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GAMMA+ Code Analysis of Steam Generation System Components for High-Temperature Steam Electrolysis

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1. Introduction

A Very High Temperature Gas-cooled Reactor (VHTR), utilizing helium as a coolant, is capable of achieving reactor outlet temperatures of up to 950°C. Such high-temperature steam is particularly suitable for hydrogen production through high-temperature steam electrolysis (HTSE). In pursuit of this application, the Korea Atomic Energy Research Institute (KAERI) has developed a 30 kW helium loop system that simulates reactor conditions [1].

Fig. 1 illustrates a schematic of the experimental facility designed for the HTSE system incorporating a helium loop [2]. Key components of the setup include an electric preheater and a main heater for the helium loop, as well as an air and purified water supply system. Additionally, the facility incorporates the HTSE unit equipped with Solid Oxide Electrolysis Cells (SOECs), a helical-type Steam Generator (S/G), a Multi-stream Heat eXchanger (MHX), a gas mixture separator, and a cooling system.

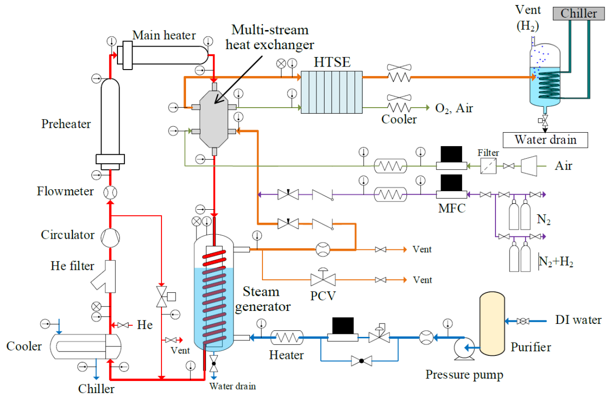


Fig. 1. Schematic of the helium loop for a HTSE system

In this paper, we present an analysis of the results obtained from GAMMA+ code [3], focusing on the performance of the steam generation system including the heaters, MHX, and S/G.

2. Steam Generation System

The steam generation system included several critical components: a preheater, main heater, Multi-stream Heat eXchanger (MHX), and Steam Generator (S/G). The preheater and main heater were responsible for elevating the temperature of the helium gas to the required operational level, with respective maximum power outputs of 42 kW and 35 kW. The MHX was designed to efficiently transfer heat from helium to steam and air. The S/G was tasked with converting the heat into steam.

To validate the design, the GAMMA+ code was used for each component in the steam generattion system under various operational scenarios. The modeling shown in Fig. 2 informed key design decisions, ensuring that each element of the system would perform under the designated conditions based on heat transfer.

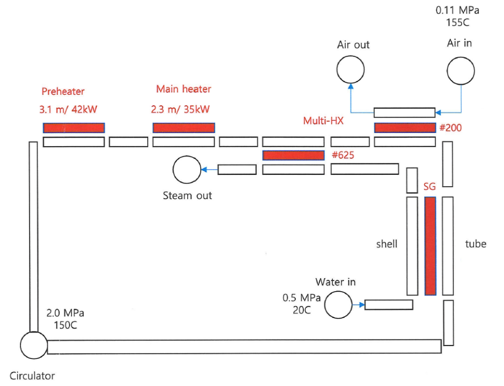
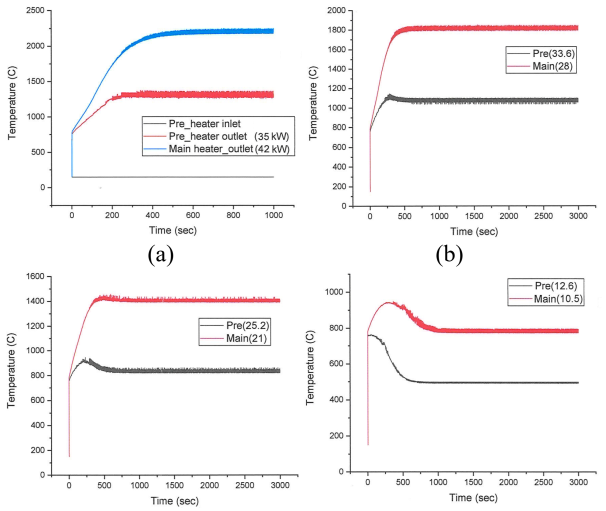


Fig. 2. Modeling scheme of the steam generation system using GAMMA+ code

2.1 Preheater and main heater

In the helium loop, designed to simulate the primary loop system of a VHTR, the preheater and main heater were implemented in place of the reactor core. These heaters were conservatively designed with maximum power consumption capacities of 42 kW and 35 kW respectively. The performance of these heaters was analyzed using the model, which was illustrated in Fig. 2, focusing on the control of helium temperature within the loop.

Fig. 3 shows the results of analysis with the heaters operating at 100%, 80%, 60%, and 30% of their maximum output. The results demonstrated that the combined power output of the heaters exceeding 23 kW was necessary to maintain helium temperatures above 800°C, a critical threshold for the efficient operation of the HTSE process.



(a) (b)

(c) (d)

Fig. 3. Temperature dependency on heater power levels in GAMMA+ code
(a: 100%, b: 80%, c: 60%, d: 30%)

2.2 Multi stream heat exchanger

The MHX in the experimental setup was designed to simultaneously exchange heat among helium, steam, and air, allowing the system to generate high-temperature steam and air according to the operating conditions of the helium loop. The design requirements for the MHX, optimized to the operating conditions, were summarized in Table 1 [4]. Using these specifications, a GAMMA+ analysis of the MHX was performed, and the results were depicted in Fig. 4.

Initial fluctuations were observed in the values. However, the system eventually stabilized with a primary side heat transfer rate of 11.01 kW, a secondary side rate of 8.61 kW, and a third side rate of 2.4 kW. The results were found to be within a 7% margin of error compared to the design values, indicating a high level of accuracy and reliability in the performance of MHX under the given conditions.

Table 1. Design specifications of the MHX

Parameter	Primary side	Secondary side	Third side
Working fluid	Helium	Steam	Air
Inlet temperature [°C]	850	155	155
Inlet pressure [MPa]	2	0.5	0.11
Flow rate [kg/min]	0.42	0.33	0.19
Outlet temperature [°C]	565	820	820
Heat transfer [kW]	-10.36	+8.05	+2.31

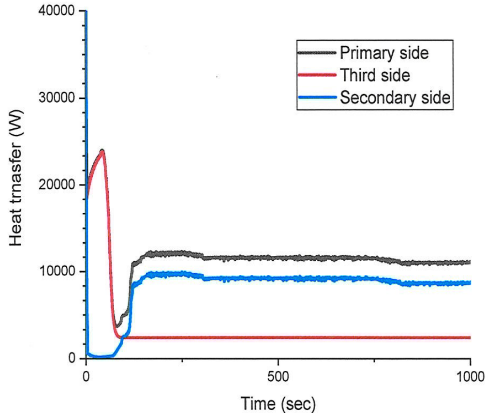


Fig. 4. Heat transfer rates in the MHX

2.3 Helical-type steam generator

The S/G utilized the residual heat of helium gas that had passed through the MHX. The S/G was designed to convert water into steam by passing high-temperature, high-pressure helium through a helical coil, effectively transferring heat to the water inside the generator. The detailed design specifications of the S/G were summarized in Table 2 [4].

One of the key performance indicators of the S/G was the steam generation rate, which could vary depending on several factors, including helium temperature, internal pressure, water level within the S/G, and other factors. To investigate the effect of water level on the S/G's performance, a model was created using the GAMMA+ code, as shown in Fig. 5 [5].

The analysis was performed under conditions where purified water was supplied at a flow rate of 0.0055 kg/s at water levels of 30% and 60%. The results of these simulations were presented in Fig. 6, where heat transfer and steam generation rates were compared across different initial water levels.

The results indicated that with a lower initial water level, the S/G produced less steam relative to the supplied flow rate, while a higher initial water level resulted in more steam generation. Ultimately, the steam generation tended to converge to the rate of water supply, demonstrating the influence of water level on the efficiency and output of the S/G. These findings highlighted the importance of maintaining optimal water levels within the S/G to ensure efficient operation and consistent steam production.

Table 2. Design specifications of the S/G

Parameter	Tube side (He)	Shell side (H_2O)
Pressure [Mpa]	2	0.5
Flow rate [kg/min]	0.42	0.33
Inlet temperature [°C]	565	20
Outlet temperature [°C]	163	155
Heat transfer [kW]	-14.84	+14.84
Pressure drop [kPa]	9.5	7x10^{-5}

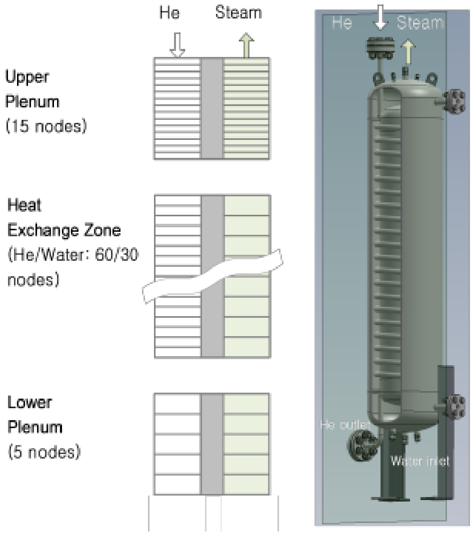
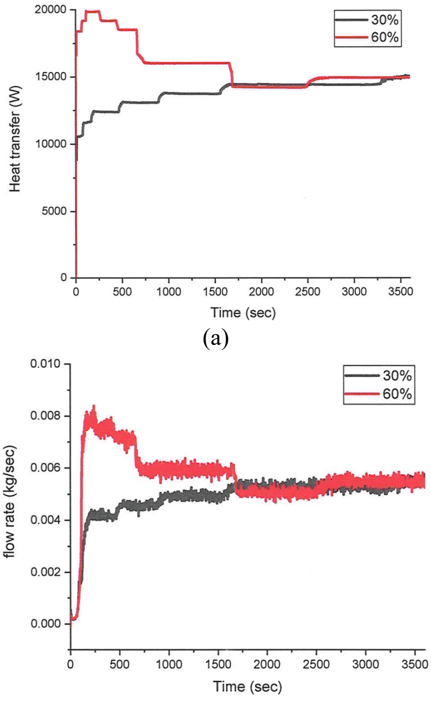


Fig. 5. Modeling scheme of the S/G in GAMMA+ code



(a)

(b)

Fig. 6. Performance of the S/G as a function of initial water level (a: heat transfer, b: flow rate)

3. Conclusion

In this study, we analyzed the performance of a steam generation system designed for HTSE. The system components, including the preheater, main heater, MHX and S/G were modeled and analyzed using the GAMMA+ code to evaluate their performance under various conditions.

Our findings indicated that the combined power output exceeding 23 kW was necessary to maintain the helium temperature above 800°C.

The MHX demonstrated reliable performance with a minimal margin of error, effectively managing heat transfer among helium, steam, and air.

The S/G's performance was observed to be highly dependent on the water level, with higher water levels leading to increased steam generation.

Overall, the GAMMA+ analysis validated the design specifications and operational performance of the steam generation system, confirming its suitability for HTSE applications. Future work may focus on comparative analysis of each component's design and experimental results.

ACKNOWLEDGMENTS

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