Flow Distribution Characteristics at the Sodium-Side Inlet of Steam Generators in Sodium-Cooled Fast Reactors

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Abstract

China has designated sodium-cooled fast reactor technology as an important development direction for future nuclear energy technologies. The steam generator, as a core component of China’ s demonstration fast reactor (CFR600), has thermal-hydraulic performance that is critical to the overall efficiency and safety of the reactor. However, the issue of non-uniform sodium coolant flow distribution is primarily induced by factors including flow distribution grid design, inlet window structure, annular channel width, inlet nozzle height, and sodium coolant inlet flow rate, which not only compromises heat exchange efficiency but also induces system instability. Therefore, this study employs Computational Fluid Dynamics (CFD) numerical simulation methods to conduct parametric sensitivity analysis on the influencing factors of sodium-side inlet flow distribution, revealing the influence mechanisms of flow distribution grid and inlet window design on flow distribution, and proposes an optimization scheme together with a non-uniformity constant as an evaluation index for flow distribution non-uniformity. The results demonstrate that following optimization, the flow distribution grid height is determined to be 1200 mm, with the inlet window structure employing 40 perforations in rows 1-4, 30 perforations in rows 5-8, and 24 perforations in rows 9-11. Although the flow distribution device introduces additional pressure loss during the flow process to a certain extent, it overall improves the flow characteristics of the steam generator, constraining the maximum relative radial velocity range within the 120-150% interval and reducing the maximum non-uniformity index below 0.35. These research findings provide a theoretical basis for the design optimization of the CFR600 steam generator.

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Full Text

Sodium-Side Inlet Flow Distribution Characteristics of the Steam Generator in a Sodium-Cooled Fast Reactor

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Abstract

The sodium-cooled fast reactor China Demonstration Fast Reactor (CFR600) represents one of the most promising directions for the future of nuclear energy in China, offering advantages such as efficient fuel utilization, higher breeding potential, and enhanced safety features. As a critical component of CFR600, the steam generator plays a pivotal role in ensuring efficient heat transfer and maintaining overall system stability. However, non-uniform coolant flow distribution poses a major challenge in sodium-cooled fast reactors, significantly affecting the thermal-hydraulic performance of the steam generator and potentially compromising operational safety. This flow maldistribution arises from multiple design and operational factors, including flow equalizing grid configuration, inlet window structure, annular channel width, inlet nozzle height, and coolant flow rate. Consequently, optimizing these parameters is essential for improving steam generator efficiency and reliability.

This study investigates sodium-side flow distribution in the CFR600 steam generator and optimizes the flow equalizing grid and inlet window design to enhance flow uniformity and thermal-hydraulic performance. A Computational Fluid Dynamics (CFD) approach using ANSYS CFX was employed for steady-state simulations of the sodium-side inlet section. A grid independence study determined that a mesh of 7.25 million elements achieved reliable results while maintaining computational efficiency. The research systematically examined three flow equalizing grid heights and three inlet window structures, conducting parameter sensitivity analyses to evaluate their influence on flow uniformity. Additionally, a dimensionless non-uniformity index was introduced to quantitatively assess flow maldistribution.

Simulation results demonstrate that the optimal flow equalizing grid height is 1200 mm, while the most effective inlet window design employs varying hole counts and arrangements that significantly improve flow uniformity. Specifically, the optimized configuration uses 40 holes in rows 1–4, 30 holes in rows 5–8, and 24 holes in rows 9–11. Although these flow equalizing devices introduce a slight pressure loss penalty, they substantially improve overall flow characteristics. The maximum relative radial velocity is controlled within 120–150%, and the maximum non-uniformity index is reduced below 0.35. These findings confirm that optimizing the flow equalizing grid and inlet window structure can significantly enhance sodium coolant flow uniformity, contributing to improved thermal-hydraulic performance, higher efficiency, and safer steam generator operation in CFR600. The results provide valuable insights for design optimization of sodium-cooled fast reactor steam generators and offer a theoretical foundation for future reactor development.

Keywords: CFR600, Steam Generator, Flow Distribution, CFD, Design Optimization

Introduction

The Xiapu Fast Reactor Demonstration Project represents a crucial component of China' s closed nuclear fuel cycle initiative and marks significant progress in fast reactor technology. As a core component of China' s demonstration fast reactor, the steam generator transfers heat from the primary circuit to the secondary circuit to produce steam, directly impacting reactor efficiency and safety. Non-uniform flow distribution on the sodium side not only creates uneven shell-side flow fields in the evaporator but also increases transverse flow velocities that can induce flow-induced vibration in heat transfer tubes, compromising structural integrity. Therefore, optimizing steam generator flow distribution to enhance thermal-hydraulic performance has become critical for improving overall operational efficiency and safety of China' s demonstration fast reactor.

Recent advances in Computational Fluid Dynamics (CFD) have enabled more comprehensive investigations of steam generator flow characteristics and distribution issues. Researchers at Harbin Engineering University conducted full-scale three-dimensional numerical simulations of coupled heat transfer in both primary and secondary sides of a once-through steam generator, while Shanghai Jiao Tong University performed thermal-hydraulic experiments on a small PWR helical-coil once-through steam generator under various thermal powers. Other studies employed porous medium methods to simulate primary-side flow distribution in Hualong One PWR ZH-65 and AP1000 steam generators, revealing temperature, flow, energy, and heat transfer coefficient distributions. However, China' s demonstration fast reactor steam generator uses a shell-and-tube once-through design with liquid sodium as the primary heat transfer fluid, resulting in different flow distribution characteristics compared to conventional PWR steam generators. Research from the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, demonstrates that hydraulic structure design plays a decisive role in flow distribution. In sodium-cooled fast reactor steam generators, heat transfer tubes are uniformly arranged, and perforated plates at the bottom inlet chamber ensure uniform flow distribution within tubes. Under this design, external sodium-side flow distribution becomes the key factor affecting steam generator performance, with inlet windows and flow equalizing grids being the primary determinants.

This study employs CFD methods to simulate sodium-side flow distribution in China' s demonstration fast reactor steam generator, providing preliminary analysis of influencing factors and baseline data for subsequent experiments. Experimental validation of flow distribution will support comprehensive testing of sodium-water-steam flow and heat transfer coupling in demonstration fast reactor steam generator prototypes, thereby promoting safe and efficient operation.

1. Research Object and Model Development

China' s demonstration fast reactor steam generator is a vertical unit offering advantages of no stagnant zones in the secondary circuit and uniform heat absorption across heating surfaces. The steam generator comprises an evaporator and superheater, both using liquid sodium on the shell side, with two-phase water and superheated steam on the tube side, respectively. This research focuses on sodium-side fluid flow in the demonstration fast reactor steam generator.

In the evaporator, sodium-side fluid enters through the upper inlet nozzle and exits via the lower outlet nozzle, while in the superheater, flow enters through the lower inlet and exits through the upper outlet. The sodium-side inlet regions of both components exhibit high structural and flow pattern similarity, allowing the evaporator's flow characteristics to represent overall steam generator sodium-side flow behavior.

Without flow distribution devices, sodium coolant exhibits significant flow non-uniformity, causing flow instabilities such as turbulence or oscillations that affect stable operation. Low-velocity regions can also lead to local overheating and increased equipment damage risk. Perforated plates are typically the preferred solution for mitigating flow maldistribution due to low cost and easy installation. To achieve uniform sodium distribution, Nguyen designed a perforated plate and used numerical simulation to optimize its geometry and placement, improving flow uniformity at the cost of slight pressure loss. Consequently, China' s demonstration fast reactor design incorporates flow equalizing grids and perforated inlet windows on the sodium side to improve inlet region flow distribution characteristics. The research object includes these flow equalizing grids and sodium-side inlet windows, as shown in [Figure 1: see original paper]. Perforation schematics for the flow equalizing grid and inlet window are presented in [Figure 2: see original paper].

The heat transfer tube arrangement exhibits periodic symmetry. Given model complexity, equivalent resistance structures were substituted based on fluid dynamics principles, eliminating the need for actual tube geometry modeling. In the evaporator, sodium-side fluid enters the inner cylinder through inlet windows with significant radial velocity that gradually diminishes to purely axial flow. Shortening the inner cylinder height does not affect inlet window flow distribution characteristics, and the region below the outer cylinder inlet nozzle exhibits slow flow that can be considered a dead zone. Therefore, the outer cylinder structure below the inlet nozzle was simplified, and the inner cylinder height was reduced.

2.1 CFD Governing Equations and Boundary Conditions

For flow distribution experimental design, this study employs CFD to analyze sodium-side flow in the demonstration fast reactor steam generator. The sodium-water-steam heat transfer coupling is neglected, and a steady-state model is adopted. The governing equations are:

Mass conservation equation:

Momentum conservation equation:

where is sodium density, **u** is the velocity vector, p is pressure, is dynamic viscosity, and **f** is the body force term including gravity and additional resistance, with gravitational acceleration of 9.81 m/s^2.

Under normal CFR600 operating conditions, the evaporator sodium-side inlet nozzle Reynolds number is 4.43$\times 10^{\{6\}, and the inlet annular channel Reynolds number is 1.05\times 10}$\{6\}$, both indicating turbulent flow. Therefore, an appropriate turbulence model is required for accurate flow prediction. The Shear Stress Transport (SST) turbulence model effectively captures turbulence behavior in both near-wall and free-stream regions, particularly in systems with strong gradient variations. The SST model is thus selected to describe sodium turbulence, with governing equations:

k-equation:

ω**-equation:**

where t is time, k is turbulent kinetic energy, ω is specific dissipation rate, is eddy viscosity coefficient, and β*, σ , β, γ, $\sigma\omega$, and P are model constants. These parameters use default values from ANSYS CFX, with F_1 representing a blending function.

For complex geometries with local flow characteristics, mass flow boundary conditions provide more stable control. Based on design conditions, the inlet mass flow rate is set to 372.625 kg/s. The pressure outlet boundary reflects environmental conditions at the steam generator exit, with the outlet pressure specified as 1.96 MPa to ensure consistency with actual pressure fields.

2.2 Grid Independence Verification

Due to numerous irregular perforations in the flow equalizing grid and sodium-side inlet window, hexahedral meshing is impractical. The analysis model therefore employs tetrahedral meshing with boundary layer refinement at thin walls and in key regions (flow equalizing grid and inlet window areas). Coarser mesh is applied in the shell-side chamber away from inlet windows to reduce computational time. CFD calculations must ensure results are independent of mesh resolution while maintaining reasonable cell counts. Grid independence is achieved when the relative error of key physical quantities between adjacent mesh levels falls below 0.5%.

compares results for different mesh quantities. When mesh count increases from 6.73 million to 8.22 million, the inlet-outlet pressure drop changes minimally (from 10,124 Pa to 10,131 Pa, a 0.06% deviation), confirming that the 7.25 million element mesh meets grid independence requirements.

3.1 Effect of Flow Equalizing Grid Height on Flow Distribution

To investigate flow equalizing grid height effects, three configurations were analyzed with grid heights of 800 mm, 1000 mm, and 1200 mm from the inlet chamber bottom. All cases assumed 42 mm diameter perforations, 45 mm center-to-center spacing, 40 holes per row, and 440 total holes, with a 470 mm total inlet window height.

[Figure 3: see original paper] compares the average mass flow rate at each circumferential angle (MC) to the average inlet window mass flow rate (MC). As grid height h increases, circumferential inflow becomes more uniform. At h = 1200 mm, circumferential uniformity significantly exceeds the other configurations, with maximum average inflow velocity occurring at 180° at approximately 1.3 times the average mass flow rate.

[Figure 4: see original paper] presents radial velocity contours at the inlet window mid-height plane. At h = 800 mm, excessive inflow velocity at 180° causes fluid outflow in the 0° direction, with sodium inflow primarily occurring between 90°-180°. As h increases, the 180° inflow velocity decreases and circumferential distribution becomes more uniform. At h = 1200 mm, no outflow occurs in the 0° direction.

To quantify circumferential flow uniformity, a dimensionless non-uniformity index is defined:

where MC is the average mass flow rate for each column of inlet window holes, MC is the average mass flow rate through the inlet window, and N is the number of hole columns. NUI = 0 indicates perfectly uniform distribution, with higher values representing greater non-uniformity.

compares circumferential non-uniformity NUI values for the three grid positions. At h = 1200 mm, the circumferential mass flow non-uniformity NUI is substantially lower than other positions. The flow equalizing grid structure thus improves circumferential inlet window flow uniformity, with greater distance from the inlet nozzle reducing pressure loss while enhancing uniformity.

3.2 Effect of Inlet Window Structure on Flow Distribution

While the flow equalizing grid improves flow distribution, height-direction non-uniformity persists in the inlet window. Therefore, different perforation patterns were analyzed to determine an optimal inlet window structure.

To optimize height-direction uniformity, variable perforation density based on vertical position was implemented. Regions with more holes have larger flow area and lower resistance. Designing inlet windows with increasing hole counts at higher elevations efficiently improves distribution uniformity. The optimization maintains constant overall height and hole diameter while reducing lower region perforations. Structural parameters for designs 2 and 3 are listed in .

To evaluate height-direction uniformity, an axial non-uniformity constant is defined:

where ṁ is the mass flow rate through each row of inlet window holes (kg/s), ṁ is the average mass flow rate per row (kg/s), ṁ is the total inlet mass flow rate, and N is the number of hole rows.

compares height-direction non-uniformity NUI values for the three inlet window structures. [Figure 5: see original paper] shows the ratio of each row' s mass flow rate (ṁ) to the average row mass flow rate (ṁ). In all three designs, top inflow is less than bottom inflow. As lower region perforation density decreases, top mass flow increases while bottom flow decreases, improving height-direction uniformity. Variable hole count arrangements enhance height-direction uniformity compared to uniform perforation. With Structure 3, ṁ remains within [0.77ṁ , 1.18ṁ].

3.3 Performance of Flow Distribution Devices

Based on analyses of flow equalizing grid height and inlet window structure, an optimized flow distribution device configuration was identified that achieves uniform axial and radial flow distribution. To validate this design, pressure drop and flow distribution performance were compared with and without the device.

compares total pressure drop with and without flow distribution devices, showing that device installation increases pressure loss.

[Figure 6: see original paper] presents radial velocity contours at the 0°-180° mid-plane and half-height cross-section. [FIGURE:6(a)] shows uniform height-direction distribution across the inlet window, though large radial velocities appear at hole locations near the bottom, rapidly decreasing and becoming uniform as flow progresses inward. [FIGURE:6(b)] demonstrates uniform inflow velocity at all circumferential angles at the half-height plane, indicating effective flow distribution control.

[Figure 7: see original paper] compares radial flow velocities at 0°, 90°, and 180° with the distribution device. At 20 mm from the inlet window [FIGURE:7(a)], radial velocity distributions exhibit gradual variation along the height due to insufficient flow development, with higher velocities at hole positions and lower velocities near walls. At 50 mm from the window [FIGURE:7(b)], radial velocity distributions become more uniform, all remaining below 1 m/s.

[Figure 8: see original paper] shows radial velocity distributions without flow distribution devices. At both 20 mm and 50 mm from the window, flow distribution remains non-uniform, with significant outflow in the 0° direction. Comparison with [Figure 6: see original paper] and [Figure 7: see original paper] confirms that flow distribution devices significantly improve inlet window flow uniformity.

A non-uniformity constant is defined based on radial velocity:

where V is the radial velocity at a given location (m/s), V is the average radial velocity at 50 mm from the inlet window (m/s), and N is the number of velocity extraction points.

Relative radial velocity is defined as:

presents the relative radial velocity V * range and non-uniformity constant V NUIq at 50 mm from the inlet window. With flow distribution devices, the maximum relative radial velocity ranges between 120–150%, and the maximum non-uniformity is below 0.35, demonstrating improved circumferential flow uniformity.

Conclusion

This study conducted CFD numerical simulations to investigate influencing factors and characteristics of sodium-side inlet flow distribution in China' s demonstration fast reactor steam generator. Parameter sensitivity analyses of flow equalizing grid height and inlet window structure revealed their impact on flow distribution, leading to an optimized flow distribution device design. Performance was quantitatively evaluated through comparative analysis of velocity distributions with and without the device, using a non-uniformity constant based on velocity definitions.

Results demonstrate that proper adjustment of flow equalizing grid and inlet window design improves distribution uniformity and thermal-hydraulic performance. The optimized configuration features a 1200 mm flow equalizing grid height and an inlet window structure with 40 holes in rows 1–4, 30 holes in rows 5–8, and 24 holes in rows 9–11. With the flow distribution device installed, circumferential and height-direction uniformity significantly improves. Although pressure loss increases slightly, overall flow characteristics are enhanced, with maximum relative radial velocity controlled within 120–150% and maximum non-uniformity index reduced below 0.35. At 50 mm radially from the inlet window, radial velocities in the 0°, 90°, and 180° directions all remain below 1 m/s.

These optimization results provide valuable flow distribution data and a theoretical basis for design and optimization of China' s demonstration fast reactor steam generator. Future research will extend to coupled sodium-water-steam flow and heat transfer analysis to further investigate uniformity effects on heat transfer performance and provide engineering design improvements.

Author Contributions

WANG Bo: Conceptualization; methodology; investigation; data curation; formal analysis. **GUO Shuo:** Data curation; writing–original draft. **ZHANG Dalin:** Formal analysis; writing–review & editing. **TIAN Wenxi:** Supervision; project administration. **QIU Suizheng:** Supervision; project administration. **SU Guanghui:** Supervision; project administration.

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