Optimization of a HRSG Inlet Duct Design for Improved Flow Uniformity for HTGR Applications

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1. Introduction

In the modern energy industry, enhancing energy efficiency while minimizing environmental impact is becoming increasingly important. The High-Temperature Gas-cooled Reactor (HTGR) is gaining attention as a next-generation reactor technology that offers high thermal efficiency, and the role of the Heat Recovery Steam Generator (HRSG) is crucial for the effective operation of such systems [1]. The HRSG efficiently recovers waste heat generated by the reactor, converts it into steam, and supplies it to a steam turbine for additional power generation. However, if the HRSG is not optimally designed, flow non-uniformity can lead to reduced heat recovery efficiency, negatively impacting the overall system performance [2]. Therefore, the optimal design of the HRSG is essential to maximize the thermal efficiency of the HTGR system and minimize energy losses.

This study aims to address these issues by optimizing flow uniformity in the HRSG to enhance system performance. By utilizing the parametric study methodology, we derive an optimal flow uniformity design based on various design parameters and analyze how the HRSG can operate efficiently within the HTGR system. Previous studies have analyzed HRSG configurations in gas-cooled nuclear systems, demonstrating their impact on overall system efficiency [3]. This research clearly demonstrates how HRSG optimization can contribute to improving reactor system performance and is expected to play a key role in achieving sustainable development goals.

2. Methods and Results

The goal of this study is to optimize flow uniformity within the HRSG of an HTGR system to improve thermal efficiency. To achieve this, Ansys Fluent 2023 was used to analyze flow characteristics under various design parameters and derive the optimal design strategy.

The CFD simulations were based on the Navier-Stokes equations and the RANS model, with the k-ε turbulence model applied. The simulations were performed using the finite volume method (FVM), which accounts for mass, momentum, and energy conservation in the fluid flow.

Previous studies have analyzed gas flow behavior in HRSG ducts and shown that shape modifications significantly affect flow uniformity [4].

This study analyzes the impact of various design parameters on flow distribution, while considering geometric constraints that limit shape modifications to a 50% range of the initial design. The optimal duct design is derived based on these considerations.

Based on the initial duct model, a total of 16 design variables were defined by creating four variables each for length, top, bottom, and width. These variables played a key role in evaluating the flow uniformity within the duct.

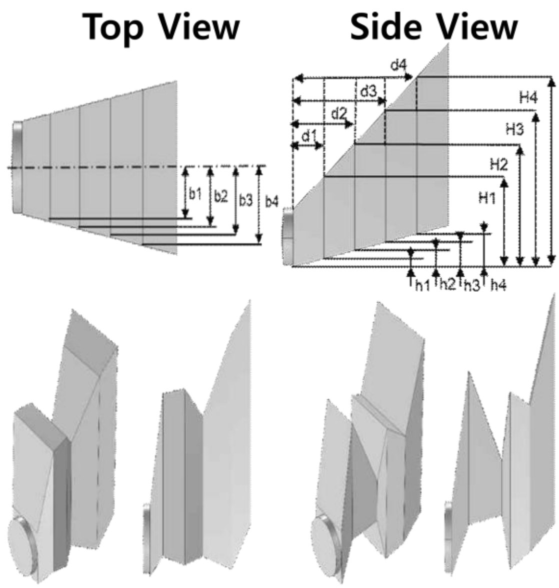

Fig. 1. 16 parameter setting conditions and two different arbitrarily generated metamodels

Using the Optimal Latin Hypercube Design (OLHD) method, a total of 160 experimental points were generated based on combinations of design variables. Through CFD analysis, the Root Mean Square (RMS) values at each duct outlet were calculated. Here, the RMS indicates the degree to which the flow exits uniformly at the outlet, and it is calculated using the following formula.

$$U_{rms} = \sqrt{\frac{\sum \omega_i (u_i - U)^2}{\sum \omega_i}}$$

ω_i : Surface Area of Each Mesh Cell
u_i : Velocity in Each Mesh Cell
U : Average Velocity

CFD analysis was conducted on 160 different shapes, including the shapes in Fig. 1. After completing the CFD analysis, an objective function was used to calculate the RMS values at the outlet for all 160 models.

Using the parameter setting conditions shown in Fig. 1, 160 parameter variable values were designated through the OLHD sampling technique, and RMS values were derived using eight different metamodeling techniques. The process of deriving RMS results with these eight metamodeling techniques is part of selecting the metamodeling technique to be used for creating the final optimized model. Later, by comparing the results of each metamodeling technique with the CFD results, we plan to select the metamodeling technique with the smallest margin of error for optimization.

Table I: Exhaust Gas Profile

	Value	Unit
Exhaust Gas Flow	755.3	Kg/s
Exhaust Gas Temperature	651	℃
Exhaust Gas Axial Velocity	55.2	m/s
Exhaust Gas Radial Velocity	2.4	m/s
Exhaust Gas Tangential Velocity	-13.7	m/s

Table I presents the boundary conditions of the entrance applied during the analysis. These boundary conditions are identically applied when analyzing 160 different shapes to derive the results of the analysis.

In this research, metamodeling and optimization techniques were applied to optimize flow uniformity in the inlet duct of the HRSG. Metamodeling is a mathematical modeling technique used to estimate the relationship between inputs and outputs of complex systems, allowing for the efficient derivation of optimal designs through the collection and analysis of experimental data.

The metamodel was generated using the Radial Basis Function Regression (RBF_r) technique. This model was constructed based on 160 experimental data obtained through parametric study. Each data point includes the design variables of the duct, and the velocity RMS values at the outlet cross-section.

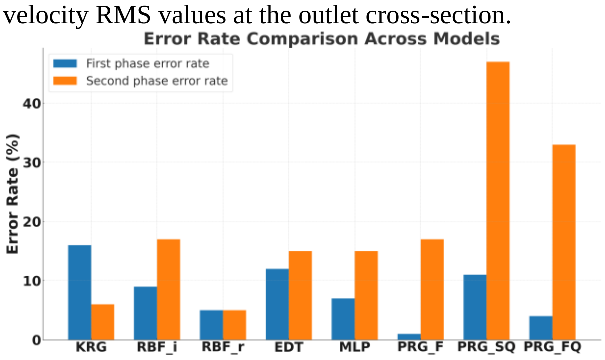

Fig. 2. A chart of error rates between the results of metamodeling and CFD analysis

The metamodel was generated using various metamodeling techniques, and to verify the reliability of the generated metamodel, two validation values were randomly selected and compared with the CFD analysis results. As shown in the table of Fig. 2, the data were mapped nonlinearly, and the RBF_r technique, which effectively captures severe nonlinearity through linear regression, exhibited the lowest error. Additionally, the error rate of the results from two trials showed no significant difference compared to the results obtained using other metamodeling techniques. Therefore, it was decided to proceed with shape optimization using the RBF_r technique.

To optimize the shape using the RBF_r metamodeling technique, the Hybrid Metaheuristic Algorithm (HMA) was applied to derive the optimal duct shape. This HMA algorithm efficiently searches for the optimal point within a complex design space by utilizing the metamodel. Therefore, after efficiently exploring the optimal point with the HMA algorithm, the RBF_r metamodeling technique is used to create the optimal shape.

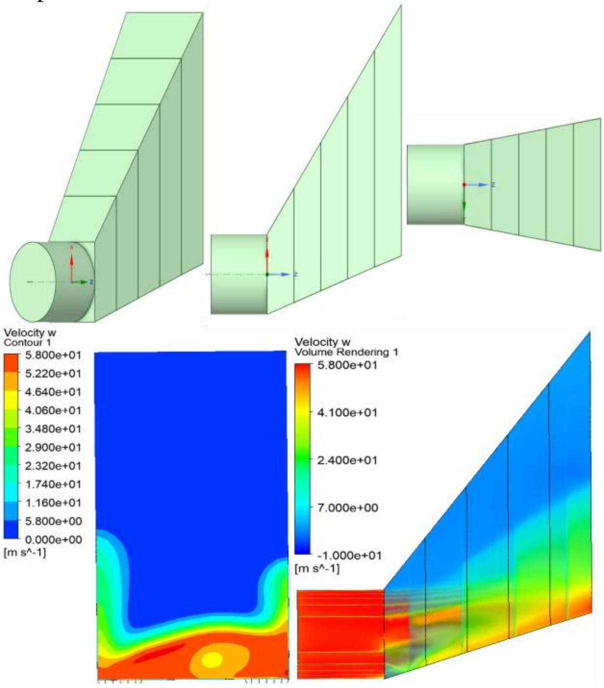

Fig. 3. The initial duct shape and CFD Result before optimization

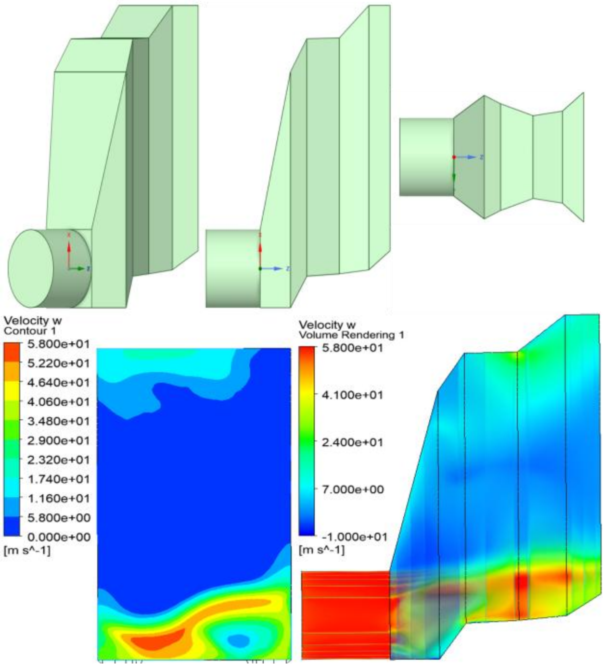

Fig. 4. The optimized duct shape and CFD Result before optimization

Fig. 3 shows the shape and CFD results of the initial model before optimization, highlighting the significant difference in flow velocity between the lower and upper parts of the outlet. The asymmetry in the flow distribution can be attributed to the high-temperature, high-velocity fluid entering the duct. The initial shape was designed with a sloped surface at the inlet, aiming to distribute the concentrated flow at the bottom of the duct toward the upper part. However, due to the high temperature and velocity of the fluid, rather than spreading the flow upwards, the fluid tends to remain concentrated at the bottom, leading to the observed asymmetry in the CFD results.

To achieve a more uniform flow at the outlet, optimization was conducted. The optimal shape created using the HMA algorithm and RBF_r metamodeling technique is presented in Fig. 4. Fig. 4 illustrates the shape of the duct after optimization and the CFD results for that shape. The optimization resulted in a change at the upper part of the duct outlet, where the flow velocity was relatively low, by redistributing the flow that was concentrated at the bottom in the initial model.

3. Conclusions

This research focused on optimizing flow uniformity in the inlet duct of the HRSG within an HTGR system to improve thermal efficiency. Using parametric study and metamodeling techniques, the optimal design was derived based on various design parameters, and the design's effectiveness was validated through CFD analysis.

As a result of the study, the optimized HRSG design significantly improved flow uniformity. This means that the flow distribution at the duct outlet became more uniform, as measured by a 22% reduction in RMS values. Flow optimization contributed to improving the quality of steam delivered to the steam turbine, thereby enhancing overall system performance.

Although the desired complete flow uniformity was not fully achieved, the flow distribution has significantly stabilized compared to the initial model results, showing a marked improvement in performance.

This study demonstrated that flow optimization within the HRSG is essential for enhancing the performance of the HTGR system and suggests that it can contribute to improving the energy efficiency of nuclear power plants. Future research aims to conduct higher-precision CFD analyses and apply the findings to actual HRSG systems to demonstrate the practical applicability of the study through experimental data. This study is expected to aid other research efforts focused on improving HTGR system performance.

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