the system code SAC with the CFD code FLUENT through a coupling interface and validated the approach using the PLANDTL experimental facility's DRACS natural circulation mode, demonstrating that the coupled code accurately reproduced experimental parameter variations at key locations during transients while revealing temperature stratification and inter-box flow phenomena. Jia Bin et al. [2] performed coupling between COBRA-IV and FLUENT through input/output file exchange for boundary condition transfer, analyzing AP1000 total loss-of-flow accidents and showing that coupled results were more realistic and effectively reduced the excessive conservatism of single-code calculations. Liu Luguo et al. [3] implemented a subchannel-CFD coupling (CORTH/FLUENT) using dynamic link libraries, simulating PNI 2 $\times$ 6 benchmark experiments with good agreement between simulation and experimental results, successfully proving the code verification under steady-state, transient, and hypothetical conditions for a 2 $\times$ 2 rod bundle with a cavity, proving that the coupled code could accurately describe core subchannel flow responses to inlet blockages. Zhao Pengcheng et al. [5] coupled the one-dimensional system code RELAP5\_{LEAD} with FLUENT using explicit overlapping methods based on dynamic link libraries, simulating transient flow in lead-cooled series and closed-loop pipes with code-to-code comparisons showing excellent capability in modeling flow transients and pressure variations. Luo Xiao et al. [6] developed a multi-scale, multi-physics coupling code (neutron diffusion/subchannel/CFD: NDK/KMC-SUB/TrioCFD) using the SALOME platform's ICoCo interface, analyzing LFR-1000 shutdown conditions and asymmetric unprotected loss-of-flow accidents, demonstrating that the unified framework could better capture three-dimensional phenomena including axial thermal stratification in the upper plenum during shutdown and significant thermal-hydraulic parameter oscillations caused by recirculation and thermal stratification in the lead pool during asymmetric accidents. The Karlsruhe Institute of Technology (KIT) in Germany [7][8][9] also conducted multi-scale coupling of system/subchannel/CFD codes based on the SALOME platform, showing improved local simulation accuracy and accurate description of local flow and heat transfer behavior.

Current domestic research primarily focuses on multi-scale coupling code development and verification, with limited work on uncertainty analysis for multi-scale coupled systems. Uncertainty analysis plays a crucial role in reactor multi-scale coupling by quantifying uncertainty propagation effects from multiple sources in neutronics, thermal-hydraulics, fluid dynamics, and

coupling interfaces, enabling comprehensive safety margin assessment and identification/optimization of key parameters with maximum impact on simulation results to enhance model accuracy and reliability. Therefore, integrating uncertainty analysis modules into multi-scale coupling codes is essential.

This study employs an explicit weak coupling approach: first, secondary development couples the subchannel code SUBCHANFLOW and CFD code FLUENT based on the open-source preCICE library; second, bash and scheme scripts externally link the DAKOTA uncertainty analysis program to develop a multi-scale coupled uncertainty analysis code; third, a  $3 \times 3$  rod bundle model validates data transfer correctness and reliability between coupled codes; finally, uncertainty quantification and sensitivity analysis are performed on five selected input parameters.

## 1. Introduction to preCICE

preCICE is an open-source coupling library jointly developed by the Technical University of Munich and the University of Stuttgart [10], featuring MPI or TCP/IP communication channels, various mapping methods between unstructured grids, and providing 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] illustrates the basic introduction to preCICE, which has three main characteristics:

### 1.1 Partitioned Solution Approach

Unlike strong coupling, which requires constructing and solving equation systems for the entire solution domain, the core idea of partitioned solution is to divide the entire physical field into several independent physical subdomains for separate solution [11]. This approach leverages existing software or algorithm modules for individual calculations of each sub-physical field, with data exchange of boundary conditions for mutual correction. Partitioned solution avoids duplicating mature work, and preCICE can achieve accurate overall simulation results by combining individual subdomain solvers with lower time costs.

### 1.2 Library Approach

preCICE employs a library approach, meaning it is inserted as a function library into each solver, with each solver calling preCICE at runtime and operating in the same thread. This contrasts with framework coupling methods, such as the ADPRES-RELAP5 coupling developed by Qian Guanhua et al. [12] based on the Salome-ICoCo upper monitoring architecture, where SALOME acts as a monitor calling ADPRES and RELAP5 through the ICoCo interface, requiring modular reconstruction of ADPRES and RELAP5 source code to adapt to ICoCo interface standards. preCICE's high-level API only requires inserting functions at appropriate locations in the solver, minimizing disruption to the

solver' s structure and computational logic. Integrating new solvers into existing programs requires minimal effort while providing high runtime flexibility. Schematics of the upper 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 adopts a black-box coupling approach to construct multi-physics collaborative simulation systems, treating each solver as an independent functional module. From a numerical methods perspective, the framework only requires three basic solver characteristics: (1) input/output data interfaces; (2) time-step advancement mechanisms; (3) single-iteration recomputation capability. While this design theoretically poses coupling stability challenges due to information limitations, preCICE effectively overcomes these issues through integrated adaptive implicit coupling algorithms, convergence accelerators, and stability enhancement modules.

This architectural design offers significant advantages for multi-physics simulation system expansion and optimization. For system scalability, new physics solvers can be rapidly integrated through standardized interfaces without requiring deep understanding of internal algorithm implementation details (black-box coupling flowchart shown in Figure 4 [Figure 4: see original paper]). For algorithm optimization, solvers for the same physics using different numerical methods (e.g., finite element vs. finite volume) can be compared through module replacement. This flexible framework not only accelerates coupled system development but also provides an efficient experimental platform for innovative numerical method validation. 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 [13]. Strong coupling combines equation systems from different scales, solving complex nonlinear equation sets. While this approach can significantly improve coupled code performance and represents the most effective coupling method, it requires extensive source code modifications, resulting in high coupling difficulty and poor feasibility. Weak coupling solves each physics field separately at each scale, exchanging boundary condition data at specific times. This approach fully utilizes existing programs for accurate simulation of each scale' s physics field. Compared with strong coupling, weak coupling ensures coupling effectiveness without requiring extensive secondary development, demonstrating strong applicability. Most domestic and international multi-scale coupling research is based on weak coupling, and this study follows the same approach.

From a data transfer perspective, coupling can be classified as internal or external [14]. Internal coupling involves overall compilation of different programs or compilation into dynamic link libraries for complete integration 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 a control program. Internal coupling offers the highest computational efficiency but demands high requirements on program source code and substantial resource investment. Among external coupling methods, file-based coupling is simplest but faces extensive I/O operations, consuming significant memory resources during long transient simulations; direct program coupling suffers from non-unified data formats when programs are written in different languages; coordination through an intermediate control program can maximize computational efficiency while ensuring program integrity. This study adopts the intermediate control program approach.

## 2.2 Coupling Process

The coupled code comprises two main components: multi-scale coupling computation and uncertainty analysis. The multi-scale coupling computation serves as the core, using the preCICE coupling library to reduce communication resource consumption and better control the coupled calculation. The uncertainty analysis component primarily uses DAKOTA for repeated calls to the coupled computation code, with core operations focused on input/output, employing bash and scheme scripts to link the multi-scale computation code with DAKOTA. Due to different coupling principles, the code is introduced in two parts.

**2.2.1 preCICE-Based Multi-Scale Coupling Computation Code** To maintain numerical stability in coupled calculations and better leverage preCICE's black-box coupling advantages, the development principle is to minimize modifications required for coupling. The main operations are:

- (1) Insert preCICE library files into the subchannel code SUBCHANFLOW and FLUENT's UDF, adding variable modules for preCICE.
- (2) Construct virtual meshes as buffer zones in SUBCHANFLOW and FLUENT. Boundary condition data obtained through coupling is first written to virtual meshes, with subsequent operations determined by the computation mode.
- (3) Insert preCICE functions into the subchannel code and reconstruct its computation termination module.
- (4) Insert preCICE-related functions [15] into UDFs, with primary macro functions listed in Table 1 :

**Table 1 UDF Macro Functions** | UDF Macro Function Name | Purpose | DEFINE\_{INIT} | Initialize preCICE |

DEFINE\_{{{EXECUTE}}}{AT}}{END} | Transient data write | | DEFINE\_{PROFILE} | Transient data read | | DEFINE\_{PROPERTY} | Modify fluid properties | | DEFINE\_{{{EXECUTE}}}{AT}}{EXIT} | Terminate preCICE | | DEFINE\_{{{ON}}}\_{DEMAND}} | Steady-state data write, manual initialization |

The DEFINE\_{INIT} macro primarily initializes the computation domain, completing preCICE initialization including solver participant creation and mapping mesh establishment. Additionally, a manual initialization function is implemented using DEFINE\_{{{ON}}}\_{DEMAND}} for convenience. Since FLUENT's material properties default to constant values, which significantly impacts results under high-temperature and high-pressure conditions, DEFINE\_{PROPERTY} is used to modify coolant fluid properties including density, viscosity, specific heat capacity, and thermal conductivity. Coupling data reading uses DEFINE\_{PROFILE}, which can modify boundary conditions such as temperature and pressure. Coupling data writing is divided into steady-state and transient cases: steady-state data writing uses DEFINE\_{{{ON}}}\_{DEMAND}}, manually invoked by users; transient data writing uses DEFINE\_{{{EXECUTE}}}{AT}}{END}, called after each time step iteration. Finally, DEFINE\_{{{EXECUTE}}}{AT}}{EXIT} closes preCICE communication channels after computation completion.

- (5) SUBCHANFLOW is compiled using the gfortran command, while FLUENT's UDF is externally compiled into a dynamic link library using GCC before being loaded by FLUENT.
- (6) Write preCICE configuration files to construct coupled code data flow.
- (7) Launch FLUENT and SUBCHANFLOW sequentially to achieve peer-to-peer startup of sub-physics fields.

In addition to these main modifications, other minor adjustments are required to prevent conflicts between the two programs during computation. The FLUENT-SUBCHANFLOW multi-scale coupling code flowchart is shown in Figure 6 [Figure 6: see original paper].

**2.2.2 Multi-Scale Coupling Data Flow** Assuming both FLUENT and SUBCHANFLOW use mass flow inlet and pressure outlet boundary conditions. In steady-state coupling, FLUENT computes the upstream section (first 2 m) and, upon convergence, transfers outlet temperature and mass flow distribution parameters to SUBCHANFLOW as inlet boundary conditions through nearest-neighbor mapping. 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 computation. After convergence, it enters transient mode, transferring mass flow and outlet temperature to SUBCHANFLOW at each time window. Upon SUBCHANFLOW completion, FLUENT reads the inlet pres-

sure from SUBCHANFLOW to update its outlet pressure boundary condition. The detailed data flow is shown in Figure 8 [Figure 8: see original paper].

### 2.3 Uncertainty Analysis Process

The external coupling approach based on DAKOTA links the multi-scale coupling component through bash scripts. First, input parameters of interest are selected and their probability distributions and uncertainties are determined through literature review. Next, the sampling algorithm and number of samples are determined; DAKOTA performs sampling and generates corresponding input parameter decks. DAKOTA then calls the multi-scale coupling code using these parameter decks as inputs. After obtaining result files, a post-processing module in the bash script extracts response variables and returns them to DAKOTA for processing and analysis. The final uncertainty analysis results are obtained, with the specific process shown in Figure 9 [Figure 9: see original paper].

## 3. Multi-Scale Coupling Code Validation

To validate the FLUENT-SUBCHANFLOW coupling results, this study assumes a  $3 \times 3$  bare rod assembly model [16] for computational analysis.

### 3.1 Component Model Description

The 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, and pitch is 20 mm. Inlet temperature is 553.15 K, inlet mass flow rate is 4.12 kg/s, fuel rod heat flux is  $60000 \text{ W/m}^2$ , and 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.

**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
Inlet mass flow rate (kg/s)	4.12
Fuel rod heat flux ( $\text{W/m}^2$ )	60000
Outlet pressure (MPa)	15.5

Boundary conditions include mass flow inlet and pressure outlet. Fuel rod modeling is simplified in FLUENT, considering only fuel rod heat flux. At the coupling interface, FLUENT's unstructured mesh is labeled according to subchannel divisions, enabling one-to-one data exchange between SUBCHANFLOW and FLUENT based on channel numbers.

### 3.2 Steady-State Validation

SUBCHANFLOW and FLUENT were used separately to compute the model as baselines. In coupled computation, FLUENT calculated the first 2 m as the upstream program, transferring mass flow and temperature boundary conditions at the 2 m location through preCICE to SUBCHANFLOW for the remaining

section. Coupled result comparisons are shown in Figure 12 [Figure 12: see original paper].

Channels 1, 2, and 6 represent corner, edge, and center subchannels, respectively. In the corner subchannel, the coupled code shows maximum errors of 1.65% compared with FLUENT and 1.24% compared with SUBCHANFLOW. In the edge subchannel, maximum errors are 0.39% (vs. FLUENT) and 0.28% (vs. SUBCHANFLOW). In the center subchannel, maximum errors are 0.79% (vs. FLUENT) and 0.32% (vs. SUBCHANFLOW). These results indicate small computational errors relative to baseline codes.

The axial temperature distributions from FLUENT and SUBCHANFLOW nearly coincide for edge and center subchannels. Larger differences appear in the corner subchannel because subchannel codes, based on quasi-one-dimensional models with empirical correlations for crossflow and heat transfer, cannot capture three-dimensional secondary flows and turbulence anisotropy caused by geometric asymmetry. FLUENT, solving the full three-dimensional Navier-Stokes equations, naturally resolves momentum and energy exchange through turbulence models, more accurately characterizing local flow separation and three-dimensional thermal-hydraulic coupling features in corner subchannels.

The temperature distribution difference between coupled and FLUENT-alone calculations for 0-2 m arises because FLUENT uses 15.5 MPa outlet pressure for the complete model, while the coupled model's FLUENT section also uses 15.5 MPa outlet pressure, introducing some error. However, the maximum relative error is less than 0.6%, which is considered acceptable.

The results demonstrate ideal coupling effects for edge and center subchannels, with larger fluctuations in corner subchannels due to solver differences but consistent overall trends. This confirms that FLUENT can correctly transfer boundary conditions to SUBCHANFLOW through preCICE communication channels.

### 3.3 Transient Validation

Transient testing builds upon steady-state calculations by applying inlet mass flow fluctuations to test the coupled code's sensitivity to varying boundary conditions. The transient calculation uses sinusoidally varying mass flow as the FLUENT inlet boundary condition with a 1 s period. FLUENT first performs steady-state computation, then begins sinusoidal variation after convergence. The fluctuation expression is:

$$\dot{m} = 0.5 \sin(2\pi t) + 4.12$$

Total transient computation time is 5 s with a time step of 0.01 s. Figure 13 [Figure 13: see original paper] shows inlet mass flow and subchannel program outlet mass flow versus time, revealing sinusoidal outlet flow fluctuations synchronized in frequency and phase with the inlet. Figure 14 [Figure 14: see

original paper] shows outlet flow variations for representative corner (Channel 1), edge (Channel 2), and center (Channel 6) subchannels. Corner subchannels show the most pronounced fluctuations, edge subchannels moderate, and center subchannels the smoothest variations. All three subchannel types exhibit sinusoidal outlet flow fluctuations synchronized in frequency and phase with the inlet, proving that the FLUENT/SUBCHANFLOW multi-scale coupling code correctly responds to boundary condition changes with accurate and timely parameter calculations.

## 4. Uncertainty Analysis

### 4.1 Uncertainty Analysis Method

The key step in uncertainty analysis is selecting and quantifying uncertainty sources. Selection typically involves expert judgment through phenomena identification and ranking tables (PIRT) or sensitivity analysis, while quantification requires specifying probability distributions or intervals for selected parameters.

Uncertainty quantification analysis evaluates the impact of input uncertainties on model outputs [17]. Based on different mathematical theories, methods can be statistical or deterministic. For reactor thermal-hydraulic analysis, statistical methods are commonly used: uncertainty computation followed by sensitivity analysis. Statistical methods can be categorized based on uncertainty propagation pathways into input parameter uncertainty propagation methods and output parameter uncertainty extrapolation methods. This study employs the input parameter uncertainty propagation method.

A  $3 \times 3$  fuel assembly is analyzed for uncertainty. Based on literature review [18], five boundary condition parameters were selected as inputs: inlet coolant temperature, inlet mass flow rate, fuel rod heat flux, outlet pressure, and cladding thermal conductivity. Four parameters were selected as outputs: DNB (Departure from Nucleate Boiling ratio), inner cladding temperature, coolant temperature, and fuel pellet temperature. Detailed information is provided in Table 3.

**Table 3 Input Parameter Uncertainty Information** | Parameter | Uncertainty ( $3\sigma$ ) | |-----| | Inlet mass flow rate |  $\pm 1.5\%$  | | Fuel rod heat flux |  $\pm 5\%$  | | Cladding thermal conductivity |  $\pm 5 \text{ W}/(\text{m} \cdot \text{K})$  |

### 4.3 Sampling Method and Sample Size Selection

Monte Carlo sampling and Latin Hypercube Sampling (LHS) are common methods. Simple Monte Carlo suffers 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 parameter samples to generate sample points that satisfy constraints. This study employs LHS.

To reduce sample numbers and save computational time for the multi-scale coupled system, Wilks' method is used to determine sample size. For two-sided tolerance intervals, the formula is:

$$1 - \alpha = \sum_{i=0}^{n-1} \binom{n}{i} (1-p)^i p^{n-i}$$

where  $n$  is sample size,  $p$  is tolerance probability, and  $\alpha$  is confidence level. The U.S. Nuclear Regulatory Commission (NRC) recommends 95% for both confidence level and probability in safety assessments, yielding a minimum sample size of 93. For conservative estimation, 100 samples were selected [19].

#### 4.4 Uncertainty Quantification Analysis

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

Figure 16 [Figure 16: see original paper] shows DAKOTA result histograms with frequency density curves for DNB, inner cladding maximum temperature, fuel pellet maximum temperature, and coolant maximum temperature. The DNB frequency density curve is left-skewed, indicating higher probability of low DNB values. All four response parameters show low kurtosis, suggesting large data fluctuation ranges with low probability of extreme values. Mean values of all response parameters fall within confidence intervals with small standard deviations, indicating high computational reliability.

**Table 4 Uncertainty Quantification Results**

Parameter	Confidence Interval Lower Bound	Confidence Interval Upper Bound
Cladding max temperature	322.097	327.341
Fuel max temperature	523.456	531.234
Coolant max temperature	553.123	558.456

#### 4.5 Sensitivity Analysis

The rank correlation coefficient reflects the direction and strength of association between two random variables' variation trends. Spearman rank correlation analysis for global sensitivity analysis can evaluate the influence of multiple input parameters on target parameters. Correlation coefficients range from -1 to +1, where positive values indicate positive correlation, negative values negative correlation, and zero no correlation; absolute values closer to 1 indicate stronger sensitivity. Typically,  $|| > 0.9$  indicates strong correlation,  $0.5 < || \leq 0.9$  moderate correlation, and  $0.3 < || \leq 0.5$  weak correlation.

This study performs sensitivity analysis on inner cladding temperature, fuel maximum temperature, coolant temperature, and cladding thermal conductivity as target parameters. To reduce mutual influence between input parameters,

Spearman rank correlation analysis is used, with results shown in Figure 17 [Figure 17: see original paper].

Results show that DNB is strongly positively correlated with inlet temperature, strongly negatively correlated with outlet pressure, and moderately affected by cladding thermal conductivity. 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 significant relationship with other input parameters.

## Conclusions

This study developed a reactor multi-scale coupled uncertainty analysis code by secondary development of the CFD code FLUENT, subchannel code SUBCHANFLOW, and uncertainty analysis code DAKOTA based on the preCICE open-source coupling library, using explicit weak coupling and external program coordination. A  $3\times 3$  rod bundle model was established for code validation, followed by uncertainty quantification and sensitivity analysis of key response parameters. The main conclusions are:

- 1) A “FLUENT-SUBCHANFLOW-DAKOTA” multi-scale coupled uncertainty analysis code was developed based on the preCICE open-source coupling library. The code is applicable to multi-scale coupling and uncertainty analysis studies at the core local level, 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) Code-to-code steady-state and transient validation was performed using a  $3\times 3$  rod bundle model. Steady-state results verified the accuracy of data transfer at coupling interfaces. Transient results demonstrated correct response to boundary condition variations. Under sinusoidal inlet flow perturbations, total outlet flow variations remained consistent, with outlet flows from three typical subchannel types synchronized in period and phase with inlet flow fluctuations.
- 3) Uncertainty quantification results show that all key parameters fall within 95% confidence intervals, following normal or approximately normal distributions with small standard deviations, indicating high computational reliability. Sensitivity analysis reveals that outlet pressure and fuel rod heat flux significantly influence system responses, while inlet mass flow rate and cladding thermal conductivity exert significant negative effects

on different response variables, and inlet temperature effects on different responses are complex.

## 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, funding support.

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

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