열선 풍속계의 해석

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Analysis of a Hot-Wire Anemometer

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1. Introduction

Flow measurement devices using hot-wire are widely utilized in gas and liquid systems due to simplicity and wide range of application capability. Most of the devices having high precision are not suitable for the industrial applications with rough environment, such as steel mill, metal heat treatment and specialty welding processes. Hot-wire anemometers are good for these implementations because they are simple and rugged to yield the measurement of reasonable precision with on-line application.

Many studies of hot-wire anemometry have been published, and in a study [1] two hot-wires were utilized for the simultaneous measurement of gas concentration and flow rate. For the selective measure of hydrogen, a tin oxide coated sensor was also introduced [2]. A coated hot-wire was used in ultra low flow measurement [3]. By determining velocity profile very near a wall, friction coefficient is evaluated from using hot-wire sensors [4].

For the compensation of temperature variation in the flow measurement, three wires were implemented to detect temperature and flow simultaneously [5]. In other study [6], the temperature compensation was conducted by adjusting applied voltage to the hot-wire. An industrial application of gas flow and concentration measurement was reported [7].

In this study, a hot-wire module of simple structure is proposed for the measurement of gas flow rate. The distribution of temperature in the measuring module of the hot-wire is computed from a numerical analysis, and the outcome is compared with the experimental measurements. In addition, the accuracy and reproducibility of the module are investigated experimentally.

2. Numerical Analysis

A simple structure of the hot-wire module proposed in this study is demonstrated in Figure 1. The hot-wire is made of stainless steel wire of 0.035 mm in diameter, and the ends of the wire is connected to a copper wire for the electrical connection to a control circuit described below. The inside diameter of the module is 18 mm. The first and last wires to the direction of gas flow are used in the flow measurement and the middle wire is a heater to raise the measurement sensitivity. They have 3 mm gap and are placed in perpendicular to the flow direction. The first measures inlet gas temperature. The middle heater raises the temperature, and the difference between the inlet and heated temperatures is detected by the last. Therefore, the flow measurement is mainly affected from the two hot-wires of the heater and the last wire which are examined in numerical analysis.

For the computation of temperature distribution, the momentum and energy balances are formulated based on the following assumptions:

1. steady state velocity and temperature profiles
2. negligible radial and angular velocities
3. negligible variation of axial velocity in angular and axial direction
4. gravitational force neglected
5. no pressure gradient
6. axi-symmetric temperature profile
7. negligible axial conduction

8. dissipation neglected

Using the assumptions a momentum balance is written as

$$-\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r}\frac{\partial v_z}{\partial r}\right] = 0 \tag{1}$$

B. C. $\frac{\partial v_z}{\partial r} = 0$ at $r = 0$

$v_z = 0$ at $r = R$

and an energy balance is

$$\rho C_p v_z \frac{\partial T}{\partial z} = k \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right] \tag{2}$$

B. C. $\frac{\partial T}{\partial r} = 0$ at $r = 0$

$T = 0$ at $r = R$

$T = T_1$ at $z = 0$ and $r = r_w$

$T = T_1$ at $z = 0$ and $r \neq r_w$

The origin of radial coordinate is the center of the measuring module, and the end is the inside wall of the module. The r_w in Eq. (2) is the radius of the hot-wire. The wire shown in Figure 1 is not a closed circle, but it is assumed to be a circle for the simplicity of the analysis. The axial coordinate spans from the location of the heater to the location of the last wire. The detailed dimension of the module is summarized in Table 1. The temperature of the heater is calculated from the electric power consumption to be included in the table.

Because the flow is laminar in steady state, the velocity is readily found from Eq. (1).

$$v_z = v_{zm} \left[1 - \frac{r^2}{R^2}\right] \tag{3}$$

where v_{zm} is the maximum gas velocity at the center and twice the average velocity. Using the velocity the energy equation is numerically solved.

The equation in dimensionless form is

$$v_z' \frac{\partial T'}{\partial z'} = \alpha' A \left[\frac{\partial T'^2}{\partial r'^2} + \frac{1}{r'}\frac{\partial T'}{\partial r'}\right] \tag{4}$$

where the primes indicate the dimensionless variables.

For the cylindrical module, the system equation is formulated in cylindrical coordinate. In the formulation of finite difference equation from Eq. (4), a two dimensional rectangular grid from the center axis in radial direction is employed as the system is axi-symmetric. The Crank-Nicholson method of an implicit technique is implemented here to solve the parabolic partial differential equation.

3. Results and discussion

From the numerical analysis using Eq. (4), the temperature distribution between the heater and sensor wires at the average gas velocity of 2.62 cm/s is yielded and displayed in Figure 2. As the distance from the heater increases, the temperature drops. Whereas convection dominates in axial direction, conduction is the main mechanism of heat transfer in radial direction. The conduction at cylindrical wall removes heat to reduce the temperature along with axial direction. The heat removal accounts for a slight skew to center of the temperature distribution of Figure 2.

The elevation of gas flow raises the axial convection to increase the temperature at the location of the sensor as shown in Figure 3. This explains the experimental outcome to be discussed later. The dislocation of the peak temperature to center with low gas flow is caused from the conduction at wall. At low velocity the wall conduction is relatively large as noticed from the temperature gradient at the wall in Figure 3, which removes heat generated from the heater. Without the conductive heat removal, peak temperature is obtained at the radial location of heater due to axial gas flow like the case of gas flow of 10 cm/s. However, the peak temperature moves inside because the wall conduction lowers the temperature in outer region at low gas velocity. Convective heat transfer is dominant near wall at high gas velocity. The temperature distributions in axial location with different gas velocities are given in Figure 4. The large temperature drop with low velocity indicates that a large amount of heat is removed at the wall.

From the experiment with varying flow rate, the variation of measured voltage signal and temperature are illustrated in Figure 5. The air flow begins with 300 mL/min. It is reduced by 50 mL/min until 200 mL/min, raised to 400 mL/min and then lowered back to 300 mL/min. The signal variation is almost linear with the flow change. As yielded from the numerical analysis, the higher the flow is, the higher the temperature is at a sensor wire. High velocity gives high temperature at the sensor, and the large difference of temperature between reference and sensor wires produces strong signal from the bridge circuit.

4. Conclusion

A low cost gas flow measurement module is proposed, and its performance is experimentally examined. In addition, a numerical analysis is conducted to understand the process of flow measurement.

The experimental outcome shows that the proposed module has a good reproducibility and comparable accuracy of measurement to commercially available low cost devices. The measurements of air and carbon dioxide show nearly linear relation between flow rate and measurement signal. Also, a good compensation of inlet gas temperature variation is observed. The outcome from the numerical analysis explains the measurement mechanism and relation between flow rate and measurement signal.

Acknowledgment

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Table 1. Parameters for numerical analysis

Symbol	Value
R	0.9 cm
Z	0.3 cm
T_1	25.6 °C
T_0	25 °C
v_{zav}	2.62 cm/s
r_w	0.25 cm
α	0.222 cm^2/s
d_w	0.0035 cm
h_w	266 W/m^2 °C
q_w	0.246 W

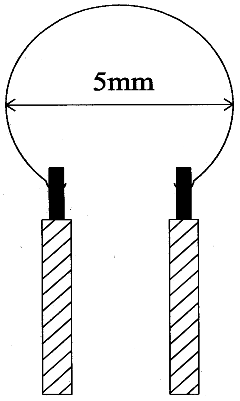

Figure 1. Description of a hot-wire.

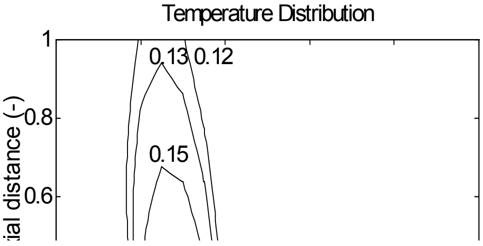

Figure 2. Normalized temperature distribution between heater and sensor wires at average gas velocity of 2.62 cm/s.

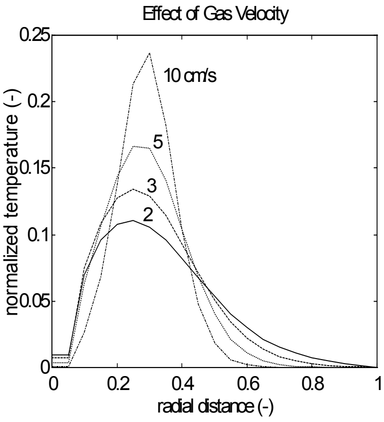

Figure 3. Effect of average gas velocity on the temperature at the axial location of sensor.

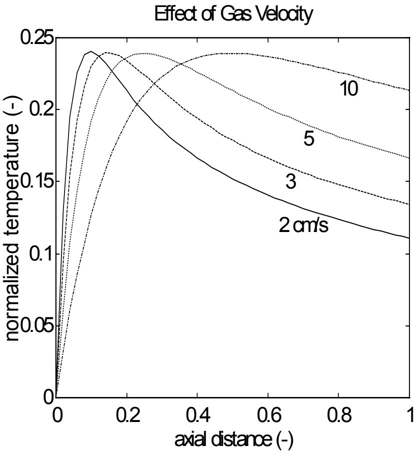

Figure 4. Effect of average gas velocity on temperature at the radial location of sensor.

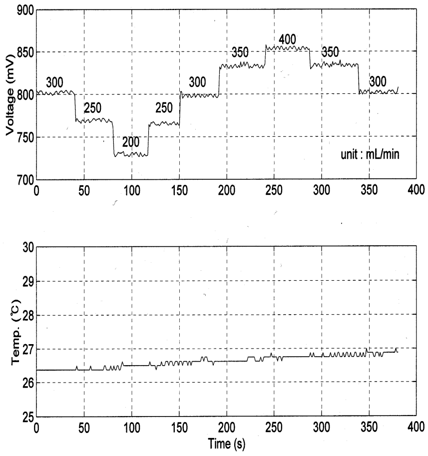

Figure 5. Variations of measurement signal and temperature with varying air flow rate.