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Reduced Radiation Error for Temperature Measurement in Internal Gas Flow

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1. Introduction

When a thermocouple is placed in a high temperature gas-flow stream, the measured temperature could be biased from the true gas temperature due to a large radiation heat loss from a thermocouple surface to its surroundings. The energy is transferred by convection to the thermocouple and then dissipated by radiation to the surroundings [1]. The energy balance on the thermocouple between the convection and radiation is written as the following equation.

$$h\left(T_g - T\right) = \varepsilon\sigma\left(T^4 - T_s^4\right) \tag{1}$$

Especially, the biased temperature measurement from the radiation is very important to development in a Very High Temperature gas cooled nuclear Reactor (VHTR).

Many investigators have suggested the various methods for correcting the radiation error, which include a probe with two thermocouples of unequal diameters [2] or of unequal emissivity values [3], a suction pyrometer, a radiation shield and others. In this study, we measured the temperature in an internal gas flow by two thermocouples of unequal diameter and estimated the effect of the diameters on the temperature measurement.

2. Methods and Results

2.1 Reduced Radiation Error

Since, unequal diameters of two thermocouples cause the difference between their convective heat transfer coefficients, two thermocouples indicate each other's difference in the case of the large temperature difference between wall and gas. The indicated temperature difference between two thermocouples makes it possible to correct the radiation error without the temperature measurement on the surroundings of the thermocouple. Brohez et al. [2] defined the Reduced Radiation Error (RRE) as the ratio of radiation error on the thermocouple with the higher temperature measurement (1/16 inch diameter thermocouple in this study) to the temperature difference between two thermocouples (1/16 inch and 1/8 inch diameter thermocouples in this study). RRE is derived from the energy balances on two thermocouples.

$$RRE = \frac{T_g - T_H}{T_H - T_L} = \frac{h_{rad} + h_L}{h_H - h_L} \tag{2}$$

2.2 Test Loop

Figure 1 shows the schematic diagram of the RRE test loop used in this study. Because this loop is opened, the pressure of the gas flow is always maintained at 1 atm. The volumetric flow rate is maintained at 30 L/min by the Mass Flow Controller (MFC). The regulator decreases the pressure of the MFC inlet at about 2 atm. The working fluid is the high purity nitrogen. The heaters designed by Hong et al. [4] are used for heating the gas flow. Test section is the stainless steel pipe whose outer diameter and length is 1.5 inch and 3 m, respectively. The pipe is not thermally insulated for the pipe cooling. Two thermocouples with unequal diameters of 1/16 inch and 1/8 inch are installed to test the RRE effect. In this paper, the experimental data measured at the inlet is analyzed to estimate the diameter effect on the temperature measurement. The pictures in Figure 1 show the installation of the thermocouples in this test loop.

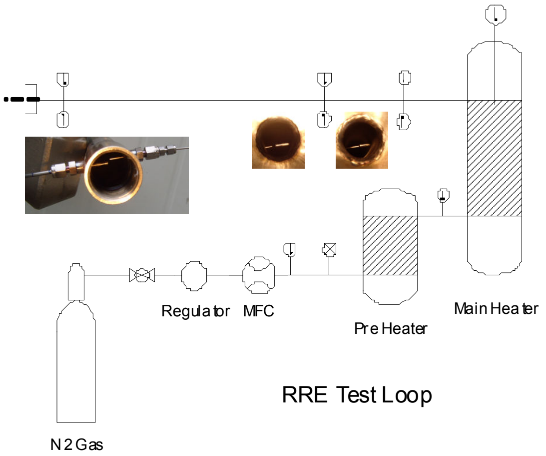

Fig. 1. Schematic diagram of Test Loop

2.3 Test Results

Figure 2 shows the temperature history at the inlet of the test section during heating the test loop. When there is no temperature difference between the gas flow and its surrounding surface, there is also no temperature difference between the measured temperatures of 1/16 inch and 1/8 inch thermocouples. When the gas temperature is higher than the wall temperature, the measured temperatures from 1/16 inch thermocouple is higher than those from 1/8 inch thermocouple. Equation (1) shows that the increased convective heat transfer coefficient results in the closer measurement of the gas flow temperature. The convective heat transfer coefficient on thermocouples can be obtained from

Whitaker [5]'s correlation, which covers not only entire range of Reynolds number but also a wide range of Prandtl number for a sphere in a cross-flow. The equation is as follows:

$$
\begin{aligned}
Nu_D &= \frac{hD}{k} \\
&= 2 + \left(0.4\,\mathrm{Re}_D^{0.5} + 0.06\,\mathrm{Re}_D^{0.667}\right)\mathrm{Pr}^{0.4}\left(\mu / \mu_S\right)^{0.25}
\end{aligned}
\qquad (3)
$$

Equation (3) shows that the thermocouple diameter decreases the convective heat transfer coefficient at the same thermo-hydraulic condition. Therefore, the measured temperatures from 1/16 inch thermocouple are higher than those from 1/8 inch thermocouple. In addition, the increased temperature difference between the gas and its surrounding surfaces increases the energy dissipated by the radiation and others from the thermocouple surface. Then, the increased energy loss increases the measured temperature difference between two thermocouples as shown in Figure 2. The response time is not considered during this radiation-correction.

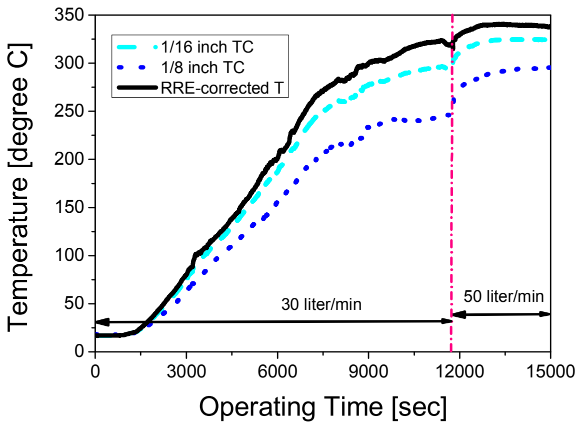

Fig. 2. Temperature Histories at the Test Section

Table 2 summarizes the measured and calculated temperature values at the operating time of 15000 sec at the quasi-steady state. When it is assumed that the corrected temperature by RRE and the wall temperature are a true temperature of the gas and the effective radiation temperature of the surroundings, the calculated temperatures of two thermocouples from Equation (1) is closer than the true temperature of the temperature. The calculated temperature difference between two thermocouples is 21.1℃, which is much lower than the measured temperature difference of 28.7℃. The underestimation of two thermocouples results from the lower effective radiation surroundings temperature than the measured wall temperature. The underestimated degree of 1/8 inch thermocouple is larger than that of 1/16 inch thermocouple, because the increased diameter of the thermocouple increases the energy dissipation by the radiation from the thermocouple sheath tube.

Table 1. Temperature at the Operating Time of 15000 sec

True Temperature of the Gas*		338.15℃
Diameter of TC	1/16 inch	1/8 inch
Measured Temperature	324.2℃	295.5℃
Calculated Temperature**	328.2℃	307.1℃

* Obtained from RRE and the measured temperatures
**Obtained from Equation (1) and the measured wall temperatures

3. Conclusions

In this study, a probe with two thermocouples of unequal diameter was experimentally estimated to apply the temperature measurement in a gas flow. The experimental results show that a thermocouple has large uncertainty at the gas temperature measurement. The uncertainty results from radiation heat transfer between the thermocouple and the surroundings, radial temperature distribution and the low convective heat transfer coefficient on the thermocouple.

In the future, the following experimental conditions are added to show the predictability of the RRE method.

- Test section with thermal insulation to minimize the radiation loss from the thermocouple
- Test section with water cooling jackets to maintain the constant wall temperature

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