Preliminary Analysis of Thermal-Hydraulic Performance for a Helium–Water Helical Coil Heat Exchanger Using MARS-KS

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***Keywords : Helical coil, Heat Exchanger, Helium-Water, MARS-KS**

1. Introduction

To achieve carbon neutrality in industry, it is essential not only to decarbonize power generation but also to replace the large-scale process heat required in sectors such as steel and petrochemicals with low-carbon heat sources. Accordingly, the High-Temperature Gas-Cooled Reactor (HTGR), which can stably supply high-temperature thermal energy, is garnering significant attention as a key alternative. Based on the MHTGR development experience [1], the United States is currently advancing the TRISO-fueled Xe-100 reactor [2] toward the demonstration and commercialization stages. Similarly, Japan has continued to evolve its high-temperature heat utilization technologies based on the operational experience of the HTTR [3]. Furthermore, China is expanding the applications of industrial process heat supply through the demonstration of small modular high-temperature gas-cooled reactors, such as the HTR-PM [4]. In line with these international trends, the development of the Helium Cooled Thermal Application Reactor (HECTAR) is being promoted in Korea with the objective of providing high-temperature industrial process heat.

The HECTAR (Helium Cooled Thermal Application Reactor) system employs a helical coil steam generator to efficiently deliver the thermal energy required for industrial processes. This heat exchanger is characterized by a helical tube-bundle configuration, which maximizes the heat-transfer area per unit volume. Such a design is advantageous for achieving a compact arrangement and offers structural benefits by effectively accommodating thermal expansion under high-temperature operating conditions. Regarding the thermal-hydraulic behavior within the steam generator, the feedwater on the secondary side (inside the tubes) flows upward from the feedwater inlet and receives heat from the helium coolant on the primary side. During this process, the fluid undergoes a phase change from saturated water through a two-phase flow regime to superheated steam. Conversely, the high-temperature helium flows downward through the flow path outside the tubes, accompanied by single-phase gas heat transfer and a pressure drop.

Reliable prediction of these complex thermal-hydraulic behaviors requires the application of a high-fidelity system analysis code. Currently, the GAMMA+ code is widely utilized for the safety analysis of HTGRs to evaluate thermal-hydraulic responses under both steady-state and accident conditions. Alternatively, the present study utilizes the MARS-KS code to investigate the detailed thermal-hydraulic performance of the steam generator. MARS-KS, a representative best-estimate system code developed for the light-water reactors (LWRs), has demonstrated high reliability in modeling two-phase flow and water heat transfer. In addition, it possesses the capability to support helium fluid properties and heat transfer models. These features indicate the high potential for applying MARS-KS to the analysis of helium-water heat exchangers, such as the steam generator in the HECTAR system.

In the present study, a preliminary thermal-hydraulic analysis of the HECTAR steam generator was performed using the MARS-KS code based on its design specifications. The objective of this work is to examine the applicability and predictive trends of MARS-KS for a helium–water helical coil heat exchanger, thereby establishing a technical foundation for the future advancement of detailed thermal-hydraulic performance analysis.

2. MARS-KS Modeling of Steam Generator

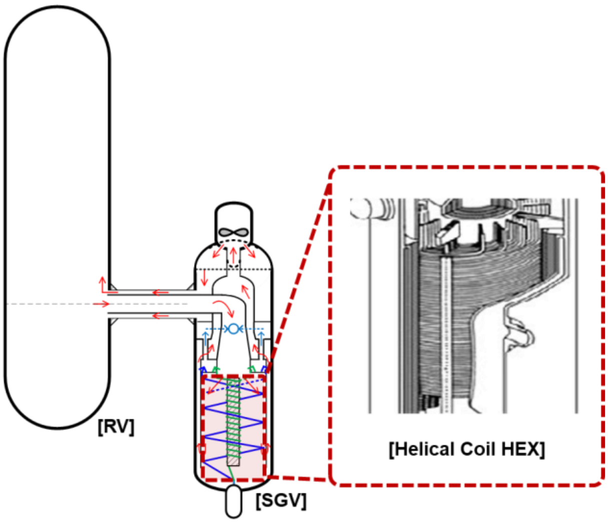

Fig. 1. Schematic diagrams of HECTAR Steam generator. [5]

In this study, thermal-hydraulic simulations were performed for the conceptual design of the HECTAR steam generator to verify the applicability of MARS-KS v2.0 to helium-water helical coil heat exchangers. As illustrated in Fig. 1, the target device features a heat exchange structure where high-temperature helium from the reactor vessel flows along the flow path outside the tube bundle, transferring thermal energy to the water/steam system inside the tubes.

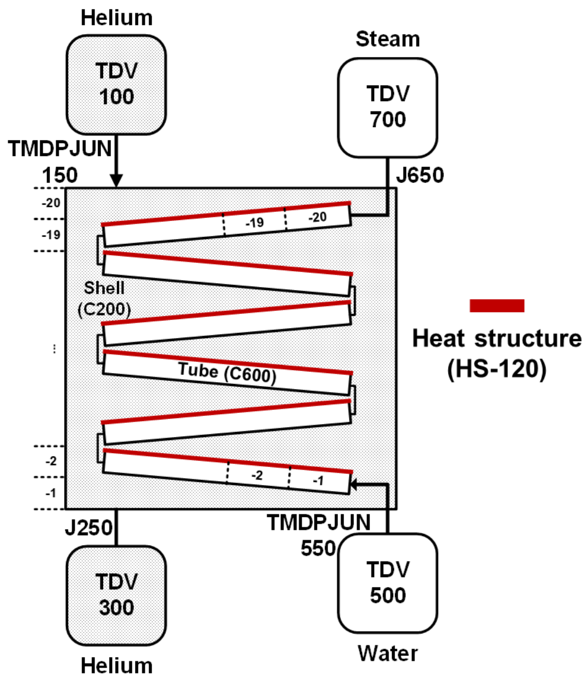

Fig. 2. Nodalization of the helium-water helical coil heat exchanger.

The MARS nodalization scheme for the helium-water helical coil heat exchanger is illustrated in Fig. 2. For the primary side, the time-dependent volume, TDV-100, was used to provide the inlet boundary condition for the helium. The inlet flow rate of the helium was controlled by the time-dependent junction, TMDPJUN-150. Helium is injected into the pipe component, C200, from TDV-100. This pipe component was used to model the test section, which was discretized into 20 subvolumes to calculate the thermal-hydraulic behavior, pressure drop, and axial state variations of the single-phase helium flow. The time-dependent volume, TDV-300, was used to provide the boundary condition for the helium pressure outlet.

Similarly, for the secondary side, the time-dependent volume, TDV-500, was used to provide the inlet boundary condition for the water. The inlet flow rate of the water was controlled by the time-dependent junction, TMDPJUN-550. The pipe component, C600, was used to model the secondary side with 20 subvolumes to simulate the phase change, two-phase flow behavior, and pressure drop resulting from the heating process. The time-dependent volume, TDV-700, was used to provide the boundary condition for the steam pressure outlet.

The heat structure, HS-120, was used to calculate the heat transferred from the primary helium side to the secondary water/steam side by thermally coupling C200 and C600. In the heat transfer modeling of the structure, Boundary Condition type 114 (Helical S/G tube side) was applied for the simulation of heat transfer inside the tubes. For the heat transfer simulation on the tube exterior, Boundary Condition type 160, which incorporates the Zukauskas heat transfer correlation for staggered bundle cross-flow on the shell side, was utilized [6]. Through this approach, the heat transfer characteristics were accurately reflected for both the phase change and two-phase flow conditions inside the tubes as well as the single-phase gas flow conditions of the helium on the shell side

3. Simulation Results

The calculation results obtained from the MARS-KS simulation are presented in Fig. 3, Fig. 4 and Fig. 5. To evaluate the predictive capability of the modeling, all calculated parameters were compared with the target values based on steady-state data, which were extracted after a sufficient transient period had elapsed to ensure numerical convergence.

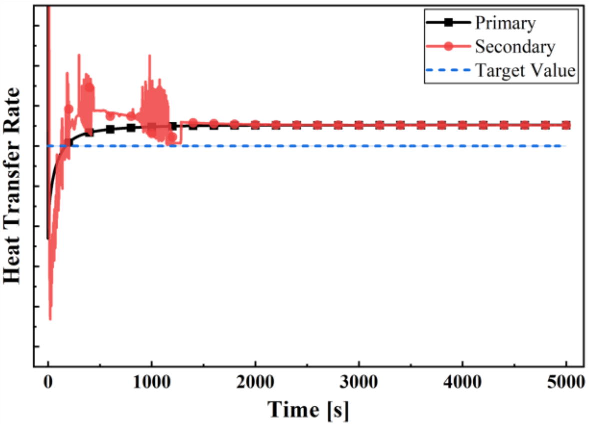

Fig. 3. Variation of heat transfer rate for helium-water helical coil heat exchanger according to time.

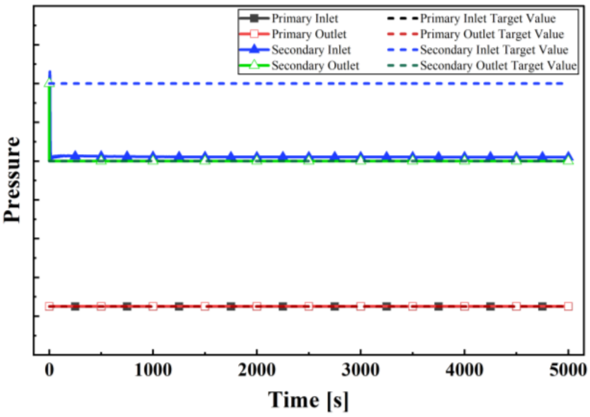

Fig. 4. Variation of pressure for helium-water helical coil heat exchanger according to time.

Fig. 3 shows the transient behavior of the heat transfer rate. Upon reaching a steady-state condition, the simulation results showed a reasonable agreement with the target value, maintaining an error rate of approximately 6%. Fig. 4 illustrates the comparison of the inlet and outlet pressures for both the primary and secondary sides over time. Following steady-state convergence, the primary inlet and outlet pressures, along with the secondary outlet pressure, were found to be in good agreement with the target values, exhibiting a low error rate of about 2%. However, a significant discrepancy of approximately 30% was observed in the secondary inlet pressure, indicating a notable deviation from the target value. Fig. 5 presents the temporal variations of the inlet and outlet temperatures for the primary and secondary sides. The simulation results generally followed the overall trend of the target values, with an error rate of about 5% at steady-state. Consequently, while the heat transfer rate, primary-side pressures, and all temperatures were successfully reproduced within an acceptable range, a relatively large difference was identified in the secondary inlet pressure. The analytical model and its constitutive relations will be continuously reviewed to enhance its applicability for secondary-side pressure drop calculations.

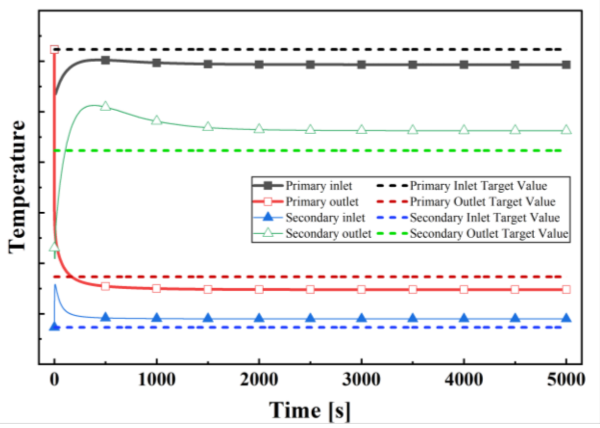

Fig. 5. Variation of temperature for helium-water helical coil heat exchanger according to time.

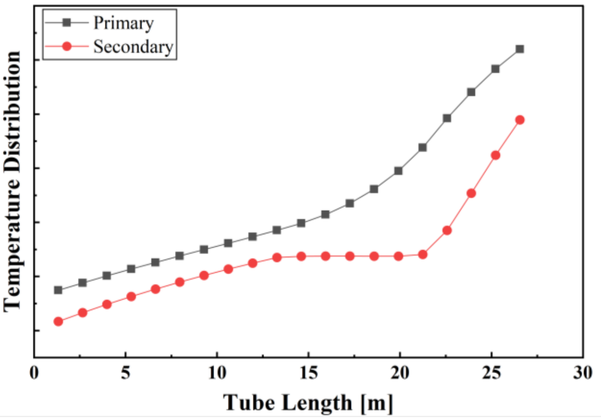

Fig. 6. Temperature distribution for helium-water helical coil heat exchanger according to tube length.

Fig. 6 illustrates the axial temperature distributions of the primary and secondary sides at 5000 seconds, which corresponds to the steady-state condition determined from Fig. 5. The origin of the axial coordinate is defined as the inlet location where the feedwater enters the secondary-side tube. Since the primary helium maintains a single-phase gas flow, its temperature varies continuously along the tube length, and no temperature plateau associated with phase change is observed. In contrast, because phase change from water to steam occurs on the secondary side, the characteristics of the phase change region are clearly observed in the axial temperature profile. Specifically, a constant temperature region resulting from the phase change appears between approximately 15 m and 21 m, suggesting the existence of a two-phase flow region during the transition from liquid to vapor. Following the completion of the phase change, the secondary-side temperature exhibits a distinct upward trend toward the outlet as the steam is further heated by the high-temperature helium.

The distribution

4. Conclusions

In this study, a preliminary steady-state thermal-hydraulic performance analysis was performed for the HECTAR steam generator (helical coil heat exchanger) using MARS-KS v2.0, and the applicability of MARS-KS was assessed through comparison with target values. The simulation results were investigated based on steady-state values reached after a sufficient transient period had elapsed to ensure numerical convergence. The heat transfer rate showed a reasonable agreement with the target value, maintaining an error rate of approximately 6%. The primary inlet and outlet pressures, along with the secondary outlet pressure, were found to be in good agreement with a low error rate of about 2%. Furthermore, the inlet and outlet temperatures for both the primary and secondary sides generally followed the overall trends within an error range of 5%. However, the largest discrepancy was identified in the secondary inlet pressure, which exhibited an error rate of approximately 30%. The axial temperature distribution at 5000 seconds revealed that the primary side exhibited continuous temperature variations characteristic of single-phase flow. In contrast, phase change (two-phase flow) characteristics were clearly observed in the secondary side between approximately 15 m and 21 m. Future work will involve investigating the sources of uncertainty in heat transfer and pressure drop predictions. Additionally, sensitivity studies on boundary conditions and nodal sensitivity will be conducted to reduce prediction errors and further verify the applicability of the MARS-KS analytical model for helical coil steam generator designs.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00457356).

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