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Gas Mixture Separation and Cooling System for 800°C High-Temperature Steam Electrolysis Experimental Facility

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1. Introduction

High-Temperature Steam Electrolysis (HTSE) for hydrogen production operates typically at temperature 750 - 950°C [1]. The major advantage of HTSE is that the total energy demand of electrolysis in the vapor phase for this electrolysis can be reduced by the heat of vaporization, which can be provided much more inexpensively by thermal rather than electric energy. HTSE requires about 35% lower electricity compared with conventional electrolysis at low temperatures. Recently, to accomplish the carbon neutrality, utilization of Very-High Temperature gas-cooled Reactor (VHTR) has been investigated for the mass production of hydrogen from HTSE. 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 HTSE [2].

A disadvantage of the planar SOEC stack currently being developed is that the stack's seal is imperfect at high temperatures, which can lead to hydrogen leakage [3]. This is because the leak rate increases when the pressure change in the flow channel increases, so the gas pressure difference across seal is generally limited to 14 kPa or less during stack operation. On the other hand, since the hydrogen produced in the stack is mixed with the remaining steam, pure hydrogen can be obtained by removing the steam. An easy way to remove steam is to use a sparger to condense the hydrogen-steam mixture in a condenser, but this can form a pressure wave depending on the thermal hydraulic conditions in the sparger. This pressure wave is feedback to the pressure-sensitive planar stack and can affect hydrogen leakage. Accordingly, a cooling and hydrogen separation system with a pressure wave mitigated device is required. The purpose of this study is to consider the design for the gas separation and vapor cooling system of the gas mixture of steam and hydrogen installed at the rear of the HTSE.

2. HTSE Experimental facility

An experiment facility to generate high-temperature steam of 800°C is designed and constructed at Korea Atomic Energy Research Institute (KAERI) for 30kW HTSE using solid-oxide electrolyte cell (SOEC) stacks. Fig. 1 describes a schematic of the experiment facility for 30kW HTSE system with helium loop. The facility

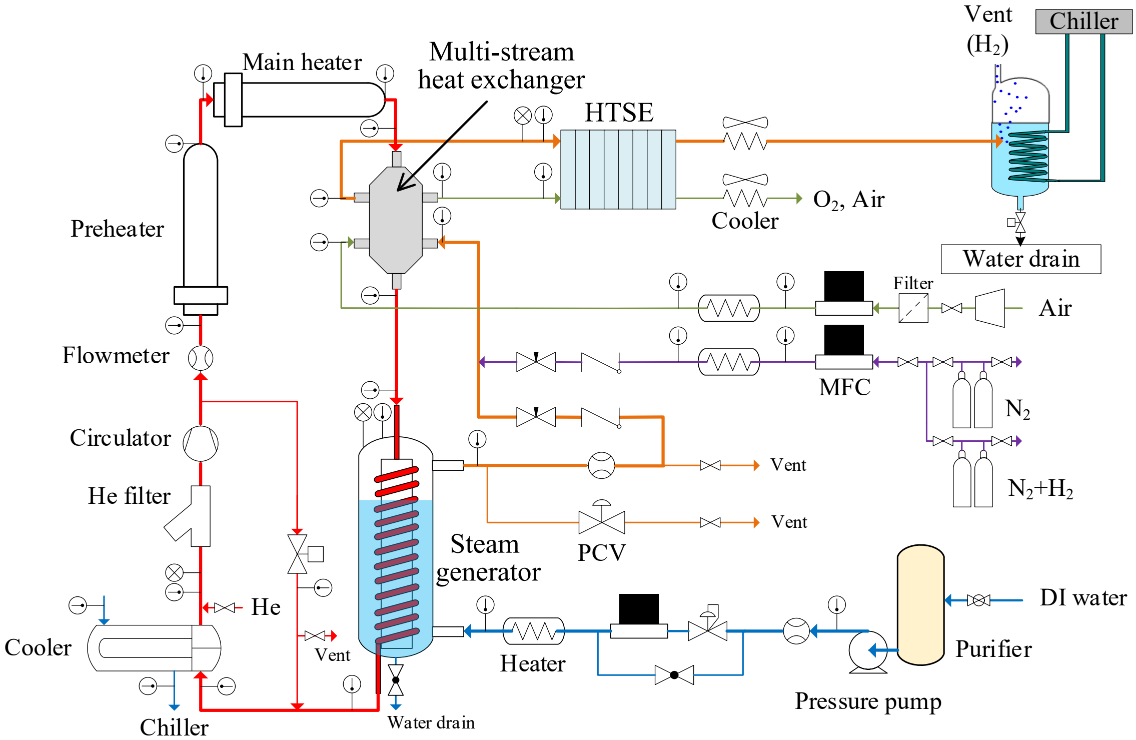

Fig. 1 Schematic of the experiment facility

is composed of the major components such as a helium loop (Electric preheater, main heater for a primary loop system of VHTR), air and purified water supply system, HTSE including SOEC, steam generator, multi-stream heat exchanger, gas mixture separator and cooling system. An HTSE includes a stack of several single repeat units. The single unit is composed of the three layer cell(cathode/electrolyte/anode) and two half-interconnects. The experiment facility equipped a 77 kW heating system to heat the helium up to 1000℃, and a shell and helical-tube type steam generator and a multi-stream printed circuit heat exchanger (PCHE) are designed and manufactured to heat the steam and air up to 800℃ with the heated helium. Purified water is evaporated via the steam generator and the steam is superheated through the multi-stream heat exchanger. [4] Air is heated up through the multi-steam heat exchanger, and it is used as sweep gas of anode side in SOEC stacks. A mixture of nitrogen and hydrogen is injected into the steam line to act as a purge gas and prevent oxidation on the cathode side. A mixture of steam and small amount of hydrogen (typically a volumetric composition of 95% steam and 5% hydrogen) [5] is supplied to the hydrogen electrode (cathode side) at 800℃. In the cathode, high temperature steam is reduced and decomposed into hydrogen and oxygen ions. The oxygen ion from cathode is transferred to the anode, and the oxygen is produced in the anode by oxidizing oxygen ion. The generated hydrogen flows out of the stack along with the remaining steam and then passes through a condenser to remove the remaining steam.

3. Gas mixture separation/cooling system

The gas mixture flows out from the cathode side of HTSE to the gas separation and cooling system. Since the hydrogen produced in the stack is mixed with the remaining steam, pure hydrogen can be obtained by removing the steam. An easy way to remove steam is to use a sparger to condense the hydrogen-steam mixture in a condenser, but this can form a pressure wave depending on the thermal hydraulic conditions in the sparger. This pressure wave is feedback to the pressure-sensitive stack and can affect hydrogen leakage.

The separation system consists of an air cooler and a condenser as shown in Figure 2. The air cooler composed of five finned-tube array is placed in front of the condenser to cool the 800℃ mixed gas to 600℃ or less. In addition, the high-temperature burden of the condenser can be alleviated, and the amplitude of the pressure wave can be lowered by maintaining the temperature of the mixed gas flowing into the condenser's sparger low.

The sparging type chilled water condenser is equipped with a transparent viewport so that the water level can be visually observed, and the sparger is placed close to the water level surface to minimize pressure waves during operation. A mixer installed below the condenser relieves temperature stratification near the water surface. A solenoid valve is installed on the drain line of the condenser to automatically control the water level by receiving feedback from the water level. The quantitative design for the heat removal and steam condensation system is as follows. For a 30 kW HTSE system, the required steam flow rate is 3 g/s, and if the surface area of the single finned-tube is estimated to be 0.86 m^2, the temperature of the fluid from the HTSE system is estimated to be reduced by 575℃, as summarized in Table 1. The fluid with reduced temperature is sparged into the condenser tank.

Table 1. Design calculation for the finned-tube

Mass flow rate	3 g/s
Tube diameter	3/4 in.
Fin height	1/4 in.
Number of fins per meter	200
Length of single finned-tube	0.8 m
Calculated surface area of single finned-tube	0.19 m^2
Number of the finned-tube	5
Assumed heat transfer coefficient of air	10 $W/m^2 \cdot K$
Assumed temperature difference between tube and environment	400℃
Estimated of heat removal by finned-tube	3.8 kW
Specific heat of steam at 600℃	2.2 $kJ/kg \cdot K$
Estimated temperature decrease	575℃

The heat removal capacity of the condenser to the heat of the discharging gas mixture is designed to be 8kW, and the chiller is designed to be 29kW (HX-85H).

Fig. 2. Design of gas mixture separating/cooling system

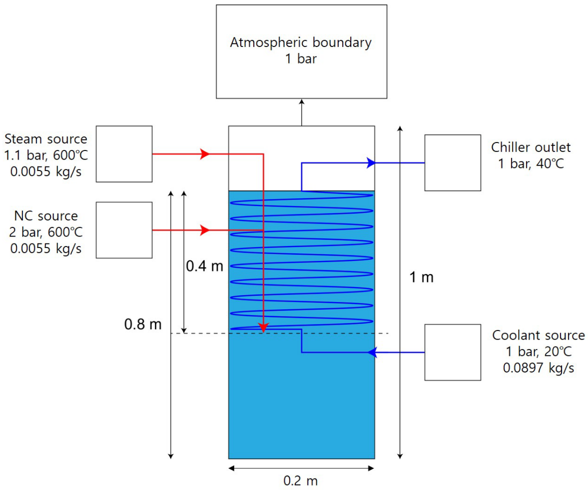

Fig. 3 MARS model for condenser

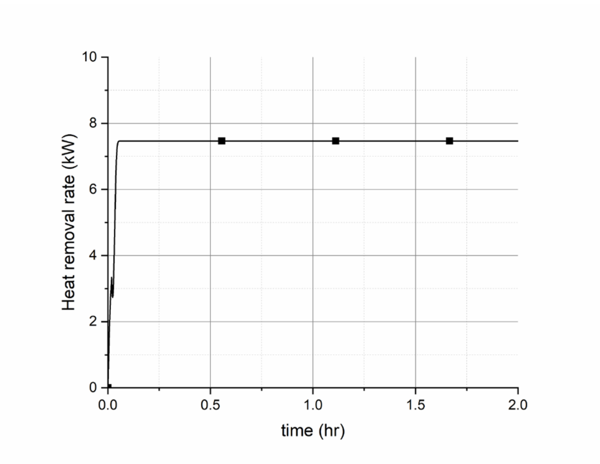

Fig. 4. Heat removal rate of the condenser

Fig 3 is a calculation model for the condenser. The released of steam The flow rate discharged to the condenser is assumed to be 0.0055kg/s, which is the design value of the steam generator. The steam is discharged to the tank through the sparging line and directly condensed in the water. The hydrogen gas is released to the top in the condenser tank. Figure 4 shows the heat removal rate calculated through MARS(system software code) inside the condenser. A helical type heat exchanger is installed to remove heat from the inside of the condenser, and the chiller coolant flow rate of 0.0897 kg/s is supplied to the heat exchanger. As a result of the calculation, it was confirmed that the heat removal rate is about 8KW.

4. Conclusions

In this study, the design of the gas mixture separation and cooling system is considered in the 30 kW HTSE experimental facility being constructed at the KAERI. In the mixed gas discharged from HTSE, steam is firstly cooled by air and sparged to a water tank to be secondarily cooled and hydrogen is separated and released. An air cooler is useful as a pre-cooler in designing a condenser that condenses 800℃ steam. Installing the mixed gas sparger in the condenser near the surface of the water level can reduce the pressure wave, and it has been analyzed that the lower the inlet temperature of the mixed gas can reduce the pressure wave, but this needs to be verified through experiments.

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