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Temperature Measurement through the Thermocouples with a Cooled Tube at a Very High Temperature Condition

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1. Introduction

Thermocouple is a widely used sensor for measuring temperature fields. When a thermocouple is placed in a high temperature gas, the measured temperature could be significantly biased from the true temperature due to a large radiation heat loss from a sensor surface to its surroundings [1].

Iodine-sulfur cycles coupled with a Very High Temperature gas cooled nuclear Reactor (VHTR) are being developed at the Korea Atomic Energy Research Institute as a nuclear hydrogen production system [2]. The working gas fluid temperature is very high for a massive hydrogen production. A radiation correction of the temperature measurement is very important for a high temperature operation.

A radiation correction is performed through a probe consisting of two thermocouples of unequal diameters [3]. The reduced radiation error (RRE) was defined by the ratio of the radiation error on the thermocouples with the higher temperature (1.0mm T/C measurement in this study) to the temperature difference between the two thermocouples [3]:

$$RRE = \frac{T_g - T_H}{T_L - T_H} = \frac{\varepsilon\sigma\left(T_L^2 + T_H^2\right)\left(T_L + T_H\right) + h_L}{h_L - h_H} \quad (1)$$

The CHNCC test loop [4] as shown in Figure 1 has a very high outlet temperature (1000℃) and a high pressure condition (6.0MPa).

Temperature measurement in this gas loop should be handled carefully for such items; compensation of thermocouple radiation loss, high temperature and high pressure sealing of a T/C, cooling of a T/C extension to maintain a fitting integrity. In this study, the applicability of RRE as in equation (1) is estimated to compensate for a radiation loss of a T/C at a cooled tube condition.

2. Methods and Results

2.1 Thermocouple Model and Boundary Conditions

Theoretical model for this study is based on the idealized heat transfer model [5]. Temperature profile in the thermocouple is calculated through the following energy balance equation.

$$k\frac{d}{4}\frac{d^2T}{dx^2} = h\left(T_g - T\right) - \varepsilon\sigma\left(T_s^4 - T^4\right) \quad (2)$$

In this analysis, the boundary conditions are categorized into a hot gas region, thermal insulator region, and a cooled region.

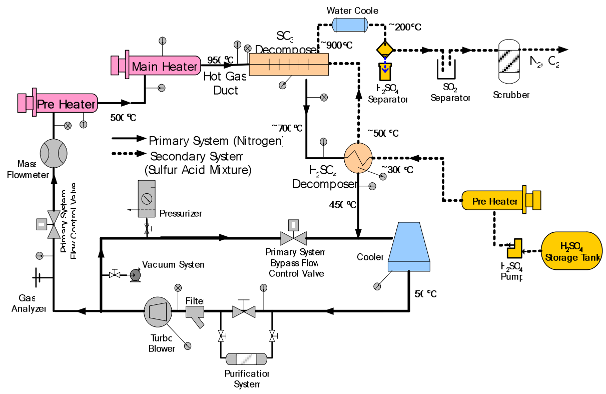

Figure 1. Schematic Diagram of CHNCC Test Loop (Referenced from Hong et al. [4])

In the hot gas convective region, the convective heat transfer coefficient between the gas flow and the thermocouple bead was referenced from Churchill and Bernstein [5]'s single comprehensive equation. In the cooled region, the heat transfer coefficient is 20W/m^2 K because the gap size between the cooled tube and a thermocouple is 1~2 mm.

The thermocouple emissivity is 0.9 which is the value for a general bare-bead thermocouple [1, 3]. In the hot gas convective region, the surrounding temperature is the liner surface temperature (850℃) from Kim et al.'s thermal analysis [6] for a hot gas duct of the CHNCC loop. In the cooled tube region, the surrounding temperature is 100℃ of the bulk liquid because the boiling and liquid heat transfer coefficient is much higher than the gas heat transfer coefficient. Figure 2 shows a schematic diagram of the thermocouple with a cooled tube in a hot gas duct.

2.2 Estimation of RRE Applicability

Figure 3 shows the temperature profile in the thermocouple with two thermocouple bead diameters (1 mm and 3.175mm). In all the cases, the slope of temperature decrease is lax in the hot gas region. In the thermal insulator region, the temperature drops at a constant slope of the tangent. Finally, the temperature profile remains stable to the coolant temperature in the cooled tube region. In this energy balance, the convective energy from the hot gas is equal to the summation of the radiation energy to liner surface and the cooled energy through the coolant. The tangent in the 1.0mm diameter is much sharper than that in the 3.175mm diameter due to the difference of the heat transferred surface area for conduction through the thermocouple. The 1.0mm diameter thermocouple is more predictable than the 3.175mm thermocouple, but the error of the measured temperature due to the radiation heat loss is about 20^{o}C.

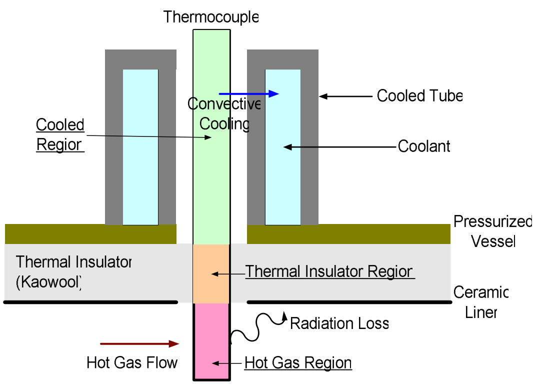

Figure 2. Schematic Diagram of the Thermocouple in the Hot Gas Duct

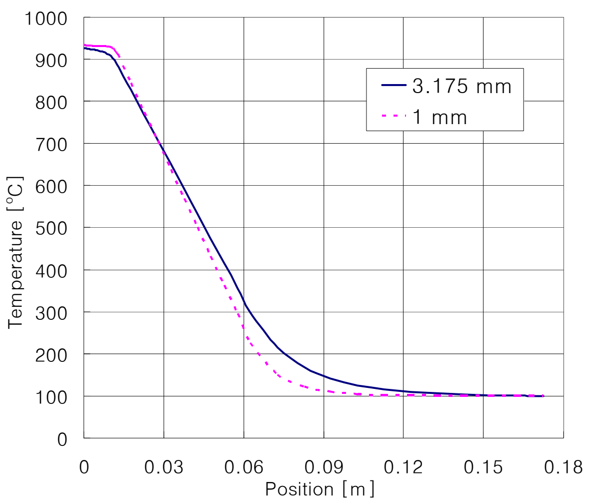

Figure 3. Temperature Profiles with Thermocouple Diameters

Table 1 shows the RRE-calculated temperatures with or without the cooled tube. In the case of no cooled tube, the convective energy from the hot gas is equal to the radiation energy from the thermocouple to the liner surface. If a thermocouple is used, the calculated temperature is 20~30℃ lower than the active temperature. The calculated temperature with a cooled tube is higher than that with no cooled tube. In the case of no cooled tube, there is no heat flux at the interface between insulated region and hot gas region in Figure 2. Otherwise, the cooled tube makes some heat flow from the hot gas region. The heat flow causes a temperature gradient as shown in Figure 3. The corrected temperature through RRE as in equation (1) is almost coincident with the true gas temperature in all the cases.

3. Conclusion

Thermocouple is widely used for measuring temperature fields in thermo-hydraulic experiments. At a very high temperature gas condition, a thermocouple reveals a large uncertainty due to a large radiation and a small convective heat transfer. From this study, a couple of two thermocouples with a cooling tube is one of the solutions for reducing this large radiation error.

Table 1. Calculated Temperatures for Measurement (True Gas Temperature: 950℃)

Case	1 mm TC, T_H	3.175 mm TC, T_L	Corrected T through RRE, T_g
w/o Cooled Pipe	931.32℃	923.48℃	949.4663℃
Cooled Pipe	933.80℃	926.65℃	950.3742℃

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