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Heat Transfer Analysis of Hot Gas in Piping for Supplying Steam Electrolysis Device Using Iterative Calculation Method

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1. Introduction

High-temperature thermal energy from nuclear power is a carbon-free source of thermal energy and a low-cost source of heat because it does not need to be converted into electricity. Nuclear high-temperature heat is useful for processes that require large amounts of steam, one of which is high-temperature steam electrolysis for hydrogen production. The Korea Atomic Energy Research Institute (KAERI) built a 30kW high-temperature water electrolysis test facility and conducted hydrogen production tests by heating steam and air with helium gas in a 6kW HTSE module [1]. The experiment confirmed that the gas lost heat in the connection pipe between the helium loop and the high-temperature water electrolysis module and gained heat in the internal connection pipe of the furnace where the water electrolysis module was placed. The temperature drops or rise of the gas in the connecting piping must be controlled to ensure consistent operation of the hydrogen production in the HTSE. The internal connecting pipe of the furnace is not insulated, but the external connecting pipe of the furnace can be insulated or a heating jacket can be used to compensate for the heat loss.

The purpose of this study is to provide a quantitative analysis model that can be used to quickly and easily design the connecting piping between the helium loop and the HTSE as a heat source. The analytical method is validated by experimental results of a 6 kW HTSE.

2. Gas contents in the connecting pipe

Fig. 1 shows a schematic diagram of the HTSE connected to the heat source. The solid-oxide electrolyte cell (SOEC) stacks that require an operating temperature of 600~900°C are usually installed inside a high-temperature environment furnace to execute electrolysis operation [2]. 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. A small amount of hydrogen (10~20% of volume fraction) as safe gas is injected into the steam channel as a reducing agent to reduce the oxidized surface with steam.

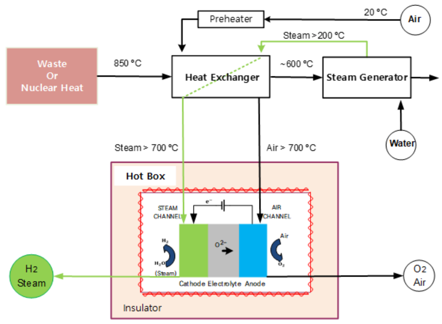


Fig. 1. Schematic diagram of the HTSE connected to the heat source

3. KAERI HTSE experiments

3.1 Experimental facility

Fig. 2 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, air and purified water supply system, HTSE including SOEC, steam generator, multi-stream heat exchanger (MHX), gas supply system and two auxiliary heating units. The experiment facility equipped a shell and helical-tube type steam generator and a MHX are manufactured to heat both the steam and air up to 800°C with the heated helium.

3.2 Selection of the validation data

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. However, heat losses occur in the hot piping between the MHX and the SOEC installed inside the furnace, causing the inlet gas temperature to drop.

Fig. 3a shows a picture of heat loss compensated pipes for the 6 kW HTSE test rig. Heat loss compensation is achieved by wrapping the heating jackets around the outside of the 1/2” pipe. The measured gas temperature drop in the connecting pipe from the experiment is shown in Fig. 3a also. The measured data are the temperature of the air and steam-mixed gas that passed through the MHX (MHX outlet temperature) and their inlet temperature to the furnace.

The experimental data extracted for validation of the self-heating analysis is located at the location shown in Fig. 3b [1]. In this case, the inlet temperatures of air and steam-mixed gas are the same as the measured values shown in Fig. 3a. As shown in the graph of the test results in Fig. 3b, the air temperature up to the furnace inlet was just over 557°C, while it reached 700°C at the stack inlet. In this experiment, the temperature of the furnace is kept at 730°C for steady-state experimental conditions.

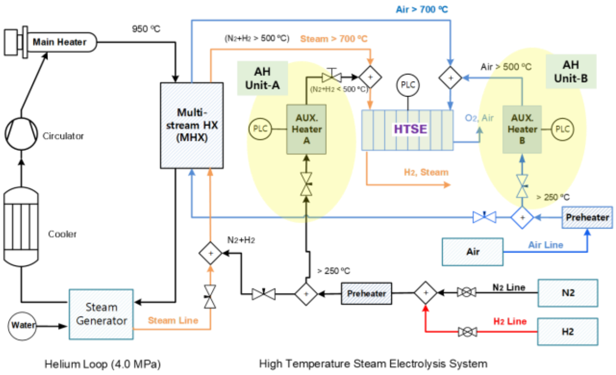
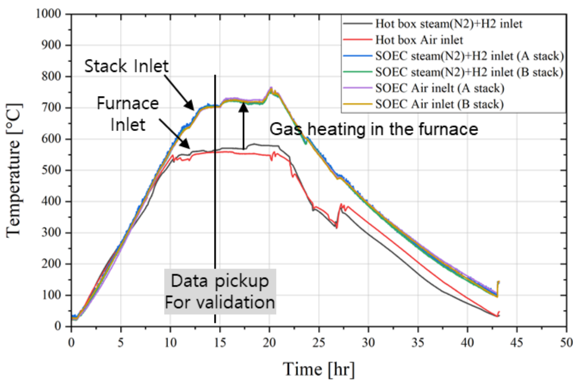


Fig. 2. Layout of the 30kW HTSE experimental facility

(a) Connecting pipes (from MHX to furnace)



(b) Measured gas temperatures in the furnace

Fig. 3. Selection of the validation data from the KAERI 6kW HTSE experiments [1]

4. Heat transfer relationship on hot gas piping

4.1 Gas temperature drops in the 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. 4 is

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

Heat conduction in a cylinder obeys Fourier's law, as shown below [3].

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

The heat loss through conduction is a function of the surface temperature of the insulation(T_s) 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

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

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

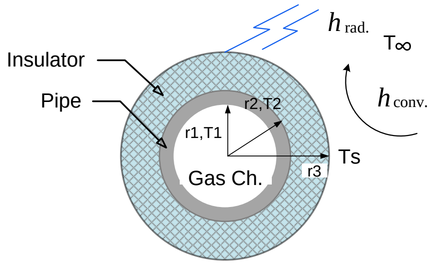


Fig. 4. Cross section of hot gas piping with insulation

4.2 Gas temperature rise in the furnace

The heat transfer equation of the gas flowing in the pipe in furnace is expressed as follows.

Newton's law of cooling:

$$Q_{HT} = hA(T_w - T_{gas}) \qquad (4)$$

Where, laminar flow in a smooth tube:

$$Nu_d = hd/k = 4.364, \qquad (5)$$

Turbulent flow in a smooth tube:

$$Nu_d = 0.023Re^{0.8}Pr^{0.4} \qquad (6)$$

4.3 Steam/hydrogen mixture property

The SOEC cathode side pipe is injected with steam/hydrogen mixed 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 mixed gas 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 mixed gas at low density is determined with the a semi-empirical equations [4,5].

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

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. Heat transfer modeling

5.1 Gas temperature drop in the connecting pipes

The key modeling assumptions introduced to simplify the analysis for a one-dimensional insulated pipe are,

- The temperature of the channel lining is equal to the temperature of the gas in the channel.
- Nodes are divided into 10 cm intervals.
- The amount of heat released to the insulating surface calculated at a node is converted to a temperature drop value at the next node.

Applying the above assumptions, the surface temperature of the insulation and the heat loss at the unit node can be obtained by iteratively solving the equations (1) and (2). The "iterative calculation" of heat loss to find the surface temperature is carried out until Qcomb equals Qcond. The iterative calculation utilizes the "Recirculation reference" function of Excel, the node size is 10cm, and it is calculated sequentially in the spreadsheet, and the gas property value calculation according to the temperature drop of the node is used REFPROP S/W [6].

5.2 Gas temperature rise in the furnace

The key modeling assumptions introduced to simplify the analysis for a one-dimensional insulated pipe are,

- The temperature of the outer wall of the channel is equal to the temperature in the furnace.
- Nodes are divided into 10 cm intervals.
- The heat calculated at a node is converted to the gas temperature rise at the next node.

Applying Equation (4) with the above assumptions, the gas temperature rise at a unit node can be easily obtained. In this case, iterative calculation is not necessary, the node size is 10cm, and the calculation is performed sequentially in a spreadsheet, and REFPROP S/W is used to calculate the gas property value according to the temperature increase of the node.

6. Results and Discussion

6.1 Temperature drops in the connecting pipes

To verify the accuracy of the modeling, the air temperature and steam/hydrogen mixture gas temperature measurements at the MHX outlet and furnace inlet in Fig. 3a are used. The channel distance from the MHX outlet to the furnace inlet is 3.3 meters for the air channel and 2.7 meters for the steam channel. The key inputs used in the calculation, including convective heat transfer coefficients, are shown below;

Air channel
- length: 3.3m
- flowrate: 1.58g/s

Steam channel
- length: 2.7m
- flowrate: steam 0.89g/s, H_2 0.0234g/s

Geometry
- tube ID: 10.9mm
- insulation thickness: 50mm

Heat transfer coefficient
- tube conductivity: 19.0 W/m-k
- insulator conductivity: 0.17 W/m-k
- convective heat transfer coefficient: 8 W/m2-k
- insulator emissivity: ϵ = 0.85

The analysis is performed without heating by a heating jacket (Method 1, no heat loss compensation) and with heating by a heating jacket when the pipe surface temperature is below 550°C (Method 2, with heat loss compensation). The calculation results show that for method 1 (no heat loss compensation), the steam-mixed gas channel is predicted very closely to the measurement without heating by the heating jacket, while the air channel shows a significant difference of 234°C (Fig. 5a, method 1). However, if we consider the case of heating with a heating jacket when the tube surface temperature is 550°C or less, which is the same as the actual experimental conditions, we can see a good agreement with the measurements (Fig. 5b, method 2).

The reason is that in the case of air with small specific heat (Table I), the temperature drops rapidly, but if the heat loss is compensated by the heating of the heating jacket, the air temperature is maintained above the set temperature of the heating jacket.

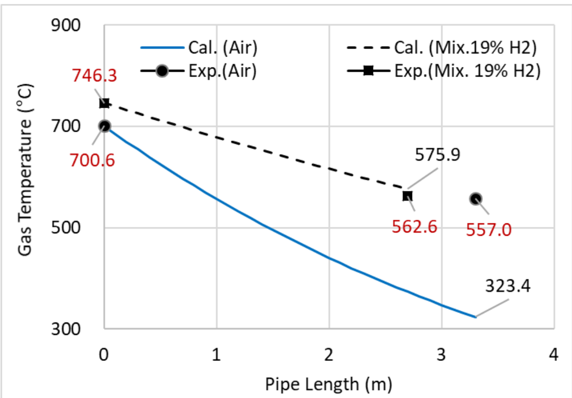
6.2 Gas temperature rise in the furnace

To verify the accuracy of the modeling, air temperature and steam/hydrogen mixed gas temperature measurements are used at the furnace inlet and SOEC stack inlet in Figure 3b. The distance between the channels from the furnace inlet to the SOEC stack is 0.5 meters for the air channel and 0.75 meters for the steam channel. Both channels are branched at 0.25 meters and connected in parallel to the two SOECs, and the inlet thermohydraulic condition of the channel is the same as the outlet of the connecting pipe whose temperature is analyzed earlier.

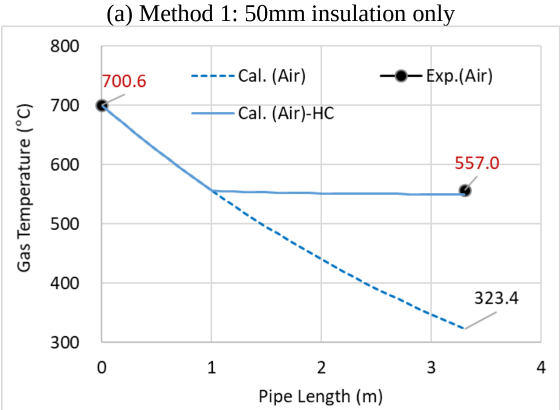
Comparing the analyzed values with the measurements (Fig. 6), it slightly overestimates the air and slightly underestimates the steam mixture, but overall it predicts the measurements very well. In the graph, we can see that the gas temperature jumps at 0.25 meters, where the pipe branches. The pipe branches into equal sized pipes, so the flow rate is halved at the bifurcation and the surface area exposed to heat is doubled. This contributed to the increase in gas temperature. The air temperature rises relatively quickly. The main reason is the difference in specific heat: the specific heat of the air is 1/3 less than the mixed gas.

Table I. 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) Method 1: 50mm insulation only



(b) Method 2: Heat compensation (keep Ts = 550 °C)

Fig. 5. Calculation results of the gas temperature drops from MHX to furnace

7. Conclusions

The purpose of this study is to provide a quantitative analysis model that can be used to quickly and easily design the connecting piping between the helium loop and the HTSE as a heat source. The analytical method is validated by experimental results of a 6 kW HTSE and we conclude the following from the modeling results.

For the gas temperature drops in the connecting pipes;

The modeling results show that the steam-mixed gas channel is predicted very closely to the measurement without heating by the heating jacket. While the air channel shows a significant difference of 234℃ without heating case. When the heat loss compensation is considered as in the experimental condition, the calculated temperature of the air channel is in good agreement with the experimental value.

For the gas temperature rise in the furnace;

The analyzed values slightly overestimate the air and slightly underestimate the steam mixture, but overall it predicts the measurements very well.

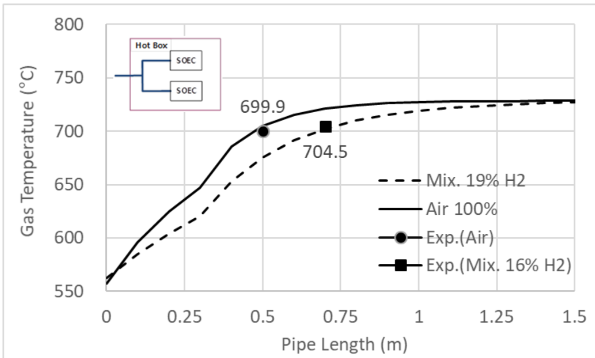


Fig. 6. Gas temperature recovery in 728.5°C furnace, channel length from furnace inlet to SOEC (flowrates are same with Fig. 5 data)

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