Design of a Heat Loss Compensation System for Reliable Operation of the 6kW High-Temperature Steam Electrolysis Device

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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].

Plate-type SOEC stack for HTSE has the advantage of being highly manufacturable and having a dense structure with very high hydrogen production efficiency. However, it is very sensitive to thermal shocks and rapid heating or cooling should be avoided during stack operation [3]. During startup and shutdown operation, the temperature change must be kept below 0.5~1.0°C per minute [4]. Typically, laboratory-scale SOEC experiments under 3 kW utilize the internal heat of the hotbox in which the SOEC is installed to preheat the gas. In other words, the gas supply piping is installed in the form of a coil inside the hot box to heat the incoming gas close to the internal temperature of the hot box. However, it is difficult to utilize the above method for large-scale SOEC operation due to the limited size and heat capacity of the hot box.

In this study, we designed a heat loss compensation system for preheating of the incoming gases suitable for SOEC operation with large capacity. A design methodology for heat loss compensation of connecting pipes that can be generally utilized in the above process is presented, and the temperature rise tendency along the length of pipes in the hotbox(furnace) is quantified.

2. Plate-type SOEC stack for HTSE

Fig. 1 shows a schematic diagram of the HTSE connected to the heat source. 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 [3]. 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.

SOEC stacks that require an operating temperature of 600~900°C are usually installed inside a high-temperature environment hotbox to execute electrolysis operation. The SOEC has a steam channel to separate hydrogen and an air channel to blow out oxygen, a by-product, and the steam and air entering the SOEC must be preheated to the SOEC operating temperature for high-temperature operation. The steam supplied by the SOEC requires a constant, high-purity steam supply. An unstable flow rate of steam can cause pressure waves that can damage the sensitive SOEC stack internals.

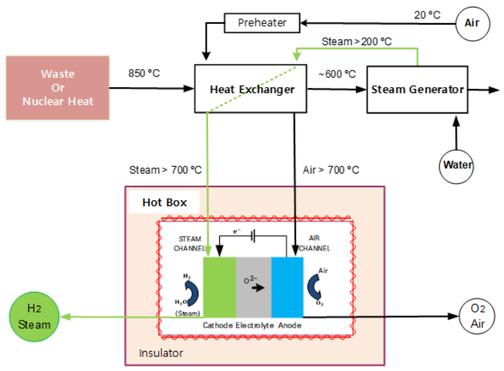


Fig. 1. Schematic diagram of the HTSE connected to the heat source.

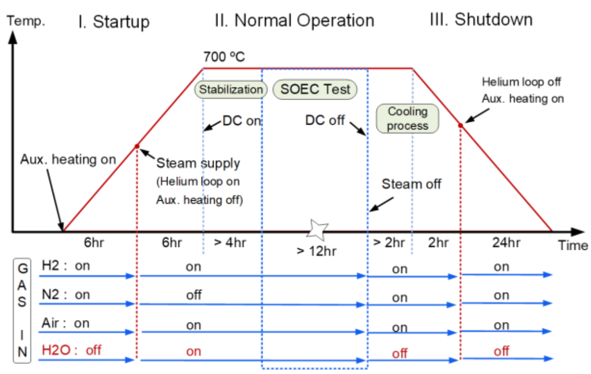


Fig. 2. Example of an operating procedure for a 6.0 kW capacity HTSE system [4].

A small amount of hydrogen (10~20% of volume fraction) as safe gas is injected into the steam channel as a reducing agent. This is to address the issue that steam can oxidize SOEC electrode materials at high temperatures, slowly degrading SOEC performance over long periods of operation. SOEC utilizes nitrogen instead of steam for heating or cooling. In addition, a trace amount of hydrogen is always introduced into the cathode (steam channel) to reduce the oxidized surface with steam.

On the other hand, the sealant of the SOEC stack is a glass material that is sensitive to high temperature thermal expansion [3]. The high temperature difference between cells can cause cracks in the glass material, which is the main cause of steam leakage, so controlling the temperature difference during cooling and heating is very important. The control logic of the stack must be configured to meet the requirements of the stack operation based on the example operating procedure in Fig. 2 [4].

3. HTSE experimental facility

An experimental facility is designed and constructed at KAERI for 30kW HTSE test using solid-oxide electrolyte cell (SOEC) stacks [2]. Fig. 3 describes a schematic of the experiment facility for 30kW HTSE system with helium loop as a heat source. The facility is composed of the major components such as a helium loop (lab-scale loop electrically simulating a VHTR), air and purified water supply system, HTSE including SOEC, steam generator, multi-stream heat exchanger (MHX), gas supply system and two auxiliary heating units(Unit-A for the steam line, Unit-B for the airline).

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 MHX are manufactured to heat both 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 MHX. Air is heated up through the MHX also, and it is used as sweep gas of anode side in SOEC stacks.

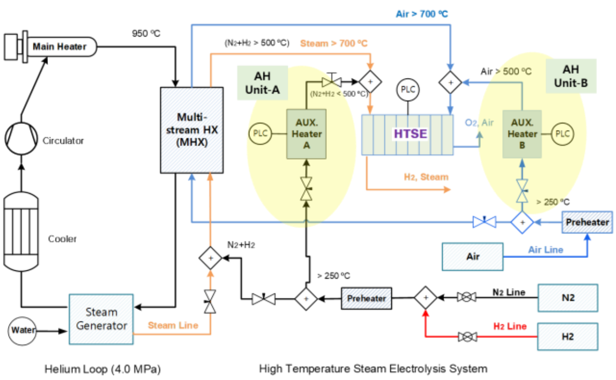


Fig. 3. Layout of the 30kW HTSE experimental facility.

4. Heat loss compensation system

The 700°C air and steam required to operate the SOEC is heated through a MHX, which is supplied with helium gas heated to over 900°C as shown in Fig. 3. However, heat losses occur in the hot piping between the MHX and the SOEC installed inside the hotbox, causing the inlet gas temperature to drop. Therefore, it is necessary to quantify the heat loss and calculate the appropriate insulation material and insulation thickness to minimize the heat loss in the connected piping and design a heat loss compensation system to compensate for the temperature drop.

4.1 Heat loss calculation of insulated pipe

Consider the circular pipe through which a given fluid is transported from one end to the other as shown in Fig. 4. It is assumed that the fluid temperature in the pipe remains constant. Heat transfer takes place through the inner surface of the pipe and outer combined (convective and radiative) heat transfer through the outer surface of the insulation.

The heat loss at steady-state from the fluid to the environment per unit length of pipe in Fig. 1 is

$$\frac{d\dot{Q}}{dx} = \frac{1}{R_{tot}}(T_1 - T_\infty) \qquad (1)$$

As shown in the Fig. 4, heat conduction in a cylinder obeys Fourier's law, as shown below [5].

$$Q_{Cond.} = -kA\frac{dT}{dx} = -2\pi krL\frac{dT}{dr} = \frac{2\pi L(T_1 - T_3)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_S} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_I}} \qquad (2)$$

The heat loss through conduction is a function of the surface temperature of the insulation where the outside air comes in contact with it. This surface temperature is also affected by atmospheric convection and thermal radiation losses. Therefore, the surface temperature is not a simple calculation, but a balance between conduction losses and losses due to convection and thermal radiation in the atmosphere. In other words, the final surface temperature and the amount of heat loss are determined by iteration.

Since the external heat loss from the insulation surface is

$$\begin{aligned} Q_{comb.} &= Convection + Thermal\ Radiation \\ &= h_{conv.}A_{I,Surf}(T_3 - T_\infty) + \varepsilon\sigma A_{I,Surf}(T_3 - T_\infty)^4 \end{aligned} \qquad (3)$$

Here, T_3 (Surface temperature of insulation) can be used as an iteration variable to obtain the insulation surface temperature and the amount of heat loss that satisfies $Q_{comb.} = Q_{Cond.}$.

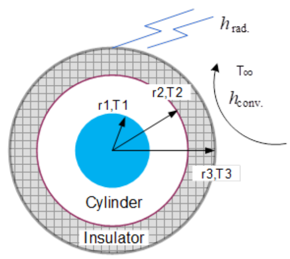


Fig. 4. Cross section of cylinder with insulation

4.2 Design methodology

Since the surface temperature and amount of heat loss varies with the insulation thickness, it is necessary to determine the "optimal insulation thickness(OIT)" at which heat loss is minimized in order to set the optimal insulation thickness [6]. Given a fixed pipe size, Equations (1) through (3) can be used to find the OIT. The Figure 5 shows the surface temperature and the heat loss per meter as a function of insulation thickness for a 1/2" tube. In the figure, the heat loss per unit length tends to decrease as the thickness increases, and it decreases nonlinearly with thickness. The OIT can be determined as a good compromise between low heat loss and a thickness of insulation that is easy to install.

Heat loss compensation can be achieved by wrapping a flexible wire heater around the outside of the tube to compensate for heat loss. Figure 6 shows a map of heat loss compensation zones for the 6 kW HTSE test rig. Each of the eight zones utilizes a PLC(Programable Logic Controller) for precise temperature control of the inlet gases as the SOEC temperature rises.

The net heat loss, , Q_{HL-net}, for each zone near the OIT is calculated and the minimum power(design limit) of the wire heater that can compensate for it is calculated by considering the insulation loss factor,F_I, as follows.

$$Q_{HL-design} = F_I \cdot Q_{HL-net} \qquad (4)$$

Table 1 shows the minimum power per zone for a wire heater with 40% insulation loss (F_I =1.4) when the insulation thickness is 30 mm.

Table I. Results of heat loss calculations by zones
(1/2" tube, T_1=700°C(Zone 1~6), T_1=250°C(Zone 7~8), t_I=30mm)

Zone	Fluid in Tube	Surface T	Length	Heat Loss (W)			Design Q
		(°C)	(m)	Conv.	Rad.	Net Loss	(W)
1	Steam+H2	189	1.5	465	217	682	955
2	Air	189	1.7	527	246	773	1083
3	Steam+H2	189	1.3	403	188	591	828
4	Air	189	1.6	496	232	728	1019
5	N2+H2	189	0.4	124	58	182	255
6	Air	189	0.4	124	58	182	255
7	N2+H2	56	2.1	139	78	217	304
8	Air	56	0.6	40	22	62	87
Total (W)				2,318	1,100	3,417	4,784

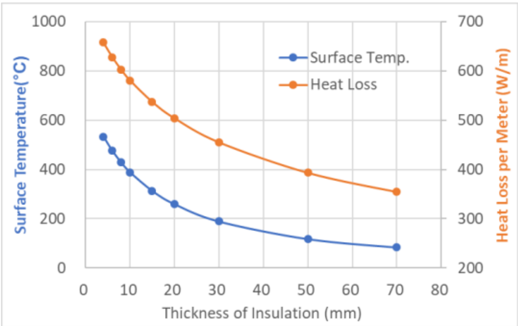


Fig. 5. Surface temperature distribution and amount of heat loss per unit length as a function of insulation thickness (1/2" tube, T_1=700°C, k_I=0.17 W/m-°C, ϵ = 0.84)

5. Gas temperature rise in the Hotbox

To compensate for heat loss, a high-temperature wire heater can maintain performance up to a piping surface temperature of 700°C, but a surface temperature of 600°C is appropriate for long-term use. However, since the operating temperature of the 6kW SOEC is 700°C, if the inlet gas temperature is always maintained at 700°C, the life of the high-temperature wire heater will be shortened. This problem can be solved by extending the length of the connecting pipe in the hotbox so that the hotbox's own heat can raise the inlet gas temperature from 600°C to close to 700°C. To estimate the required length of the connecting piping, heat transfer calculations is performed for air, steam, and steam/hydrogen mixtures for a 6kW SOEC test.

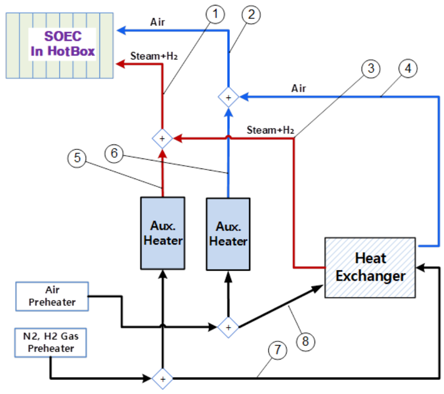


Fig. 6. Map of heat loss compensation zones

5.1 Heat transfer equations in the hotbox

The heat transfer equation of the gas flowing in the piping in the hot box is expressed as follows.

Newton's law of cooling:

$$Q_{HT} = hA(T_w - T_{gas})$$

Turbulent flow in a smooth tube:

$$Nu_d = 0.023Re^{0.8}Pr^{0.4}$$

The SOEC cathode side pipe in the hot box is injected with steam/hydrogen mixture gas, and the anode side is injected with air. Therefore, the heat transfer calculation of the cathode side where the mixed gas flows requires the mixed gas physical properties as shown below.

- Mixture properties (steam and hydrogen) for density and specific heat capacity of a gas mixture at low density follows the Amagat's law of partial volume: the total volume of a non-reacting mixture of gases at constant temperature and pressure should be equal to the sum of the individual partial volumes of the constituent gases.

$$\rho_{mix} = \sum_{\alpha=1}^{N} x_\alpha \rho_\alpha,\ C_{p,mix} = \sum_{\alpha=1}^{N} x_\alpha C_{p,\alpha}$$

- The viscosity and the thermal conductivity of a gas mixture at low density is determined with the a semi-empirical equations [7,8].

$$\mu_{mix} = \sum_{\alpha=1}^{N} \frac{x_\alpha \mu_\alpha}{\sum_\beta x_\beta \Phi_{\alpha\beta}},\ k_{mix} = \sum_{\alpha=1}^{N} \frac{x_\alpha k_\alpha}{\sum_\beta x_\beta \Phi_{\alpha\beta}}$$

In which the dimensionless quantities $\Phi_{\alpha\beta}$, a weighting factor, are

$$\Phi_{\alpha\beta} = \frac{1}{\sqrt{8}}\left(1+\frac{M_\alpha}{M_\beta}\right)^{-1/2}\left[1+\left(\frac{\mu_\alpha}{\mu_\beta}\right)^{1/2}+\left(\frac{M_\beta}{M_\alpha}\right)^{1/4}\right]^2$$

Hear,
N is the number of chemical species in the mixture,
x_α is the mole fraction of species α,
μ_α is the viscosity of pure species α at the system temperature and pressure,
M_α is the molecular weight of species α,

5.2 Results of pipe length calculation in the hotbox

The length of internal hotbox piping required for 700°C operation of a SOEC unit consisting of 1/2" tubing is evaluated. Figure 7 shows the tendency of the gas temperature to rise due to the heat of the hot box itself, assuming that the surface temperature of the piping inside the furnace is always 700°C and the inlet gas to the furnace is 600°C. In the figure 7-(a), Case 1 is a single channel 6KW SOEC with the fastest air temperature rise. On the other hand, it can be seen from the figure that the temperature rise of the steam/hydrogen mixture slows down as the concentration of hydrogen increases. The main reason is the difference in specific heat: the specific heat of the air is 1/3 less than the gas mixture(Table II), so the air temperature rises relatively quickly. In Case 2 (Fig. 7-(b)), the 1/2" piping branches into two 3KW SOECs after 0.3 meter inside the furnace, splitting the flow in half. In the case of steam/hydrogen mixture, the temperature tended to increase rapidly after the pipe branched into two(Fig. 7-(b)). The temperature of the mixed gas increased more than that of air, which is relatively slow to change.

In general, the optimum operating temperature for high-temperature wire heaters is 600°C. In this case, we can assume that the gas enters the hotbox at 600°C and calculate the length of connecting pipe required to achieve a 700°C gas mixture temperature by self-heating inside the furnace. It can be seen from the figure that the gas composition required for SOEC operation is a 20% hydrogen mixture and requires more than 2 meters of connecting piping inside the hotbox. On the other hand, if the pipe branches into two, it'll need about a meter of pipe as shown in the Fig. 7-(b).

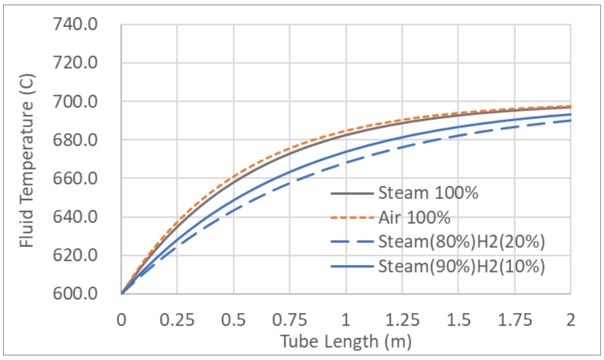
6. Conclusions

Introduced the heat loss compensation system for preheating of the incoming gases suitable for SOEC operation with large capacity. A design methodology for heat loss compensation of connecting pipes that can be generally utilized in the SOEC operation process is presented, and the temperature rise tendency of the incoming gases along the length of pipes in the hotbox(furnace) is quantified.

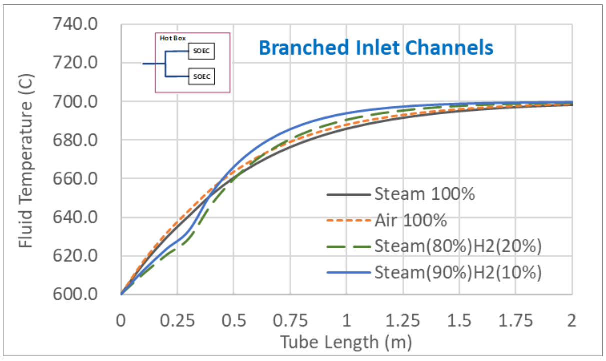
The optimal insulation thickness design for high-temperature pipes is highly influenced by thermal radiation and surface temperature. In addition, additional pipe heating in the hotbox has the effect of restoring the heat loss of the inlet gas of SOEC, so it is found that it is advantageous to increase the length of the pipe in the hotbox as much as possible to operate the heat loss compensation system.

Table II. Specific heat of the air steam, and mixed gas

Unit	Temp.	Air	Steam	H2	Mix. 20% H2
(kJ/kg-K)	500K	1.03	1.985	14.507	4.645
	700K	1.075	2.085	14.574	4.809



(a) Case 1: single channel (600°C inlet gases)



(b) Case 2: channels branched into two paths

Fig. 7. Length of 1/2" tubing to reach gas temperature of 700°C inside the hotbox (Air 100%: 1.3g/s, Steam 100%: 0.9g/s, 10%H2: Steam 0.9g/s, Hydrogen 0.011g/s, 20%H2: Steam 0.9g/s, Hydrogen 0.025g/s)

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