Preliminary Overview of a Helium Cooling System for the Secondary Helium Loop in VHTR-based SI Hydrogen Production Facilities

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1. Introduction

Nuclear hydrogen production facilities consist of a very high temperature gas-cooled nuclear reactor (VHTR) system, intermediate heat exchanger (IHX) system, and a sulfur-iodine (SI) thermochemical process [1, 2]. This study focuses on the coupling system between the IHX system and SI thermochemical process. To prevent the propagation of the thermal disturbance owing to the abnormal operation of the SI process components from the IHX system to the VHTR system, a helium cooling system for the secondary helium of the IHX is required [3]. In this paper, the helium cooling system has been studied. The temperature fluctuation of the secondary helium owing to the abnormal operation of the SI process was then calculated based on the proposed coupling system model. Finally, the preliminary conceptual design of the helium cooling system with a steam generator and forced-draft air-cooled heat exchanger to mitigate the thermal disturbance has been carried out.

2. Method and Results

2.1 Description of the IHX-SI coupling system

The KAERI-SI flowsheet using precipitation, electrodialysis, and membrane separation was introduced in 2012 [2].

Based on the recommended IHX secondary helium pathway, the conceptual flow diagram of the IHX-KAERI SI coupling system can be established as shown in Fig. 1.

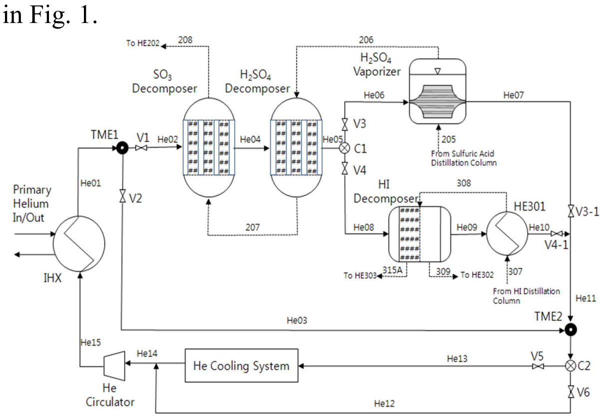

Fig. 1. Conceptual flow diagram of the IHX-KAERI SI coupling system.

The IHX-KAERI SI coupling system consists of the IHX, helium cooling system, helium circulator, and SI process components such as SO_3 and H_2SO_4 decomposers, H_2SO_4 vaporizer, and HI decomposer including a HI pre-heater (HE301). The helium cooling system will only be operated under abnormal operation of the IHX-SI coupling system. Under normal operation, the secondary helium discharged from the IHX provides heat to the process components in a regular sequence, and the cooled helium passing through He12 is compressed by the helium circulator and recycled to the IHX for reheating. In Fig. 1, there are two temperature measuring elements (TME1 and TME2) and two comparators (C1 and C2) to inspect the operating status of the IHX-KAERI SI coupling system. If any abnormal operation condition is observed from the temperature and pressure indicators, the proper helium path is led by the actuating valves (V1 through V6).

Table 1 shows the steady state operation condition of the IHX-KAERI SI coupling system with a hydrogen production rate of 60 mol/s. The amount of thermal load at each SI component in Fig. 1 is shown in Table 2.

Table 1. Steady state operation condition of the IHX-KAERI SI coupling system

Line No. in Fig. 1	*Stream Information*	*Temperature (^oC)*	*Pressure (bar)*
He01	Pure helium	910.0	40
He11	Pure helium	450.0	40
205	90 mol% of sulfuric acid	B.P.	7.09
207	H_2SO_4 decomposer outlet	750.0	7.09
208	SO_3 decomposer outlet	850.0	7.09
307	$H_2O/HI/I_2$ mixed vapor	274.4	40
308	-	450.0	39.5
309	-	450.0	39.5
315A	HI decomposer outlet	450.0	38

Table 2. Amount of thermal load at each SI component on the basis of 60 $H_2 \cdot mol/s$

Components	*Sensible Heat (kJ/s)*	*Latent Heat (kJ/s)*	*Heat of Reaction (kJ/s)*	*Total Heat (kJ/s)*
H_2SO_4 Vaporizer	2,925.8	6,425.7	3,284.8	12,636.3
H_2SO_4 Decomposer	3,876.7	-	4,868.4	8,745.1
SO_3 Decomposer	1,134.3	-	5,619.5	6,753.8
Heat Exchanger (HE301)	3,034.7	-	-	3,034.7
HI Decomposer	-	-	763.5	763.5
Subtotal Heat (kJ/s)	10,971.5	9,710.5	11,251.4	31,933.4

2.2 Transfer function and response curves

To analyze the thermal fluctuation behaviors of the IHX-KAERI SI coupling system, the transfer function of the IHX-KAERI SI coupling system was derived. Based on the conceptual flow diagram of the IHX-

KAERI SI coupling system shown in Fig. 1, the first order heat balance on the helium flow gives

$C_{p,He}m_{He}(T_{TME1} - T_{TME2}) - \Sigma Q_i = \Sigma V_i\rho_{He}C_{p,He}\, dT_{TME2}/dt$ (1)

And the transfer function $G(s)$ can then be obtained as follows.

$G(s) = \Delta T_{TME2}(s)/\Delta Q(s) = A/(\tau s+1)$ (2)

$A = 1/(C_{p,He}m_{He})$ (3)

$\tau = \Sigma V_i\rho_{He}/m_{He}$ (4)

The forcing function $\Delta Q(s)$ in Eq. (2) is a step change owing to the closing of the valve resulting from the SI component failure.

Prior to evaluating the response curve using Eq. (2), the possible malfunction scenarios of the IHX-KAERI SI coupling system owing to a serious defect in SI components such as the component destruction including a crack or pinhole on the partition wall between helium and process stream paths have been considered: 1) defect of SO_3 and/or H_2SO_4 decomposers, 2) defect of H_2SO_4 vaporizer, and 3) defect of HI preheater and/or decomposer.

In each accident case, the helium path is determined by the on/off actuation of valves V1-V4.

Fig. 2 shows the dynamic response curves of helium temperature predicted at TME 2 in each accident case.

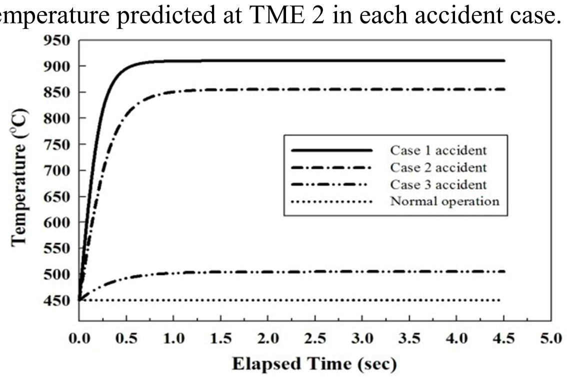

Fig. 2. Dynamic response curves of helium temperature predicted at TME 2.

2.3 Conceptual design of helium cooling system

In this study, the conceptual design of a helium cooling system was carried out according to the JAEA's methodology presented in 2006 [4]. The helium cooling system is composed of a steam generator and forced-draft air-cooled heat exchanger, as shown in Fig. 3.

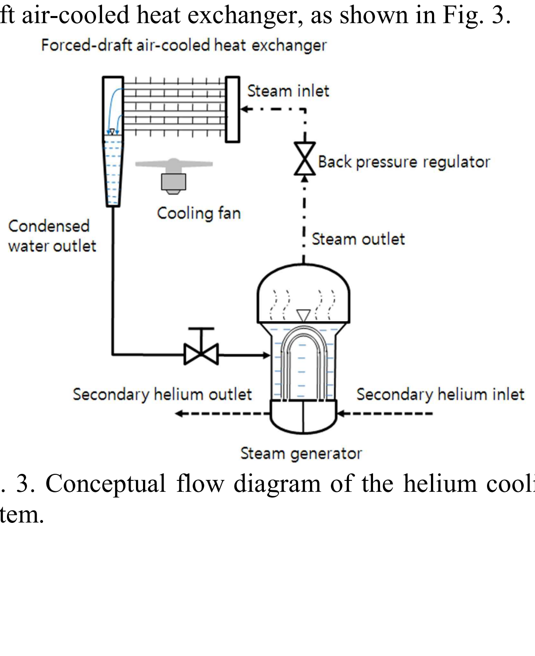

Fig. 3. Conceptual flow diagram of the helium cooling system.

3. Conclusions

A conceptual flow diagram of a helium cooling system between the IHX and SI thermochemical processes in VHTR-based SI hydrogen production facilities has been proposed. A helium cooling system for the secondary helium of the IHX in this flow diagram prevents the propagation of the thermal disturbance from the IHX system to the VHTR system, owing to the abnormal operation of the SI process components.

As a result of a dynamic simulation to anticipate the fluctuations of the secondary helium temperature owing to the abnormal operation of the SI process components with a hydrogen production rate of 60 mol·H_2/s, it is recommended that the maximum helium cooling capacity to recover the normal operation temperature of 450 °C is 31,933.4 kJ/s.

To satisfy this helium cooling capacity, a U-type steam generator, which has a heat transfer area of 12 m^2, and a forced-draft air-cooled condenser, which has a heat transfer area of 12,388.67 m^2, are required for the secondary helium cooling system.

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REFERENCES

[1] JH Norman, GE Besenbruch, LC Brown, DR O'keefe and CL Allen, Thermo-chemical Water-splitting Cycle, Bench-scale Investigations, and Process Engineering, General Atomic Company, GA-A16713, General Atomics, 1982.

[2] Shin Y, Lee K, Kim Y, Chang J, Cho W, Bae K. A sulfur-iodine flowsheet using precipitation, electrodialysis, and membrane separation to produce hydrogen. International Journal of Hydrogen Energy 2012; 37:16604-16614.

[3] Sakaba N, Sato H, Ohashi H, Nishihara T, Kunitomi K, Shiozawa S. Development strategy for non-nuclear grade hydrogen production system coupled with the Japan's HTTR. ANS Embedded Topical Meeting-2007 International Topical Meeting on Safety and Technology of Nuclear Hydrogen Production, Control, and Management, Boston, MA, USA; June 24-28, 2007.

[4] Ohashi H, Inaba Y, Nishihara T, Takeda T, Hayashi K, Takada S, Inagaki Y. Development of control technology for HTTR hydrogen production system with mock-up test facility/System controllability test for loss of chemical reaction. Nuclear Engineering and Design 2006;236:1396-1410.