Experimental performance evaluation of a printed circuit type multi-stream heat exchanger with helium loop for hydrogen production

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1. Introduction

With recent establishment of carbon reduction goals for carbon neutrality, there is a growing interest in the hydrogen economy. Very high-temperature gas-cooled reactor (VHTR), which uses helium as a coolant, can be utilized for hydrogen mass-production due to coolant outlet temperature up to 950°C [1]. To demonstrate a high-temperature steam supply system in conjunction with a helium loop for hydrogen production using the VHTR, integrated test study with helium loops and high-temperature electrolysis systems needs to be conducted. For an experimental demonstration, Korea Atomic Energy Research Institute (KAERI) is conducting a study in collaboration with POSCO Holdings, generating high-temperature steam using a helium loop and supplying it to Solid Oxide Electrolysis Cell (SOEC) stacks to produce hydrogen through high-temperature steam electrolysis (HTSE) [2].

For the high-temperature steam generation in connection with helium loop, KAERI designed two heat transfer devices. One is a shell and helical tube type steam generator and the other is a multi-stream heat exchanger. In this study, we conducted an experimental performance evaluation of the fabricated multi-stream heat exchanger and confirmed that it can reliably supply high-temperature steam and air. The design condition is to supply steam and air above 700°C to a 30kW SOEC system, and the heat transfer performance evaluation results of the multi-stream heat exchanger are reviewed. In the future, this high-temperature steam and air supply system would be connected to a SOEC system for a demonstration test of hydrogen production with the helium loop.

2. Design of the multi-stream heat exchanger

Fig. 1 shows a schematic of the experiment facility for high-temperature steam generation with helium loop of 2 MPa. The high-temperature steam production system consists of a steam generator and a superheater. The steam generator is a shell-and-tube type heat exchanger, separated from the superheater to mitigate flow instabilities that can result from the phase change from water to steam [3]. The steam superheater was designed and fabricated as a printed circuit heat exchanger (PCHE), wherein flow channels are etched onto metallic plates and the plates are diffusion bonded. The steam superheater was designed to transfer heat from helium to steam and air simultaneously.

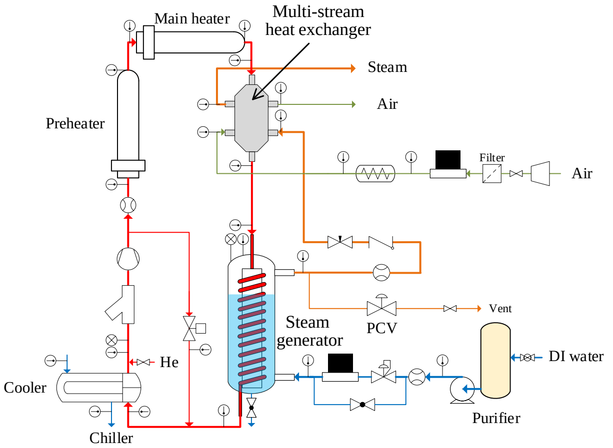

Fig. 1. A schematic of experiment facility for high-temperature steam generation with helium loop.

Design requirements for the multi-stream heat exchanger and the steam generator to produce 820°C steam and air for a 30 kW SOEC system were derived based on the operational requirements of the helium loop, and they are summarized in Tables I and II. Major design parameters such as the helium outlet temperature of the multi-stream heat exchanger were assumed to be the same as that of the steam generator's helium inlet temperature, and the helium temperature and mass flow rate were obtained using an iterative method.

Table I. Design requirements of the multi-stream heat exchanger.

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

Table II. Design requirements of the steam generator.

Parameter	Primary side	Secondary side
Working fluid	Helium	Steam
Inlet 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

Considering diffusion bonding characteristics and high-temperature experimental conditions, SUS304 material was chosen for the PCHE. SS304 is suitable for temperatures up to 816°C [4]. Based on the operational characteristics of the helium loop, heat exchanger design was conducted using a diameter of 1.5 mm for the flow channels, considering pressure drop and flow fouling. Heat exchanger thermal design was carried out using the Logarithmic Mean Temperature Difference (LMTD) method with an overall heat transfer margin of 1.3. After designing heat exchangers for helium-steam and helium-air systems separately, the final design was determined by adjusting the number of channels per stack to ensure consistency and overall performance. The final size of the heat exchanger core was determined to be $136 \times 52 \times 99$ mm³. To achieve a more uniform temperature distribution, air flow channels were arranged between steam flow channels within the PCHE.

3. High-temperature steam/air supply system

The process flow diagram of high-temperature steam/air supply system is described in Fig. 1. It is the preliminary experiment to generate high-temperature steam and air, which will be supplied for the hydrogen production in HTSE system. In this preliminary study without SOEC stacks, the high-temperature steam and air produced through the experiment are exhausted to the outside of the building. Fig. 2 shows the experiment facility for high-temperature steam and air supply with helium heating system constructed with the designed heaters and heat exchangers. It is intended to reduce heat loss through insulation.

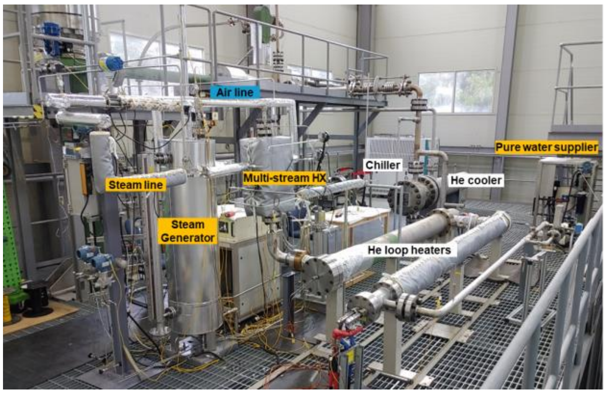

Fig. 2. Experiment facility for high-temperature steam/air supply with helium loop.

For the stable operation of the steam generator, a water mass flow controller is used to supply a constant flow rate for the target water level of steam generator internal. It also controls the pressure variation of the water due to the intermittent operation of the water supply system. Excess steam can be generated to reduce the superheat of steam through the helical tube exposed above water level in the steam generator. A pressure control valve is used to control the steam flow rate to the multi-stream heat exchanger, by discharging the excess steam through the steam vent line. The pressure control valve is controlled using the pressure at the upper plenum of the steam generator, and the stability of steam supply at the steam generator is secured.

4. Results of the experiment

Fig. 3 shows the results of high-temperature steam generation experiment with helium loop. It describes the inlet and outlet temperature of helium, steam and air in the multi-stream heat exchanger. The steam outlet temperature reaches 800°C after 6 hours of data acquisition, and it is demonstrated that the high-temperature steam generated with helium loop can be stably supplied under steady state operation for 4 hours with the required steam outlet temperature over 800°C. From these results, it is confirmed that the superheated steam over 800°C can be stably produced and supplied with the steam generator and multi-stream heat exchanger.

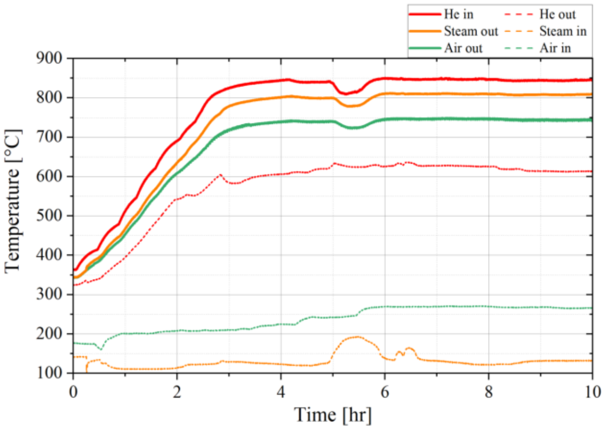

Fig. 3. Inlet and outlet temperatures of each fluid in the multi-stream heat exchanger

Fig. 4 presents the mass flow rate of pure water supplied to the steam generator and the amount of steam discharged externally. Fig. 5 shows the pressure at the upper plenum of the steam generator. The stable maintenance of steam outlet temperature, pressure, supply of pure water, and external steam discharge from the steam generator after 9 hours confirms that the steam supplied to the multi-stream heat exchanger has reached a steady state condition and can be maintained consistently.

Table III summarizes the test results with the average values and 95% confidence interval of the steady-state conditions for one hour in the steam generator and the multi-stream heat exchanger compared with the design values. Table IV presents the comparison of the heat transfer performance test results obtained from the experimental results. The mass flow rate of the helium loop is measured using a Coriolis mass flow meter. Due to the pressure drop from the mass flow meter, the system pressure of the helium loop was increased to meet mass flow rate of the helium. From the results, it was confirmed that the outlet temperature of helium from the multi-stream heat exchanger and the inlet temperature of helium to the steam generator can exceed 40°C.

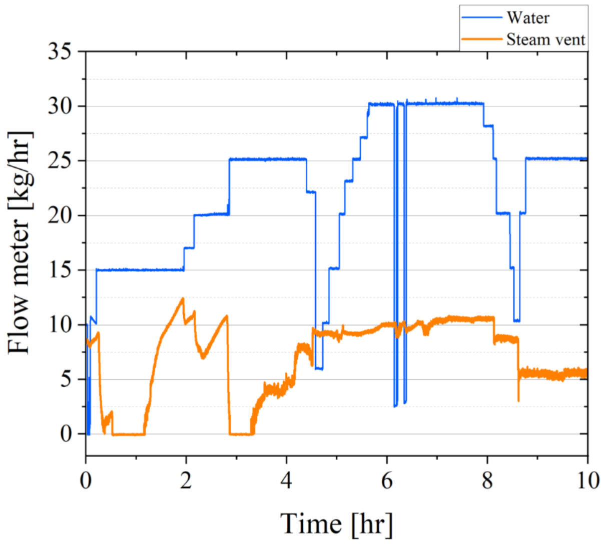

Fig. 4. Mass flow rate of pure water supplied to the steam generator and the discharged steam.

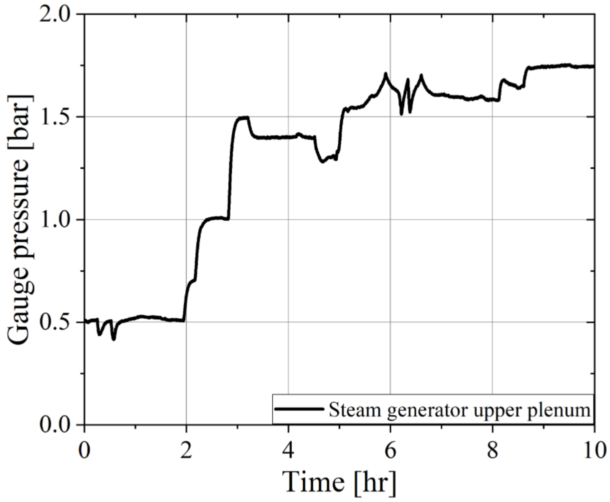

Fig. 5. Pressure at the steam generator upper plenum

Table III. Test results compared with the design.

Parameter	Design	Test result
Heat transfer device	**Multi-stream heat exchanger**	
Helium flow rate [kg/min]	0.42	0.418±0.004
Helium pressure [bar]	20	33.83±0.07
Helium inlet temperature [°C]	850	844.4±1.7
Helium outlet temperature [°C]	564.5	613.2±1.0
Steam flow rate [kg/hr]	20	19.7±0.5
Steam inlet temperature [°C]	155	132.0±0.8
Steam outlet temperature [°C]	820	808.2±1.0
Air flow rate [kg/s]	160	109.6 ± 6.3
Air inlet temperature [°C]	155	266.4±2.3
Air outlet temperature [°C]	820	744.3±1.2
Heat transfer device	**Steam generator**	
Helium inlet temperature [°C]	564.5	572.2±0.8
Helium outlet temperature [°C]	155	52.4±0.9
Water flow rate [kg/hr]	20.16	25.22±0.06
Water inlet temperature [°C]	20	29.7±0.6
Steam pressure [bar]	5	2.75±0.01
Boiling temperature [°C]	151.8	130.6
Steam outlet temperature [°C]	155	138.4±0.8

Table IV. Heat transfer results compared with the design.

Parameter	Design	Test result
Heat transfer device	**Multi-stream heat exchanger**	
Helium heat transfer [kW]	10.36	8.36
Steam heat transfer [kW]	8.05	7.96
Air heat transfer [kW]	2.31	1.14
Heat loss [kW]	-	-0.74
Heat transfer device	**Steam generator**	
Helium heat transfer [kW]	14.84	18.77
Water/steam heat transfer [kW]	14.84	18.31
Heat loss [kW]	-	0.46

For the multi-stream heat exchanger, although the steam heat transfer performance is 1.1% lower than the design, it still satisfies the design conditions within the measurement error range of steam mass flow rate. The steam inlet and outlet temperature difference satisfies the design target of 665°C, as the test result shows 676.2°C. The negative heat loss of the heat exchanger is due to maintaining the heating jacket outside the multi-stream heat exchanger at 520°C during the experiment, to reduce high-temperature radiant heat loss and improve reaching steady state.

The difference in air flow is attributed to the blockage in the air flow channels of the multi-stream heat exchanger occurring during repeated high-temperature experiments. It results in a 31.5% decrease in air flow due to increased flow channel pressure drop. The air heat transfer performance is 50.6% lower than the design, therefore, it was estimated that the reason of the blockage could affect surface heat transfer such as oxidation of the flow channel walls rather than blockage of the flow channel cross-section.

Regarding the steam generator, it was confirmed that the steam production heat transfer performance exceeds the design by 23.4%. The low heat loss of 2.5% in water/steam heat transfer is due to the structure where high-temperature helium tubes are surrounded by water and steam.

The steam supply pressure between the design value and the test results is different, because the steam supply pressure in this experiment is determined by the pressure drop through the flow channels of the heat transfer devices and piping. To examine the effect of the pressure conditions, computational analysis using the PCHE design program was conducted. If the steam mass flow rate and temperature conditions remain constant, the difference in heat transfer rate of the multi-stream heat exchanger can be ignored, showing a difference of less than 1°C in steam outlet temperature criterion. This is because the kinematic viscosity coefficient of steam, which affects the heat transfer coefficient, is not sensitive to pressure changes. This indicates that even in conditions of low pressure for high-temperature electrolysis test, where relatively small amounts of steam are supplied and heat transfer occurs, the heat transfer performance of the multi-stream heat exchanger would not be reduced.

5. Conclusions

In this study, experimental performance evaluations were conducted on a printed circuit type multi-stream heat exchanger capable of producing high-temperature steam and air using a helium loop. The multi-stream heat exchanger was designed to meet the requirements for a 30 kW high-temperature electrolysis. Performance evaluations confirmed the stable supply of steam over 800°C at a rate of 20 kg/hr and air over 750°C at a rate of 110 SLPM through the high-temperature steam/air supply system. Heat transfer capacities for steam and air were determined to be 7.96 kW and 1.14 kW, respectively. The steam heat transfer capacity met the design specifications within the margin of error, while the air heat transfer capacity was found to be approximately 51% lower than the design value due to flow blockage in the multi-stream heat exchanger. In the future, 6 kW SOEC system will be connected to the high-temperature steam/air supply system for a demonstration test of hydrogen production with the helium loop.

ACKNOWLEDGEMENT

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