Parametric Investigation on the Measurement Accuracy of Differential Pressure System for Nuclear Power Plant Steam Generator

*ShengWen ZHOU, ZhengGang LI, Ying ZHU, XiuChen LI, MaoLong XIE**

Liaoning Hongyanhe Nuclear Power Co., LTD, Dalian, Liaoning, China, 116321

Corresponding author: Maolong Xie;Email: 373969710@qq.com

Abstract

Steam generator is an important equipment of nuclear power unit, and its flow rate is directly related to the operating power of the unit. Accurate flow measurement and monitoring is an effective prerequisite to ensure stable and long-term operation of the unit. However, when the pressure taking system is used to measure the steam flow rate, the phenomenon that the flow indication number is abnormal but the actual flow rate does not change occasionally often occurs, which affects the normal production operation. Based on the principle of differential pressure method, this study studied the influence of flow resistance and flow characteristics of waveform plate steam separator, an important part of steam generator, on flow measurement, and completed the analysis of waveform plate flow field and the establishment of benchmark model through numerical simulation. The uncertainty quantization method based on MOAT (Morris One at A Time) was used to analyze the sensitivity of the deviation factors affecting the accuracy of flow measurement at the waveform plate. By comparing MOAT mean and MOAT standard deviation, it is found that the assembly inclination angle of the corrugated plate is the most important factor affecting the measurement accuracy of flow rate, and should be the key check item during the maintenance of steam generator.

Key words: Steam Generator, Pressure Taking Measurement System, Corrugated Plate Separator, Computational Fluid Dynamics, Quantization of Uncertainty

1. Introduction

The steam generator (SG) is a critical component in nuclear power plants. Its primary function is to serve as a heat exchanger that transfers thermal energy from the primary loop coolant to the secondary loop feedwater, thereby generating saturated steam for secondary-side power systems. Due to the large diameter and high steam velocity in SG outlet pipelines, several challenges arise in steam flow measurement, including erosion of throttling components, reduced measurement accuracy caused by variations in saturated steam density, and damage to instruments from high-temperature media.

Youshen Shen [1] established a finite element numerical simulation model of the secondary side of the steam generator and performed numerical analysis on the flow field and characteristic parameters within the system. Liu Fei [2] investigated the mechanical properties of pipeline materials, providing a reference for routine equipment maintenance. Wang Zhiqiang et al. [3] proposed a feasible and rational flow measurement design scheme through the design of the main steam throttling components and differential pressure measurement system, ensuring accurate and stable measurement of main steam flow. Steam-water separators induce phase separation of gas and liquid through complex geometries, and both Chinese and international scholars have conducted research on their flow characteristics. Zeng Chunjie et al. [6] developed a full-scale model of the SG steam-water separation device and systematically studied the separation efficiency and its influencing factors. Xu Dehui et al. [7] examined the separation efficiency of swirl-vane separators through hot-state testing. Huang Zhen et al. [8] analyzed the separation mechanism and efficiency of swirl-vane separators by establishing computational models. Li Jia [9] investigated the factors affecting the separation efficiency of corrugated plate separators using a combination of experimental and numerical methods. Benjamin Ortner et al. [10] explored the effect of interfacial shear forces on flow characteristics inside the separator using computational fluid dynamics (CFD). Bo Hanliang et al. [11] studied droplet behavior in the flow field through multi-droplet CFD simulation, providing guidance for simulating water accumulation inside SGs. Haichuan Xu et al. [12] examined the separation stress and fatigue life of steam-water separators through a combination of theoretical and finite element analysis. Kvascev Goran S et al. [13] developed an adaptive feedwater flow control strategy based on steam parameters. In summary, existing research has successfully established numerical models for various SG components. However, studies on the effects of internal structural variations and assembly deviations on the overall flow characteristics remain insufficient.

This study, based on the differential pressure measurement principle, investigates the flow resistance and flow characteristics of the corrugated plate steam-water separator—an important component of SGs—and their impact on flow measurement. A numerical simulation model is developed to analyze the flow field of the corrugated plates. High-precision computational fluid dynamics (CFD) methods are employed to assess how the flow characteristics in the corrugated plate region contribute to abnormal steam flow readings, aiming to provide theoretical support and reference data for future development in the nuclear power sector.

2. Differential Pressure Measurement System in Steam Generators

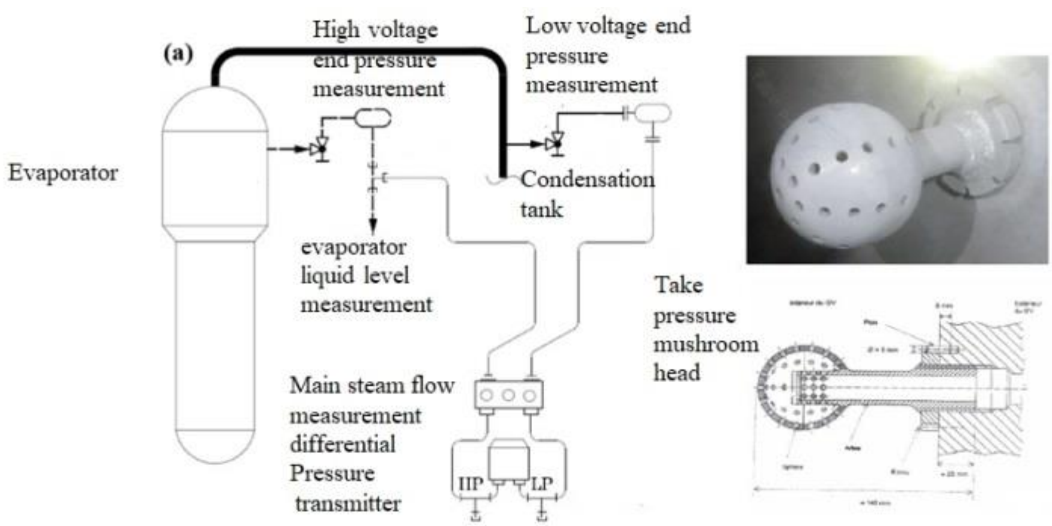
During the operation of a certain advanced Chinese nuclear power unit, a step-change phenomenon has been observed in the steam flow measurement readings. Specifically, after a period of operation, the measured main steam flow shows a sudden increase and exhibits larger fluctuations—despite post-maintenance inspections confirming that the actual flow rate remains unchanged. This phenomenon has persisted since the commissioning of steam generators (SGs) in the early 21st century and continues to impact the development of the nuclear power industry. Numerous studies have demonstrated that the steam flow rate is proportional to the square root of the differential pressure across the throttling device, as expressed by:

$$Q_{st} = K_1(\rho_v \Delta p)^{\frac{1}{2}} \tag{1}$$

where ρ_v is the fluid density at the measurement pressure, ΔP is the measured differential pressure, and K_1 is determined by boundary conditions and calibration data. Based on this principle, the internal flow stability of the steam generator directly affects the accuracy of differential pressure-based flow measurement.

The pressure tapping design for main steam flow measurement is shown in Figure 1a. The calculated flow rate is derived from the pressure difference between the high-pressure and low-pressure tapping points. In analyzing the step-change behavior of flow measurements, particular attention must be paid to two key characteristics: load-dependence and abrupt variation. The low-pressure tapping path primarily involves two 90° bends downstream of the evaporator outlet, where the flow is relatively stable and pressure loss is negligible, thus exerting minimal influence on the differential pressure measurement.

In contrast, the high-pressure tapping path involves multiple flow components, including the flow restrictor, swirl-vane separator (primary separator), and corrugated plate separator (secondary separator). Among these, the flow restrictor provides the primary throttling function and forms the fundamental basis of the differential pressure method for measuring main steam flow. Shi Zhilong et al. [4] used numerical simulations to analyze the flow field around the restrictor and investigated its protective role in reactor safety. Yang Xuelong et al. [5] conducted 3D numerical simulations to study the flow resistance and detailed flow structures within the restrictor, confirming its stable flow characteristics. Due to its high structural rigidity and stable internal flow, the restrictor is unlikely to cause step-changes in flow readings due to uncertainty.



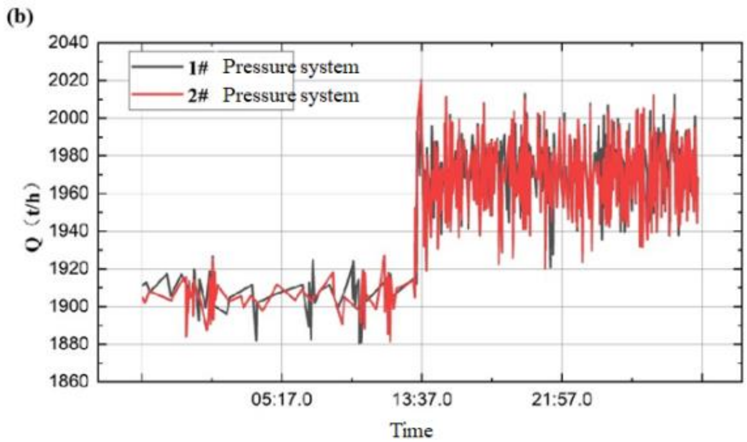


Figure 1. (a) Mass flow measuring system for steam generator; (b) monitored mass flow sudden increment phenomenon during operation.

However, as shown in Figure 1b, a step increase followed by stabilization is often observed in the measured main steam flow after a period of SG operation. A comparison with actual operating data confirms that the real steam flow remains unchanged, suggesting that the flow structure inside the SG may have altered over time, resulting in a step-change in sensor differential pressure. This abnormal pressure behavior is currently suspected to be associated with changes in the upper shell of the evaporator, which includes components such as the steam-water separator, restrictor, and throttle piping. A review of Chinese and international literature shows that existing research on the upper shell of SGs mainly focuses on the throttling characteristics and flow structures of restrictors, as well as the separation efficiency and structural fatigue of steam-water separators. Few studies have investigated the impact of internal flow structure alterations on abnormal flow measurement readings. Current research on restrictors and swirl-vane separators indicates that their internal geometries are stable and unlikely to cause significant variations in pressure loss within the SG. In contrast, the corrugated plate steam-water separator is characterized by low structural rigidity, low manufacturing precision, and complex flow geometry. Under high-temperature and high-pressure steam impact, it is prone to deformation, vibration, and other uncertain behaviors. Therefore, this study focuses on the detailed flow characteristics within the corrugated plate region and investigates how structural deviations influence flow resistance.

3. Research Methodology

At the initial stage of the study, a root-cause fault tree was established, as shown in Figure 2a, to identify possible uncertainty factors. On one hand, it is considered that many factors can influence local flow characteristics by altering the geometry of specific components, thereby increasing flow resistance and pressure loss. Such structural influences may originate from assembly errors—particularly relevant to components like the corrugated plate separator that require complex assembly processes—including lateral misalignment and inclination angle deviations. Flow-induced deformation is another major factor, where pressure from the fluid applies loads to non-rigid walls, causing deformation or vibration. Water accumulation—such as droplets attaching to the surface—can restrict local flow, thus significantly disturbing nearby flow fields.

On the other hand, certain parameters may not only influence overall flow resistance but also interact with the structural factors above, leading to coupled effects that further amplify pressure loss. In this study, macro-level uncertainties such as wall roughness, humidity, and material properties (e.g., Young's modulus) are considered as influencing factors.

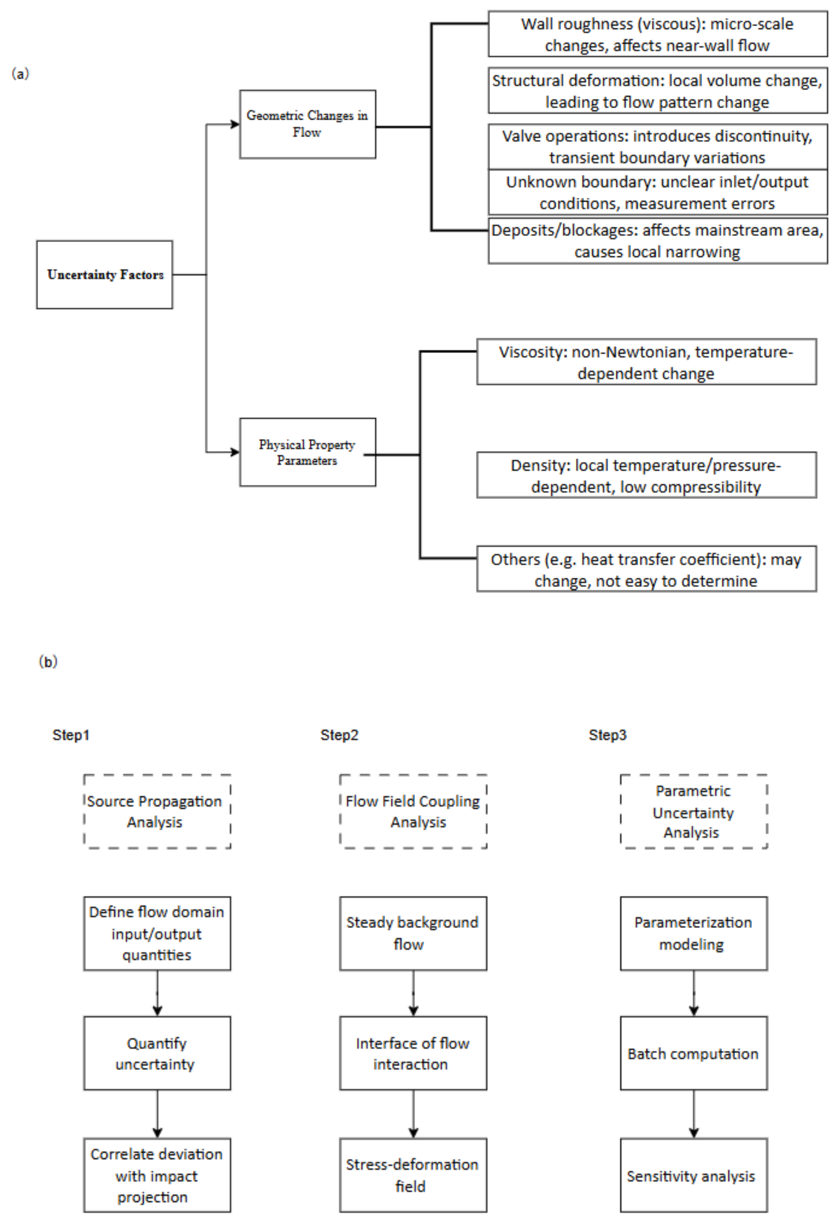


Figure 2. (a) Root-cause fault tree for analyzing factors contributing to flow rate step change; (b) Technique route to quantify the effects of wavy-plates separator.

For the corrugated plate separator itself, the research methodology is outlined in Figure 2b, consisting of the following steps: Based on 2D blueprints and partial 3D models of the SG, the fluid domain is extracted, discretized with a 3D mesh, and simulated using high-fidelity computational fluid dynamics (CFD). This captures detailed flow field data (velocity, pressure distribution, wall pressure, etc.), which enables establishing a connection between uncertain parameters and pressure tapping accuracy on both the high- and low-pressure sides. Based on the above CFD framework, a combination of uncertainty quantification techniques, including Morris screening, adaptive surrogate models, sensitivity analysis, and kernel density estimation, is employed to evaluate the interaction and influence of multiple uncertain parameters, ultimately yielding a distribution of sensitivity metrics. Structural simulations are carried out using finite element methods and solid domain meshing. A one-way fluid–structure interaction (FSI) is implemented by mapping fluid pressure loads onto solid boundaries, enabling analysis of how fluid-domain uncertainty propagates into the structural domain. Based on feedback from each SG maintenance cycle, the findings are validated and used to refine subsequent research directions, forming a positive feedback loop. The entire study is built upon a CFD-based framework, supplemented with uncertainty quantification methods for sensitivity and reliability analysis, forming a comprehensive and systematic understanding of the problem.

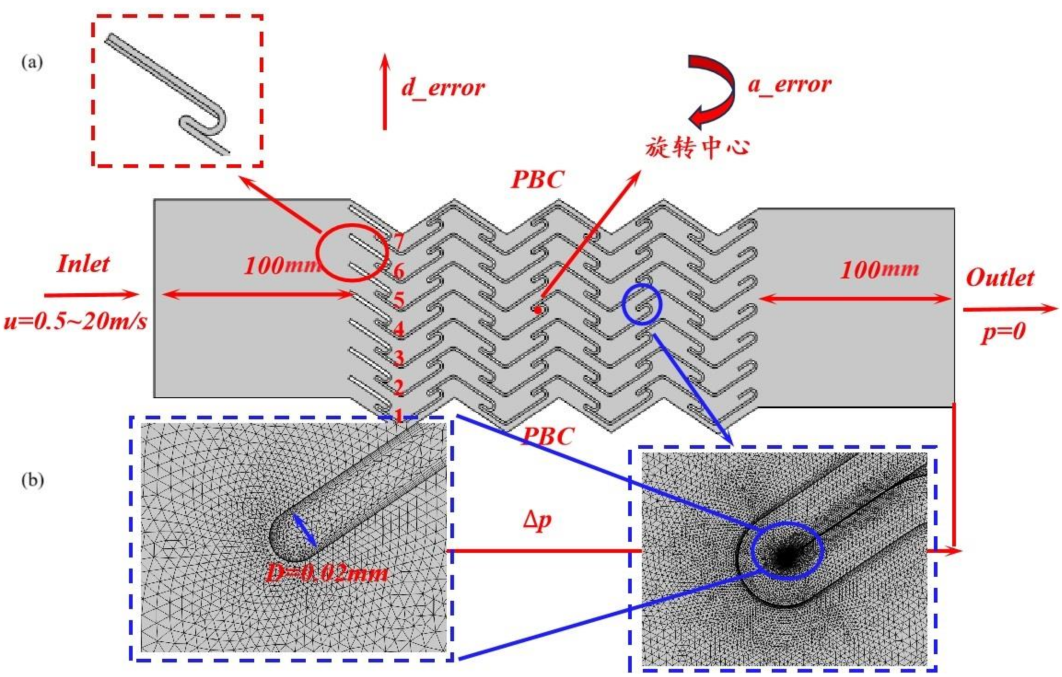


Figure 3. Numerical Model for Corrugated Plates Flow Field (a: Boundary Conditions, b: Meshing)

As shown in Figure 3, a numerical model was developed for the flow region of the SG corrugated plate separator. Given that the spanwise height of the separator (~1 m) is significantly greater than its streamwise characteristic scale (inter-plate spacing ~5 mm), a 2D numerical model is used to focus on streamwise flow features. To ensure fully developed flow, 100 mm-long channels were added upstream and downstream of the simulation domain. Seven identical plates were arranged in parallel with a spacing of d = 5 mm in the core flow region. Boundary conditions were set as follows: Inlet: velocity boundary condition, uin=0.5~20m/s, covering all typical operating conditions. Outlet: static pressure boundary, pout=0. Top and bottom boundaries: periodic boundary conditions (PBC), mimicking the continuous stacking of plates in actual SGs.

It is worth noting that, due to the steam-water separation process, water accumulation tends to occur at the first curved section of the plate inlet. To replicate this, the wall of the first segment is parametrically thickened in the model.

Three uncertain input variables are defined:

Lateral assembly deviation (transverse displacement of the central plate),

Assembly inclination angle (rotation of the central plate about its centroid),

Thickness of the water film deposited at the plate inlet.

The quantity of interest is defined as the pressure drop between inlet and outlet, representing the flow loss through the corrugated plates. A non-structured adaptive mesh was used to discretize the model, with a total of 371k cells. Model verification was conducted using three mesh densities:

① Mesh A: 265k cells (max ΔP = 520 Pa)

② Mesh B: 371k cells (max ΔP = 600 Pa)

③ Mesh C: 450k cells (max ΔP = 605 Pa)

The difference between Mesh B and Mesh C is within 0.8%, so Mesh B was chosen for this study. The simulation result for Mesh B closely matched the on-site measurement of 590 Pa, with only 1.7% error, which is acceptable for engineering applications.

In this study, an incompressible k-ε turbulence model was employed to solve the flow field, with wall functions applied for near-wall treatment. A first-order polynomial discretization scheme was used, meaning that linear shape functions were adopted for solving the velocity and pressure fields.

Since a primary swirl-vane separator is installed upstream of the corrugated plate separator, the majority of steam droplets are already separated before reaching the corrugated plates. Thus, the inlet to the corrugated plate can be considered as high-temperature dry steam. As a result, a single-phase flow model was adopted for subsequent numerical simulations, which were performed using the COMSOL Multiphysics simulation software. For uncertainty quantification, the MOAT method (Morris One-At-A-Time) was adopted. A sample space of 16 cases was used, with single-variable stepwise variation. The method evaluates the correlation between input variables and the pressure drop across the corrugated plate.

The MOAT method is a lightweight global screening algorithm that qualitatively and quantitatively assesses the importance of each input parameter with relatively low computational cost. The procedure includes:

① Initialize a base input sample and set the number of iterations.

② Use CFD to solve the flow field for the current set of input parameters.

If the maximum iteration count is not reached, one input variable is perturbed by a defined step while others remain constant. The flow field is re-solved and the change in output is used to calculate local sensitivity. For each variable, compute the mean and standard deviation of local sensitivities, yielding the MOAT mean and MOAT standard deviation. A high MOAT mean indicates a strong influence of that parameter on the quantity of interest, revealing its relative importance. A high MOAT standard deviation suggests a more complex or nonlinear impact, possibly due to variable coupling or internal nonlinearities.

4. Results and Discussion

4.1 Flow Field Structure Analysis

A reference model for the steam generator was established with an inlet velocity of u=1.0 m/s, no assembly error, and no water-film accumulation at the inlet. The results from modified configurations—rotation of the corrugated plate, vertical displacement, and water film presence—were compared against the reference case, as shown in Figure 4. The simulation results indicate that the flow loss in the reference case ranged between 500–600 Pa, and the flow exhibited good periodicity in both the streamwise and spanwise directions. A clear main flow channel formed between adjacent plates, with a peak local velocity of approximately 4.5 m/s due to the throttling effect. Flow stagnation zones were also observed in the grooves of each plate, which are beneficial for gas-liquid separation. When the central plate was rotated by 2°, the flow area between it and adjacent plates was compressed, creating two narrow passages and intensifying the throttling effect. This also led to a significant distortion in the pressure field compared to the baseline case. Conversely, a 2 mm upward displacement of the central plate widened the lower flow path, increasing local velocity without causing notable pressure distortion. Since the water film is located outside the main flow channel, its effect on the velocity and pressure fields was negligible. To quantify the impact of these factors on flow resistance, uncertainty quantification techniques were applied.

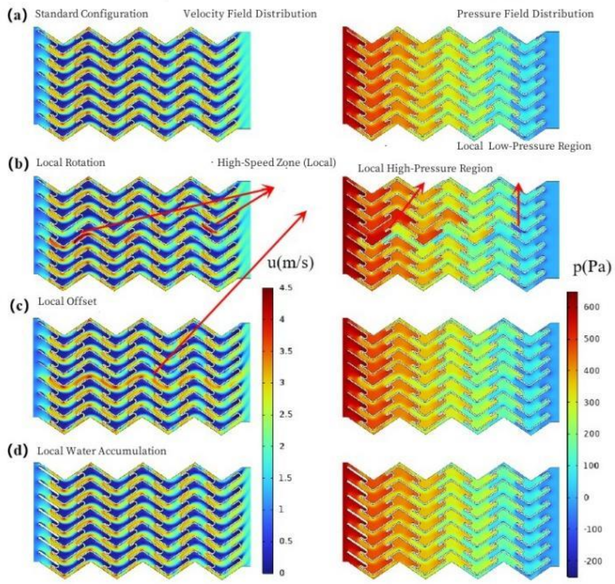


Figure 4. Flow Field Results(a) Standard(b) Rotation (2°)(c) Vertical Displacement(2mm) (d) Water Film (1 mm)

4.2 Uncertainty Quantification Analysis

The following probability distributions were assigned to the uncertain input parameters:

Lateral assembly deviation ~ N(0,0.5) mm;

Assembly inclination angle ~ N(0,1)deg;

Water-film thickness ~ U(0.25,1.5) mm.

Where N(μ,σ) is a normal distribution and U(a,b)is a uniform distribution.

Uncertainty quantification was carried out using the MOAT (Morris One-At-a-Time) method. The results are shown in Table 1.

Table 1. MOAT Results

Uncertainty Parameter	MOAT Mean	MOAT Std. Dev.
Lateral Deviation	148.63	193.70
Inclination Angle	2802.23	2804.31

Water-Film Thickness	197.65	26.65

Comparison of MOAT means shows that inclination angle is significantly more influential than other parameters, indicating that slight angular deviations during assembly can greatly affect the flow resistance. The high MOAT standard deviation of the inclination angle suggests considerable nonlinearity, possibly due to complex coupling effects or intrinsic nonlinearity of the variable.

The flow field structure analysis provides physical insight into these results. The main flow channel between plates is the key determinant of flow resistance. Lateral displacement alters the width of adjacent channels, increasing throttling on one side but reducing it on the other, resulting in a net cancellation. Therefore, the impact on overall pressure drop is minimal. The water film is located outside the high-speed flow region, contributing little to the pressure drop. In contrast, even small inclination angles compress both side channels, intensify local throttling, and disrupt flow direction, leading to turbulence and instability. These findings are further validated by the Sobol sensitivity analysis results shown in Figure 5.

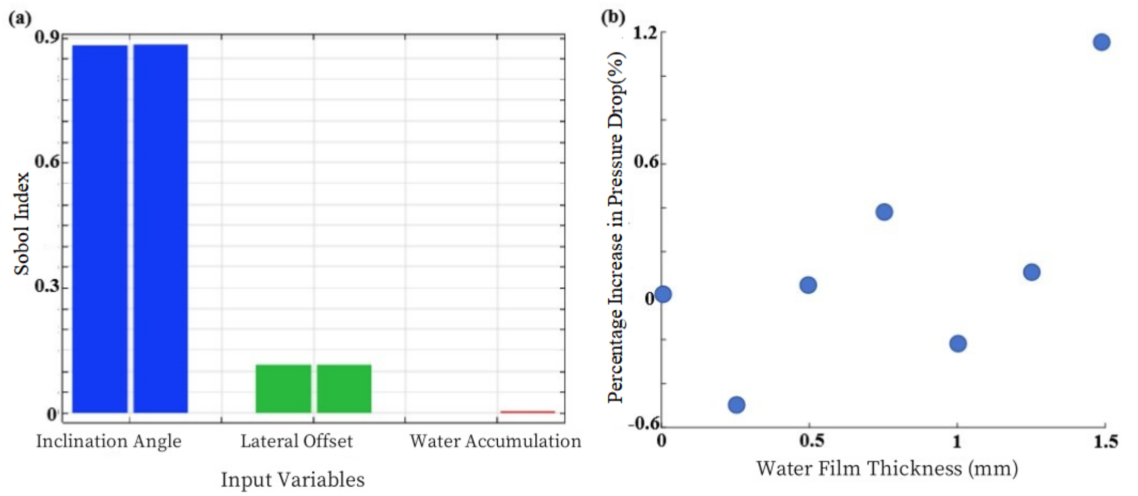


Figure 5. (a) Sobol Sensitivity Analysis (b) Effect of Water-Film Thickness on Pressure Drop

4.3 Flow-Induced Deformation Analysis

This section investigates flow-induced deformation at different vertical locations on the corrugated plates and evaluates its influence on flow resistance within the SG. A one-way fluid–structure interaction (FSI) model was used, focusing only on how the fluid affects structural deformation, while neglecting any feedback from deformation to the flow field. Unlike the previous 2D flow-only model, this simulation treats the corrugated plates as solid structures. The interface between fluid and structure (plate surfaces) was set as an interface boundary instead of a no-slip wall. Fixed constraints were applied at both upstream and downstream ends of the plate to simulate actual mounting conditions.

The process involves extracting pressure distributions from background CFD simulations and applying them as loads to the structural domain, which are then used to compute stress–strain responses. Deformation results under various inlet velocities are shown in Figure 6. At u=5 ,15 m/s, deformation was negligible. As velocity increased, noticeable deformation appeared (magnified ×10 for clarity). At the maximum velocity of u=50 m/s, the structure experienced a deformation of approximately 1.2 mm.

These findings suggest a time-accumulated effect of deformation, and a positive correlation between inlet velocity and deformation magnitude. When deformation becomes significant, it can alter the geometry of the flow domain, affecting pressure drop and potentially causing the observed step-change in flow readings.

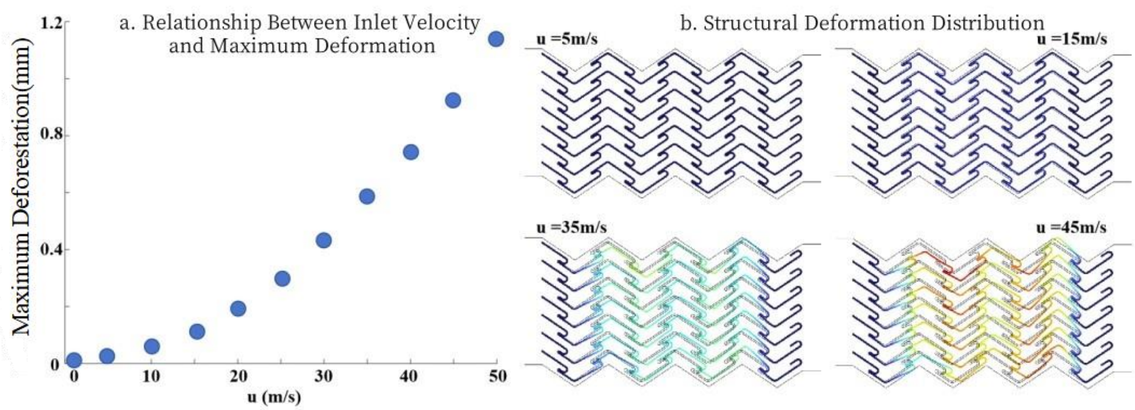


Figure 6. (a) Relationship Between Inlet Velocity and Maximum Deformation (b) Structural Deformation Distribution

5. Conclusion

This study investigates the phenomenon of fluctuating flow measurements in steam generators (SGs), tracing the issue to pressure variation between high- and low-pressure tapping points induced by internal flow structures. The corrugated plate steam–water separator was identified as a key component, and its influence was analyzed in terms of assembly uncertainties, water accumulation, and flow-induced deformation.

Using high-precision CFD simulations, the MOAT method was employed to assess the effects of three input parameters: lateral assembly deviation, inclination angle, and water-film thickness on the flow resistance. Flow field visualizations and structure analysis revealed that the inclination angle had a significant impact on throttling behavior between plates, far exceeding the sensitivity of the other two variables.

The MOAT mean value for the inclination angle was 2,802.23, over 14 times greater than that of the other variables. Its first-order Sobol index and total Sobol index were both above 0.85, identifying it as the dominant parameter. Even a small angular deviation can generate two narrow high-resistance flow paths and cause substantial distortion in velocity and pressure fields.

Based on these results, it is recommended that special attention be paid to potential plate inclination during SG maintenance and inspection, as this may be a primary cause of step-change flow reading anomalies.

References

[1] Shen, Y., Study on Flushing Technology for Tube Sheet on the Secondary Side of Nuclear Power Steam Generator Based on Numerical Simulation, Cleaning World, 40 (2024), 3, pp. 63–66+69

[2] Liu, F., Discussion on Welding Technology for In-Service Replacement of Nuclear Power Plant Steam Generator, Welding Technology, 53 (2024), 4, pp. 63–67

[3] Wang, Z. Q., Mo, D., Zhang, N., Design Scheme of Main Steam Flow Measurement for Nuclear Power Plant, Pipeline Technology and Equipment, (2021), 4, pp. 16–19

[4] Shi, Z. L., Meng, J., Song, Y. X., et al., Flow Field Analysis and Structural Optimization of Steam Generator Restrictor, Chemical Equipment Technology, 39 (2018), 1, pp. 27–30

[5] Yang, X. L., Feng, J., Zhang, Q., et al., Influence of Steam Restrictor Structure on Flow Resistance and Flow Field Details, Nuclear Power Engineering, 36 (2015), 4, pp. 23–27

[6] Zeng, C. J., Wang, M. J., Tian, W. X., et al., Development of a Full-Scale Steam-Water Separation Device Model for Steam Generators, Atomic Energy Science and Technology, 56 (2022), 11, pp. 2253–2261

[7] Xu, D. H., Gu, H. Y., Liu, L., et al., Thermal State Test and Numerical Study of a New Conical Swirl-Vane Steam-Water Separator, Journal of Shanghai Jiao Tong University, 55 (2021), 9, pp. 1087–1094

[8] Huang, Z., Yan, X., Xiao, Z. J., et al., Study on Separation Efficiency Model of Swirl-Vane Steam-Water Separator, in: Proceedings of the 2017 Annual Meeting of the Chinese Nuclear Society (Eds. China Nuclear Power Research and Design Institute), Vol. 3, 2017, pp. 7

[9] Li, J., Theoretical and Experimental Study on Corrugated Plate Steam-Water Separator, Ph. D. thesis, Huazhong University of Science and Technology, Wuhan, China, 2007

[10] Ortner, B., Schmidberger, C., Prieler, R., et al., Analysis of the Shear-Driven Flow in a Scale Model of a Phase Separator: Validation of a Coupled CFD Approach Using Experimental Data from a Physical Model, Int. J. Multiphase Flow, 177 (2024), 104852

[11] Liu, Z. W., Bo, H. L., Three-Dimensional Euler Grid Approximation Method for

Multi-Droplet Motions in the Steam-Water Separator, Case Studies in Thermal Engineering, 51 (2023)
[12] Xu, H. C., Zhang, H., Sun, H. L., Stress Calculation and Analysis of a 600MW Supercritical Boiler's Steam-Water Separator, E3S Web of Conferences, 261 (2021), 01050
[13] Kvascev, G. S., Zahirovic, D. M., Water Level Control in the Thermal Power Plant Steam Separator Based on New PID Tuning Method for Integrating Processes, Energies, 15 (2022), 17, 6310

- Paper submitted: 26 April 2025
- Paper revised: 18 June 2025
- Paper accepted: 18 June 2025