Numerical Simulation and Sensitivity Analysis of Nitrate Natural Circulation Loop (NNCL)

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Abstract

Background: The nitrate natural circulation loop (NNCL) is an important experimental platform for investigating the characteristics of molten salt natural circulation. Through numerical simulation of the NNCL and sensitivity analysis of parameters, this study deepens the understanding of molten salt natural circulation and accumulates experience for the design of passive residual heat removal systems in molten salt reactors. Objective: To verify the validity of numerical simulation and uncertainty analysis through experimental data, and to investigate the effects of input parameters on natural circulation flow rate using sensitivity analysis methods. Methods: A modified RELAP5/MOD4.0 program was employed to establish an analysis model of the NNCL, and a Monte Carlo-based uncertainty analysis method was utilized to calculate the uncertainty of the numerical analysis. Multiple linear regression was adopted to study the sensitivity of input parameters. Results: The numerical simulation results agree well with experimental data, and the upper and lower bounds from uncertainty analysis can envelope the NNCL experimental results and their errors. Through sensitivity analysis, the importance of input parameters affecting natural circulation was ranked. Conclusion: The modified RELAP5/MOD4.0 program combined with uncertainty analysis is applicable to numerical analysis of nitrate natural circulation. The three most sensitive factors affecting natural circulation are the air-side convective heat transfer coefficient, loop resistance coefficient, and nitrate density.

Full Text

Numerical Simulation and Sensitivity Analysis of the Nitrate Natural Circulation Loop (NNCL)

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Abstract

Background: The nitrate natural circulation loop (NNCL) serves as a crucial experimental platform for investigating molten salt natural circulation characteristics. Through numerical simulation and parameter sensitivity analysis of the NNCL, this study aims to deepen understanding of molten salt natural circulation and accumulate experience for the design of passive residual heat removal systems in molten salt reactors. **Objective:** Using experimental data, we validate the accuracy of numerical simulations and uncertainty analysis, and investigate the influence of input parameters on natural circulation flow rate through sensitivity analysis methods. **Methods:** A modified RELAP5/MOD4.0 code was employed to establish an NNCL analysis model. Uncertainty in the numerical analysis was calculated using a Monte Carlo-based uncertainty propagation method, while multiple linear regression was applied to study input parameter sensitivity. **Results:** The numerical simulation results show good agreement with experimental data, and the uncertainty analysis bounds effectively envelope the NNCL experimental results and their measurement errors. Through sensitivity analysis, the importance ranking of input parameters affecting natural circulation was established. **Conclusion:** The modified RELAP5/MOD4.0 code combined with uncertainty analysis is suitable for numerical analysis of nitrate natural circulation. The three most sensitive factors affecting natural circulation are the air-side convective heat transfer coefficient, loop resistance coefficient, and nitrate density.

Keywords: Molten salt natural circulation; RELAP5/MOD4.0; Uncertainty analysis; Sensitivity analysis

1. Introduction to NNCL

Molten salt reactors represent one of the six Generation IV nuclear reactor candidates [1-3]. In addition to their inherent safety features, they employ passive residual heat removal systems that can effectively mitigate the consequences of accidents such as loss of off-site power [4-6]. To investigate the heat removal capacity, stable operation, and transient response characteristics of high-temperature molten salt natural circulation loops, the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, constructed a high-temperature molten salt natural circulation loop using nitrate salt as the working medium, designated as NNCL (Nitrate Natural Circulation Loop). This facility serves as an important platform for validating the applicability of molten salt system analysis codes and thermal-hydraulic calculation methods, providing crucial experience for the design and construction of passive residual heat removal systems in molten salt reactors. Sensitivity analysis examines how different values of independent variables affect specific dependent variables, enabling deeper understanding of how various parameters (such as fluid properties, heat transfer models, and loop resistance) influence natural circulation. This paper establishes a nitrate natural circulation analysis model, employs a Monte Carlo-based uncertainty analysis method to calculate uncertainty bounds, validates the numerical analysis and uncertainty models against experimental data, and subsequently performs sensitivity analysis on input parameters to investigate their impact on natural circulation flow rate.

The NNCL uses a ternary nitrate salt mixture ($NaNO_3$-$NaNO_2$-KNO_3) as the fluid medium. Nitrate salts exhibit high stability, excellent safety characteristics, and a high boiling point, with widespread applications in industrial production. Scaling analysis demonstrates that they can effectively simulate fluoride salt natural circulation characteristics within certain ranges. Therefore, nitrate salt is used as a substitute for fluoride salt to validate the feasibility of passive residual heat removal systems in molten salt reactors and to address potential issues during standby, startup, and stable operation [7]. The NNCL system consists of a molten salt pool, DRACS heat exchanger (DHX), air cooling tower, natural-draft air-cooled heat exchanger (NDHX), expansion tank, gas system, molten salt storage tank, and other components, as shown in [Figure 1: see original paper]. The main design parameters are listed in . The air cooling tower features two air intake methods: side intake (shown by black arrows in [Figure 1: see original paper]) and bottom intake (shown by red arrows in [Figure 1: see original paper]). The tower bottom is equipped with a fan and damper to regulate air flow rate. An electric heater at the bottom of the molten salt tank heats the salt [8]. Heat is transferred from the electric heater to the molten salt pool, and the DHX heat exchanger, immersed in the pool, transfers heat from the pool nitrate to the nitrate inside the DHX tubes. The nitrate inside the DHX tubes absorbs heat, its temperature rises and density decreases, causing it to rise along the piping into the heat rejection section (NDHX). Heat is removed by air in the cooling tower, the nitrate temperature decreases and density increases, and it flows back down through the return piping to the DHX tubes to be reheated, thus establishing a circulation loop.

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2. Methods

2.1 Uncertainty Analysis Method

This study employs the "input uncertainty propagation method" [9], which is based on Monte Carlo methods. The core of this approach involves characterizing input parameter uncertainties, propagating them through calculations, and finally evaluating their impact on parameters of interest. This method requires extensive random sampling to simulate input parameter uncertainties. For each uncertain input parameter, its possible range of values and probability distribution must be determined. Probability distributions typically include normal, uniform, and trapezoidal distributions. [Figure 2: see original paper] illustrates the schematic of this method.

2.2 System Analysis Code

RELAP5 is a light water reactor transient analysis code developed by Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (NRC) and approved by NRC for engineering safety review [10]. Its component models include pipes, valves, pumps, turbines, branches, and control system components, along with hydraulic models for abrupt area changes, crossflow, and choked flow. It has been widely applied in accident analysis of various light water reactors. RELAP5/MOD4.0 is the latest version in the RELAP5 series, developed by Innovative System Software (ISS), which retains all RELAP5 models while adding more fluid working substances.

RELAP5/MOD4.0 alone cannot meet all requirements of this study. Therefore, secondary development was performed on the RELAP5/MOD4.0 code. Nitrate salt fluid properties were added, and molten salt natural circulation-related heat transfer correlations were incorporated based on relevant experimental results [7] to meet the simulation requirements for nitrate natural circulation loops. Additionally, a molten salt uncertainty analysis package was developed based on the uncertainty analysis method employed and the identified uncertain input parameters to satisfy the requirements for NNCL uncertainty analysis.

2.3 Input Uncertainty Parameters

Uncertain parameters were determined based on fundamental natural circulation equations, expert judgment, and previous research results [11]. To date, a series of experiments have been conducted on the NNCL, including natural circulation heat transfer tests and system resistance tests [8,12-14]. Based on these experimental results and expert opinion, uncertainty parameters and their ranges were determined. The selected input uncertainty parameters are listed in . This study uses Wilks' formula [15] to calculate sample size, which depends on confidence level β and tolerance level γ. The mathematical expression of Wilks' formula is given by equation (1):

$$1-\gamma^m=\sum_{i=0}^{m-1}\binom{N}{i}\beta^i(1-\beta)^{N-i}$$

where N is the sample size, β is the confidence level, and m is the order.

2.4 Sensitivity Analysis Method

Sensitivity analysis is an important method for evaluating how input variables affect model outputs. It quantitatively examines the degree of influence that relevant factors have on specific key indicators when they undergo certain changes. Sensitivity analysis includes two types: local sensitivity analysis, which focuses on the effect of input parameter changes at a specific point or small range on the output, and global sensitivity analysis, which considers variations across the entire parameter space to assess the overall impact of input parameters on the output. This study employs global sensitivity analysis to investigate the influence of all selected parameters on model outputs.

Multiple linear regression (MLR) is a commonly used sensitivity analysis method. This study adopts MLR [16] for input parameter sensitivity analysis, with its mathematical expression given by equation (2):

$$y = \beta_0 + \beta_{1x}1 + \beta_{2x}2 + \cdots + \beta_{kx}k + \varepsilon$$

where β_0 is the regression constant, β_i are regression coefficients, and ε is random error.

An F-test is used to assess model significance, with α set to 0.01. The adjusted R^2 is employed to evaluate goodness-of-fit for the linear formula, as it accounts for the number of independent variables and sample size, providing a better measure of linear correlation between dependent and predictor variables. Variance inflation factor (VIF) is used to evaluate parameter collinearity; values below 5 indicate no collinearity issues, otherwise parameter selection must be reevaluated. Standardized regression coefficient (SRC) is used as the sensitivity analysis metric, with its absolute value magnitude indicating parameter importance. The specific steps for sensitivity analysis are shown in [Figure 3: see original paper].

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3. Results and Discussion

3.2.1 Uncertainty Samples

This study selects $\gamma = 95\%$, $\beta = 95\%$, and order $m = 1$. According to Wilks' formula (see equation (1)), the minimum required sample size is 59. The selected uncertain input parameters and their probability distributions are listed in .

3.2.2 Analysis Model

This study employs the modified RELAP5/MOD4.0 code to establish an NNCL system analysis model. The system nodalization is shown in [Figure 6: see original paper] and includes three coupled systems: (1) Molten salt pool, represented by control volumes 1XX. Volume 100 represents the bottom of the molten salt pool connected to the electric heater. Volume 106 represents the upper plenum of the pool. Volumes 114 and 104 represent assumed natural circulation riser and downcomer channels in the pool; while no actual riser or downcomer exists in the pool, the model uses "multiple junctions" to laterally connect volumes 114 and 104 to simulate crossflow. (2) Primary loop, represented by control volumes 2XX. Volumes 202 and 224 represent the DHX and NDHX heat exchanger pipes, respectively. Volumes 252 and time-dependent volume 254 represent the expansion tank for primary loop pressure regulation. Heat transfer between volume 202 and 104 is modeled via heat structures. (3) Air cooling tower, represented by control volumes 3XX. Volume 306 represents the air side of the NDHX heat exchanger, which exchanges heat with primary loop volume 224 via heat structures. Time-dependent volumes 352 and 354 represent the air system.

3.2.3 Analysis Results

[Figure 7: see original paper] through [Figure 9: see original paper] compare numerical simulation results with experimental data. The simulation curves show that after opening the air cooling tower damper, the DHX inlet temperature first drops sharply then gradually increases. The DHX outlet temperature rise rate continuously decreases as the damper opens. The NNCL primary loop nitrate flow rate increases with damper opening. The simulated temperature and flow trends are consistent with experimental trends.

[Figure 7: see original paper] through [Figure 9: see original paper] also present uncertainty analysis results, where "Lower limit case" represents the uncertainty lower bound and "Upper limit case" represents the upper bound. Relative to experimental data, the maximum percentage difference between uncertainty bounds is -5.7% to 4.2% for DHX inlet temperature, -3.5% to 4.0% for DHX outlet temperature, and -12% to 12% for NNCL primary loop nitrate flow rate. The uncertainty bounds effectively envelope experimental data and measurement errors, demonstrating that the modified RELAP5/MOD4.0 code can satisfactorily predict NNCL system operational characteristics.

3.3 Sensitivity Analysis

Natural circulation flow rate is a critical parameter that directly affects the heat transfer capability of natural circulation. This study analyzes and investigates the sensitivity of NNCL system uncertainty input parameters to primary loop flow rate. The comparison between simulation and experimental results in Section 3.2 demonstrates that the numerical analysis model based on modified RELAP5/MOD4.0 is suitable for NNCL system characteristic analysis. Building upon this, this study employs multiple linear regression to analyze parameter sensitivity, as detailed in Section 3.3.

With heater power set at 40 kW and uncertain input parameters selected from , 93 samples were calculated. The results for these 93 input samples are shown in [Figure 10: see original paper]. An F-test assesses model significance at $\alpha = 0.01$, where $F_{0.01}(14, 78) = 2.32$. The calculated F-value is 2682.0, exceeding 2.32, indicating a significant linear relationship between NNCL system nitrate flow rate and the 14 input parameters at the $\alpha = 0.01$ significance level. Statistical analysis yields an adjusted $R^2 = 0.998$, exceeding 0.7, confirming the statistical significance of the multiple linear regression model.

VIF calculation results are shown in [Figure 11: see original paper], all below 5, indicating no collinearity among input parameters. Therefore, SRC is used for parameter importance identification. The absolute SRC values for each parameter indicate sensitivity strength. The absolute SRC values for the 14 parameters are shown in [Figure 12: see original paper], where the three most important parameters affecting NNCL primary loop flow rate are air-side convective heat transfer coefficient, loop resistance coefficient, and nitrate density.

Natural circulation relies on the driving pressure head generated by fluid density differences between hot and cold legs. The air-side convective heat transfer coefficient significantly affects NDHX heat rejection, directly influencing cold leg temperature and consequently the density difference between hot and cold legs, ultimately affecting natural circulation driving force and flow rate. Loop resistance coefficient is also a crucial parameter affecting natural circulation, as flow rate is essentially determined by the balance between driving force and resistance. Larger resistance leads to smaller flow rate, and vice versa. The resistance coefficient directly represents loop resistance magnitude. Density itself also affects loop resistance and the temperature change rate during heat absorption and rejection, making nitrate density another important parameter influencing natural circulation flow rate.

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4. Conclusion

This study performed numerical simulation and uncertainty analysis for the high-temperature molten salt natural circulation loop (NNCL) and investigated the sensitivity of input parameters to natural circulation flow rate. Numerical analysis results show that NNCL hot/cold leg temperatures and primary loop nitrate flow rate trends are consistent with experimental trends. Uncertainty analysis bounds effectively envelope experimental data and measurement errors, demonstrating that the modified RELAP5/MOD4.0 code combined with uncertainty analysis can satisfactorily predict NNCL system operational characteristics. Through multiple linear regression sensitivity analysis, the three parameters with the greatest impact on natural circulation flow rate are identified as air-side convective heat transfer coefficient, loop resistance coefficient, and nitrate density. To reduce design and analysis errors in high-temperature molten salt natural circulation systems, future research should focus on these parameters.

Author Contributions

Kai Wang: Conducted research, collected and analyzed/interpreted data, drafted manuscript, acquired funding. **Chaoqun Wang:** Provided critical review of intellectual content. **Chuangxiong Cai:** Provided critical review of intellectual content. **Qun Yang:** Provided critical review of intellectual content. **Zhaozhong He:** Provided technical support and critical review of intellectual content. **Naxiu Wang:** Supervised research.

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