Experiments and Analysis of a Helical-type Superheated Steam Generator for a Lab-scale HTSE Experimental Facility

S. D. Hong, H. S. Lim, S.Y. Kim, K. J. Kang, C. S. Kim
Korea Atomic Energy Research Institute, Yuseong-Gu, Daejeon, Korea, 305-600
sdhong1@kaeri.re.kr

1. Introduction

Hydrogen production efficiency using High Temperature Steam Electrolysis (HTSE) improves as the temperature of the supplied steam increases. Accordingly, a High Temperature Gas-cooled Reactor (HTGR) capable of supplying a high temperature is very suitable as a HTSE heat source. The high-temperature steam production system that connects the nuclear reactor and HTSE system is a major concern of nuclear hydrogen production technology because there is no research related to it.

A Lab-scale HTSE system is now under constructing at the Korea Atomic Energy Research Institute [1]. The Lab-scale helium loop will be connected to 30kW capacity HTSE system as a function of high-temperature steam supply to the SOEC (Solid Oxide Electrolyzer Cell) for hydrogen production. In order to supply high-temperature steam at 820℃ to SOEC furnace, pure water goes through a steam generator and superheater. Currently, the experimental facility is connected to each other with the helium loop and steam generator (without superheater) as shown in Figure 1. The steam generator is a helical type steam generator, and high-temperature helium of 565°C flows into the helical tube inside to generate steam. The helical type has a structure that can easily absorb high-temperature thermal expansion, suitable as a HTSE steam generator.

In this study, the results of experiments after connecting the steam generator to the helium loop and the results predicted by the GAMMA+ code [2] are compared and discussed.

2. Steam Generator System

The steam generating system is to continuously and constantly supply high-purity steam to the steam superheater for a long time, and it consists of an ultra-pure water production device, a pressure pump, a preheater, and a steam generator. Pure water with a specific resistance of higher than 5MΩ manufactured in a pure water production device reduces high-temperature corrosion of steam generators and steam superheaters. The pressurization pump is used to supply the flow rate and maintain the pressure in the steam generator. The preheater is configured to control the unstable operation of the steam generator by controlling the temperature of the injection water.

The steam generator is a shell-tube type helical steam generator, and has a structure in which high-temperature helium at 565℃ flows into the helium to generate steam (Figure 1). The helical type has a structure that can easily absorb high-temperature thermal expansion. The helical tube is made of SS310, which has excellent corrosion resistance at high temperatures. The steam generator layout and design specification are shown in Figure 2.

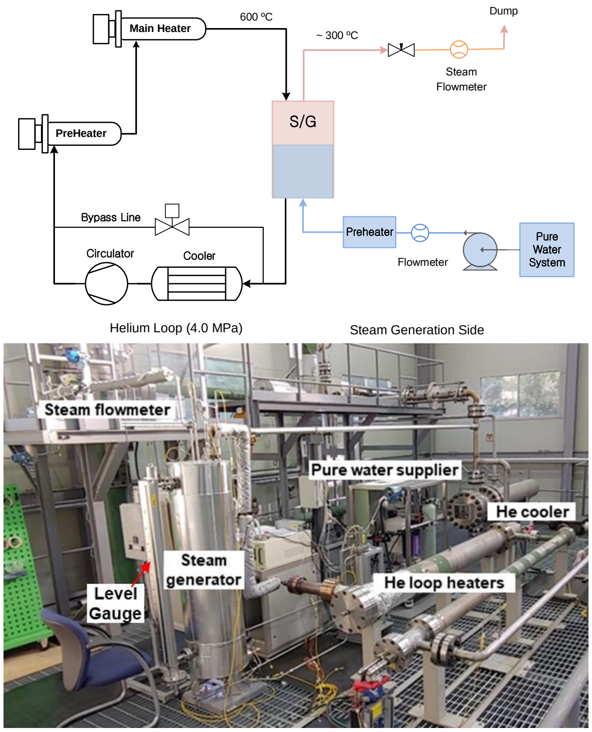

Fig. 1. Layout and photo of a S/G experimental loop

3. S/G Experiments

The experiment is performed to approximate the S/G design condition. The design condition satisfies the 30kW HTSE steam supply capacity. The main concern of the experiment is the maximum flow rate and temperature of steam discharged from the shell side of the steam generator. As a result of the measurement (Table 1), the maximum flow rate of steam exceeded the design value by 30%. At this time, the steam outlet temperature is also maintained at 180.1 ℃ which is higher than the design value of 155℃. The outlet temperature of the steam is superheated upto 43℃, and it is found during the experiment that this steam superheating reacts sensitively to the water level of the steam generator internal. At this time, the water level observed in the experiment is 0.97m (the helical tube is 90.1% submerged in water).

Table 1. Results of S/G experiments

Parameter		Unit	Design	Experiments
Required duty		kW	14.8	19.6
Tube side (He)	Inlet temperature	℃	565	567.7
	Outlet temperature	℃	155	29.6
	Inlet pressure	Mpa	2	1.97
	Mass flowrate	kg/s	0.007	0.007
Shell side (H_2O)	Inlet temperature	℃	20	24.2
	Outlet temperature	℃	155	180.8
	Inlet pressure	Mpa	0.5	3.35
	Steam flowrate	kg/s	0.0056	0.0073

Parameter		Unit	Design
Tube side (He)	Type	-	Helical
	Outer/Inner Dia.	mm	21.7/16.1
	Length(turn)	m	15.7(20)
	Design temp.	℃	650
	Design Pressure	Mpa	4.0
	Mass flowrate	kg/s	0.02
Shell side (H_2O)	Hight	m	1.35
	Inner Diameter	mm	310
	Design temp.	℃	600
	Design Pressure	Mpa	2.0
	Mass flowrate	kg/s	0.02
Required duty		kW	14.8

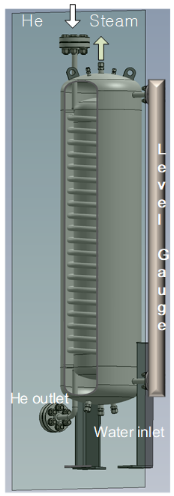

Fig. 2. Helical-type steam generator

4. Steady-state T/H Analysis

Thermal performance for the S/G is predicted with sophisticated design tools, GAMMA+ code [2]. The two-phase flow dynamics incorporated into GAMMA+ code are based on the field equations for a two phase mixture combined with dynamic or algebraic slip momentum. The thermal equilibrium is assumed between phases and the non-equal velocities are considered for nonhomogeneous two-phase flow.

The description of the GAMMA+ modeling scheme for the S/G is as follows;

- Axial nodes (Figure 3)
  - Upper plenum: 15 cells
  - Lower plenum: 5 cells
  - Heat exchange zone
    + Helium side 60 cells
    + Water/steam side 30 cells
- Heat transfer model
  - Tube side of a helical tube [Mori & Nakayama correlation]
  - Shell side of heat exchanger tube bundle [Zukauskas correlation]

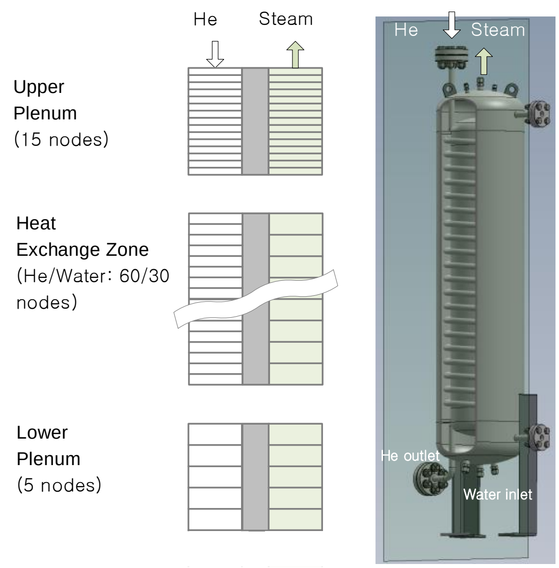

Fig. 3. S/G modeling scheme for GAMMA+ analysis

Based on the experimental results, GAMMA+ analysis is performed. As a result of GAMMA+ analysis, it can be seen that the outlet steam temperature varies according to the water level (Table 2). When the measured water level is input (run Case 1), the calculated outlet steam temperature is 251°C, which is 70.6°C higher than the experimental value of 180.8°C. As a result of calculating the water level by increasing the steam side node of the GAMMA+ model one by one from the observed water level of 0.97m (run Case 2&3), it can be seen that the outlet steam temperature decreases rapidly. This is because the heat capacity of steam is small, so it is easy to superheated even with the heat of a slightly exposed high-temperature helical tube (the heat that superheated steam with a saturation temperature of 138°C to 180.8°C to 43°C is 600W). The analyzed water level equal to the measured steam outlet temperature is calculated to fill the helical tube more than 97%. This suggests that the GAMMA+ analysis predicts the experimental value well considering the amount of heat loss of the S/G during the experiment.

Table 2. Results of GAMMA+ analysis

Parameter		Unit	Experiments	GAMMA+		
				Case 1	Case 2	Case 3
Heat Capacity		kW	19.6	<--	<--	<--
Tube side (He)	Inlet temp.	℃	567.7	<--	<--	<--
	Outlet temp.	℃	**29.6**	41.2	41.2	41.2
	Inlet pressure	Mpa	1.97	<--	<--	<--
	Mass flowrate	kg/s	0.007	<--	<--	<--
Shell side (H_2O)	Inlet temp.	℃	24.2	<--	<--	<--
	Outlet temp.	℃	**180.8**	**251.4**	198.1	142.4
	Pressure	Mpa	0.335	<--	<--	<--
	Steam flowrate	kg/s	0.0073	<--	<--	<--
	Water Level	m	**0.97**	**0.97**	1.003	1.036

5. Conclusions

Experiments are performed on a helical-type steam generator in which high-temperature helium of 565℃ or more is introduced into a helium tube to generate steam. The experimental results are compared with the analysis with the GAMMA+ code, and the following results are obtained.

The steam outlet temperature and steam superheat are sensitively affected by the water level filling the helical tube.

It is found through experiments that the helical tube located above the water level easily increases the temperature of the steam, and the analysis code GAMMA+ predicted this well.

From the point of view of the analysis code, it is confirmed that the steam generator design is possible only when one of the two is fixed because the outlet temperature of steam and the water level of the steam generator are not independent of each other.

ACKNOWLEDGEMENTS

This study is supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2021M2D4A2046777)

REFERENCES

[1] B. H. Park, et al.,"A 30 kW High Temperature Electrolysis Experimental Facility for Nuclear Hydrogen Production," KNS Spring meeting, Jeju, 2022.
[2] H. S. Lim, “GAMMA+2.0 이론기술서= GAMMA+2.0 Volume II: Theory Manual,” KAERI/TR-8662/2021, Korea Atomic Energy Research Institute (2021).