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Experimental Study on the High-Temperature Steam Supply System using Helium Loop for Reliable Steam Generation Control

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1. Introduction

Very high-temperature gas-cooled reactor (VHTR) is one of GEN-IV nuclear reactor concepts using helium as a coolant, and it can be utilized for hydrogen mass-production and industrial applications due to coolant outlet temperature up to 950°C [1]. For an experimental demonstration, Korea Atomic Energy Research Institute (KAERI) is conducting a study in collaboration with Research Institute of Industrial Science and Technology (RIST), 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 (MHX). The shell and helical tube type steam generator handles the two-phase heat transfer process of heating purified water to produce steam, while the MHX heats the single-phase steam from the steam generator up to 800°C. With this separation, it is intended to control the flow instability induced by the boiling of water and enhance heat transfer efficiency.

In this study, design considerations of the steam supply system of the experiment facility are examined, mainly for the shell and helical tube type steam generator. Factors that are related to the steam supply instability in the system are discussed, a control methodology is established, and a design of steam supply system is determined for reliable steam generation control. Finally, the stable steam supply and control are verified through experiments.

2. Design of steam generator

Fig. 1 shows a schematic of the experiment facility for high-temperature steam generation with helium loop of 2 MPa. In this experiment facility, two heat transfer devices are designed and equipped; steam generator and MHX. Because the MHX serves to efficiently heat the steam and air up to 800°C with high-temperature helium, the flow instability and control of steam generation should be managed in the steam generator. Preliminary experiment was conducted by the authors to confirm the heat transfer performance of the steam generator as designed, and improvements to the flow instability were required [3]. Therefore, the design and control methodology of the shell and helical tube type steam generator is mainly investigated in this study.

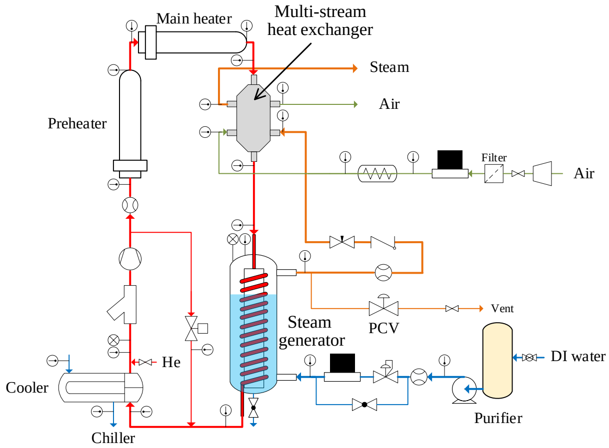

Fig. 1. A schematic of experiment facility for high-temperature steam generation with helium loop.

As described in Fig. 2, the steam generator is designed as the shell and helical tube type with a core tank, which is to prevent vibration of the helical tube and for the structural integrity of the steam generator. Helium flows inside of the helical tube and water is filled between the outer shell and the core tank. The amount of steam generation and superheat of the steam varies according to the water level inside the steam generator.

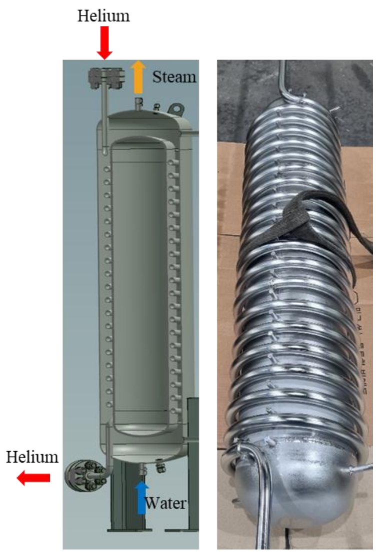

Fig. 2. Design of steam generator (left) and the core tank with helical tube (right).

In steady state, the water level in the steam generator is constant, and the steam generation is same with the flow rate of injected water because the tube side submerged in the water is constant. The steam superheat is also constant because it is determined by the length of the tube exposed to steam. Therefore, higher water level from increased water injection results in more steam generation and less superheating, and lower water level from decreased water injection results in less steam generation and more superheating [3]. In other words, if water injection is stable, the water level, steam generation and superheating of the steam are automatically adjusted.

However, if the flow rate of feed water is unstable due to the intermittent operation of the water supply pump or other pressure fluctuation sources, it is difficult to control the amount and conditions of the steam supply. This is because the response time of the water supply, the water level and the pressure at the upper plenum of the steam generator do not match. Thus, sudden change in water supply causes sudden changes in the water level, the pressure at the upper plenum, the steam supply, the boiling point, steam superheat and so on. All of these factors, especially pressure instability, make it difficult to control the steam supply. Therefore, control of the steam generator inlet conditions is essential for reliable steam generator operation.

An additional consideration is that if the feed water supply is significantly lower than the heat transfer performance of the steam generator, the outlet temperature of the superheated steam exceeds 300°C, which may cause damage to the instrumentation at the steam outlet of the steam generator. Therefore, if the required steam flow rate is less than the design performance of the steam generator, a methodology is required to generate more steam than the required steam and supply only the required flow rate to the MHX. In this way, the superheat of the steam needs to be reduced while controlling pressure instability.

3. Steam supply system control methodology

The process flow diagram of steam supply system investigated in the present study is described in Fig. 1, including a purified water supply system. As discussed above, the prerequisite for controlling the steam supply is to provide a constant feed water flow. In the water supply system, a power pump does not quantitatively control the water flow rate or pressure, therefore it causes primary source of the flow fluctuations, leading to instability in the steam supply.

To control this, a pressure regulator and a mass flow controller (MFC) for water are installed. In this steam generator, the steam production follows the water supply because the steam production is dominated by the water level over other factors. And water level and steam production respond more slowly than changes in the water supply, which allows the stable operation of this shell and helical tube type steam generator design.

Even if the injection of water is constant, when the water flow rate is much less than the heat transfer capability of the steam generator, the superheated steam over 300°C can damage the flow meter or pressure control valve. To prevent this, steam is overproduced in steam generator to keep the steam superheating temperature at a low level, and the required amount of steam is supplied to the MHX. The rest of the steam produced was vented to the outside through the pressure control valve (PCV), which serves to maintain pressure condition at the upper plenum of the steam generator as shown in Fig. 1. By keeping the conditions of the feed steam constant with this PCV vent line, the reliability of the steam supply control to the MHX and SOEC stacks that will be connected later can be improved.

However, the heat transfer capacity of both heat exchangers depends on the pressure, mass flow rate and temperature conditions of working fluid in helium loop. Therefore, in this study, stable generation and supply of the superheated steam over 10.8 kg/h and 800°C is tested through the experiment facility, and the suggested control methodology for steam supply system is examined experimentally.

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 and steam in the steam generator and MHX. The steam outlet temperature of the MHX 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. Table I summarizes the average inlet and outlet temperatures and 95% confidence interval under the steady-state condition. From these results, it is confirmed that the superheated steam over 800°C can be reliably produced and supplied with the steam generator and MHX as designed.

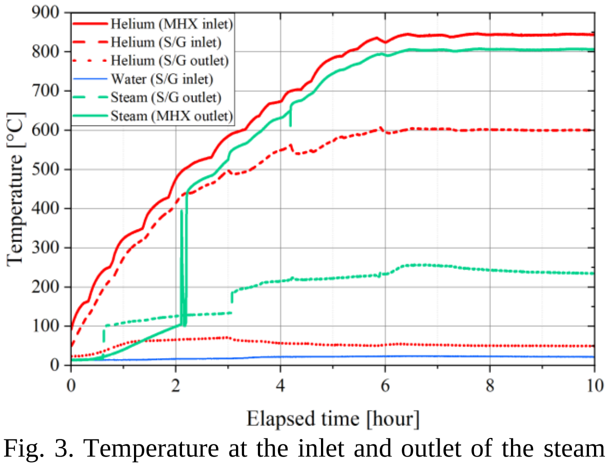

Fig. 3. Temperature at the inlet and outlet of the steam generator and multi-stream heat exchanger.

Table I. Temperature results of the three working fluids

Component	Location	Average temperature [°C]
Multi-stream heat exchanger	Helium inlet	843.1 ± 4.7
	Helium outlet	625.3 ± 4.1
	Steam inlet	209.4 ± 13.1
	Steam outlet	805.2 ± 5.1
Steam generator	Helium inlet	601.2 ± 2.5
	Helium outlet	50.8 ± 1.7
	Water inlet	23.1 ± 1.0
	Steam outlet	244.4 ± 12.2

Fig. 4 shows the mass flow rate of the supplied pure water to the steam generator and the measured steam supplied to the MHX. After 3 hours operation, a part of the generated steam is discharged through the PCV, and the steam measured by the vortex flow meter is injected to the MHX. This overproduction of steam was intended to reduce the outlet temperature of the steam generator below 300°C.

Under the steady-state condition, the steam supply to the MHX was stably maintained, and the average mass flow rate values and other operating conditions with 95% confidence interval are summarized in Table II. 29.3 kg/hr of water was supplied and became superheated steam in the S/G, and 14.5 kg/hr of steam is supplied to the MHX. The pressure at the upper plenum of the steam generator was 2.65 bar and it was controlled to be almost constant at the steady state with a small fluctuation range.

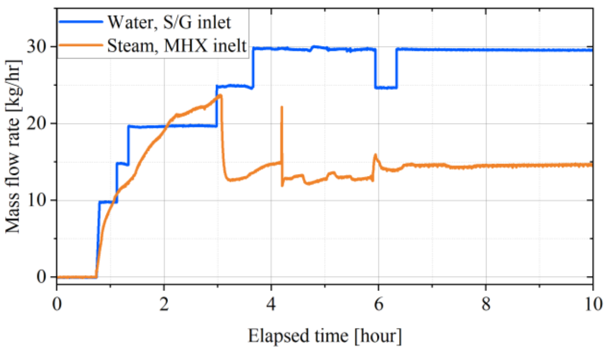

Fig. 4. Mass flow rate of the supplied water and the steam supplied to the multi-stream heat exchanger.

Table II. Operation conditions of the experiment

System	Parameter	Average value
Helium loop	System pressure [bar]	21.36 ± 0.02
	Helium flow rate [kg/min]	0.347 ± 0.0009
Steam supply system	Pressure at the steam generator [bar]	2.65 ± 0.03
	Purified water injection [kg/hr]	29.31 ± 0.04
	Supplied steam into the MHX [kg/hr]	14.53 ± 0.20

5. Conclusions

In this study, high-temperature steam generation experiment facility was designed using helium loop. To control the steam supply and flow instability, it is important to maintain the water level and the pressure at the upper plenum of the steam generator constantly. It is achieved by injecting water through the pressure regulator and MFC for water, and controlling the pressure with the steam discharge line with PCV monitoring the upper plenum pressure of the steam generator. From the experiment results it was confirmed that the superheated steam of 800°C over 10.8 kg/hr could be stably supplied with the suggested steam supply system control methodology. In the future, the operating conditions will be examined by controlling the helium pressure, mass flow rate and temperature depending on the required temperature and flow rate of the high-temperature steam.

ACKNOWLEDGEMENT

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