Theoretical and Experimental Studies in the Temperature Measurement due to the Combined Heat Transfer

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1. Introduction

The accurate measurement of the temperature of a hot gas flowing in a pipe is more difficult than the accurate measurement of the temperature of a solid and liquid. When an appreciable temperature difference exists between the gas stream and pipe wall, errors arise from the temperature gradient in the gas stream and a loss of heat by conduction and radiation from the thermocouple. Convective heat transfer between the gas stream and thermocouple is balanced against the radiative heat transfer between its enclosing wall and thermocouple, and simultaneously against the conductive heat transfer between thermocouple and its supports. The problem of measuring the temperature of a gas stream by employing a thermocouple has been researched well by Hennecke[1], Clarksean[2], and Otter[3]. It is important to recognize the number of possible errors in the temperature measurement, since many of these errors can be reduced by a proper design and installation. This paper discusses the errors associated with a heat conduction, radiation, and convection that should be taken into account in both the design and installation of the thermocouples to minimize these errors. A mathematical model for estimating the errors is discussed, and calculations are performed over a range of immersion depth and flow conditions. The results are compared to those obtained by the experiment.

2. Combined Heat Transfer Equation

Consider a gas stream flowing through a pipe into which is immersed a thermocouple and its support. The pipe is not completely insulated, and it is assumed that an equilibrium has been reached. Thermocouple sheath is divided into 3 meshes in the R direction and some meshes in the Z direction, as shown in Fig. 1. The temperature at the tip of thermocouple indicates the gas temperature, T_g, and the temperature at the wall of the support indicates the wall temperature, T_w.

2.1 The heat balance

When the wall is hotter than the gas, the thermocouple temperature is such that the rate of the heat transfer by a convection from the thermocouple to the gas plus a radiation from the thermocouple to the gas plus conduction from the wall to the thermocouple is equal to zero. This may be stated in equation form, as follows;

$$q_c + q_r + q_k = 0 \qquad (1)$$

where,

q_c = *rate of heat transfer by convection.*
q_r = *rate of heat transfer by radiation.*
q_k = *rate of heat transfer by conduction.*

2.2 Convective heat transfer

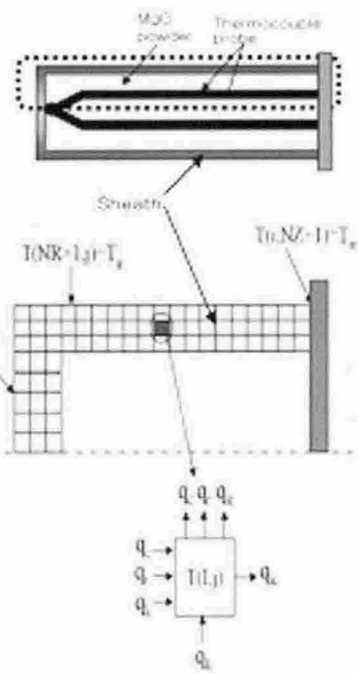

Figure 1. Heat transfer model for the thermocouple.

Heat will be transferred to the gas from the thermocouple by a forced convection. This phenomena is described as

$$q_{c,i,j,r} = h_{c,j,r}(T_{i,j}-T_{g,j}) \qquad (2)$$
$$q_{c,i,i,,z} = h_{c,j,z}(T_{i,j}-T_{g,j}) \qquad (3)$$

where,

$q_{c,i,j,r}$ = *rate of heat transfer by convection in R direction.*

$q_{c,i,i,,z}$ = *rate of heat transfer by convection in Z direction.*

2.3 Radiative Heat transfer

There will be an interchange of the radiant energy between the thermocouple and the enclosing wall. This phenomena is defined as

$$q_r = \varepsilon\sigma[\pi D_{TC}\Delta Z_j\delta(i-NR)+ \pi(r_i^2-r_{i-1}^2)\delta(j-1)](T^4_{wall}-T^4_{i,j}) \qquad (4)$$

where,

ε = Emissivity
σ = Stefan-Boltzman constant

2.3 Conductive Heat transfer

Heat will be transferred from the tip of the thermocouple to its base by means of a conduction. For four sides, the conductive heat transfer equation is as follows.

$$q_k = q_{k,z,i-1,j} - q_{k,z,i,j} + q_{k,r,i,j-1} - = q_{k,r,i,j} \quad (5)$$

An initial $T^{(0)}_{i,j}$ is assumed, and all the other temperatures are obtained according to equations (1), (2), (3), (4), (5). The calculated $T^{(N+1)}_{i,j}$ is compared to $T^{(N)}_{i,j}$. Iteration schemes(Gaussian elimination method) rapidly lead to a unique solution.

3. Experimental

The air is passed through the pipe at the room temperature and hence to the test section of the pipe(Fig. 2), which is 106mm in diameter and 500mm long. The wall temperature is measured using a 1/4 inch diameter special surface thermocouple embedded into the wall. And the gas temperature is measured using the thermocouple with a radiation shield. Two sets with different diameters, 6.35mm and 4.76mm, and each set in three different immersion lengths, 18.2, 35.2, 53.2mm is tested at the gas flow of 0.24, 0.50, and 0.76m^3/min.

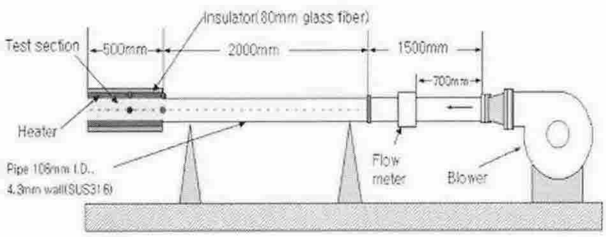

Figure 1. Experimental Device.

4. Results

The measurement errors tended to become lower as the air flow rates increased. When the length of the immersed portion of the thermocouple was short, the measurement errors were greatly affected by the conduction heat from the wall. As the immersion length of the thermocouple was lengthened, the measurement errors became lower. In the case that the immersion length of the thermocouple was short, the measurement error of the thermocouple with the large sized diameter was greater than that of the thermocouple with a small sized diameter. However, in the case that the immersion length of the thermocouple was long, the measurement error of the thermocouple with the small sized diameter was greater than that of the thermocouple with a large sized diameter.

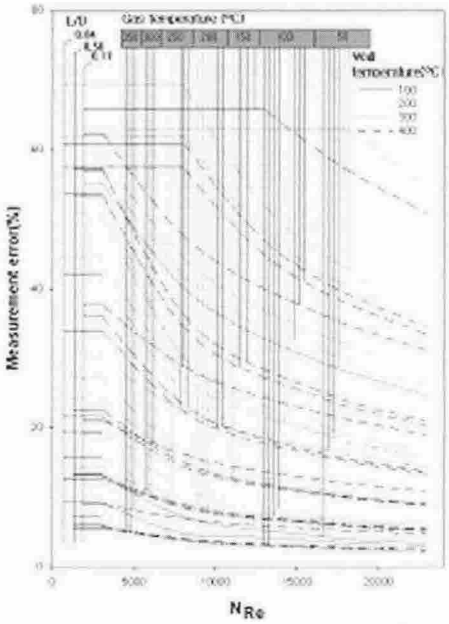

Figure 2. Guidelines for the design and installation of the thermocouple.

5. Conclusions

The theory of the thermocouple errors caused by a combined heat transfer, which was developed by this study, was verified by an experiment using air flows under various experimental conditions. The measured errors were in good agreement with the theory and they were greatly affected by the wall temperature, the air flow rate, and the diameter and the length of the sensor. Optimum conditions to minimize the measurement errors were obtained by plotting the theoretical results.

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