Numerical and Experimental Analyses of a Hot-Wire Gas Flowmeter

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Abstract: A measurement device for gas flow rate using hot-wire module is developed for the utilization in low-accuracy industrial applications. The module has three wires of measuring and heating, and a bridge circuit is installed to detect electric current through the wire in the module. An amplification of the signal and conversion to digital output are conducted for the on-line measurement with a personal computer. In addition, temperature distribution in the module is numerically analyzed to examine the measured outcome from the module experiment.

The flow rate of air and carbon dioxide gas is separately measured for the performance examination of the device. The experimental relation of measurement and flow agrees with the prediction from the numerical analysis. The outcome of the performance test indicates that the accuracy and reproducibility of the module is satisfactory for the purpose of industrial applications.

Keywords: hot-wire, gas flow meter, on-line measurement, process monitoring, anemometry

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 three wires of the figure are installed in a module given in Figure 2. 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

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

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

$v_z = 0$ at $r = R$

and an energy balance is

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

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

$T = 0$ at $r = R$

$$T = T_1 \quad \text{at } z = 0 \text{ and } r = r_w$$
$$T = T_1 \quad \text{at } z = 0 \text{ and } r \neq r_w$$

The origin of radial coordinate is the center of the measuring module described in Figure 2, 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).

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

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

$$v_z' \frac{\partial T'}{\partial z'} = a' A \left[\frac{\partial T'^2}{\partial r'^2} + \frac{1}{r'} \frac{\partial T'}{\partial r'} \right] \quad (4)$$

where the primes indicate the dimensionless variables as below.

$$T' = \frac{T - T_0}{T_1 - T_0},$$
$$r' = \frac{r}{R},$$
$$z' = \frac{z}{L}$$
$$v_z' = \frac{v_z}{v_{zm}}$$
$$a' = \frac{a}{v_{zm} Z}$$

and

$$A = \frac{Z}{R}$$

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 [8] is implemented here to solve the parabolic partial differential equation.

3. EXPERIMENTAL

3.1 Preparation of hot-wire module

The three wires shown in Figure 1 are installed in parallel and perpendicular to the direction of gas flow in the module illustrated in Figure 2. The sensor is made of a stainless steel wire of 0.035 mm in diameter and the ends are connected to a copper wire of 0.75 mm in diameter by plier-pressing. The resistance of the hot-wire is 7 ohms.

The module is made of 15 mm pipe fittings, such as a tee and hose nipples. The wires are connected to a bridge circuit to detect the variation of electric current. The center wire is heater as denoted H in the electric schematic of Figure 3 and two side wires are sensor as denoted S1 and S3. One of the two sensors is for the compensation of air temperature, and the other works for flow measurement. The gas temperature is separately detected with a platinum resistance thermometer.

3.2 Experimental setup

A rotameter is installed as shown in Figure 4, and the air flow is adjusted with a needle valve attached on the rotameter. A blower provides air supply for experiment.

A bridge circuit of Figure 3 is implemented to measure the electric current varying with gas flow rate. The voltage of the power to the circuit is 1.5 volts. The variation of the current is so small that direct measurement of the current is difficult. An amplification of the voltage signal converted from the current is carried out with the circuit described in Figure 5. The amplified signal is relayed to a personal computer through an A/D converter. Because commercially available converters are designed for the application of high sampling rate, they are prone to noisy conversion. The signal variation in this study is relatively slow, in which an integration-type A/D converter is suitable thanks to its good performance in noise rejection. Figure 6 shows the schematic of a home-made A/D converter of integration type. A multiplexed analog signal through the component 4051 is provided to the A/D converter MC14433, and the resulted digital data is buffered through the component 74373 and fed to the PC for data collection and storage.

3.3 Experimental procedure

Two kinds of gases of air and carbon dioxide are used in the experiment. The air is fed with a small blower, and the carbon dioxide is supplied from a liquefied gas cylinder. While the flow of the air is readily adjusted because of its low pressure, that of the carbon dioxide in high pressure is difficult. Two 1/8-inch needle valves are installed in the line from the pressure regulator attached at the gas cylinder. The gas flow is measured with the rotameter shown in Figure 4.

The gas flow rate is adjusted between 100 mL/min and 400 mL/min. With continuous measurement of the voltage signal from the hot-wire module and thermometer, the flow is varied by 50 mL/min and the measurement is stored in the PC for the later analysis of experimental outcome.

4. RESULTS AND DISCUSSIONS

From the numerical analysis using Eq. (4), the temperature distribution between the heater and sensor wires given in Figure 2 at the average gas velocity of 2.62 cm/s is yielded and displayed in Figure 7. 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 7.

The elevation of gas flow raises the axial convection to increase the temperature at the location of the sensor as shown in Figure 8. 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 8, 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 9. 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 10. 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. The air flows in the beginning and the end of the experiment are adjusted to be same to examine the reproducibility of the measurement. The experimental outcome shows a good reproducibility. Comparing the noise in the measurement with flow variation shows that the current device can detect as small as 10 mL/min of flow variation. This measurement accuracy is comparable to any low cost flow measurement devices. Moreover, the hot-wire module is readily connected to a PC for on-line applications.

The same process of experiment is conducted with carbon dioxide, and the result is shown in Figure 11. The pattern of signal variation and reproducibility are similar to the experiment of air. The range of flow rate is between 100 mL/min and 250 mL/min, and the higher flow rate gives stronger signal as obtained with the previous experiment and the numerical analysis. The reproducibility found from the experiment with air is also yielded in this experiment. The experimental outcomes of air and carbon dioxide are plotted in Figure 12 to examine the relation between flow rate and measured signal. The figure shows almost linear relation for both gases. The sensitivities ~~the~~ slope of the curves in the plot ~~of~~ both gases are nearly same.

The effect of inlet gas temperature is investigated with air of varying temperature, and the measurement is given in Figure 13. The fluctuation of measurement is barely observable while the air temperature varies about 10 degrees. This result indicates the measurement system of this study has a good temperature compensation mechanism.

5. 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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NOMENCLATURE

C_p	= heat capacity	[kJ/kg °C]
d_w	= wire diameter	[cm]
h_w	=convection heat-transfer coefficient on heater	[W/m^2 °C]
k	= conductivity	[W/m °C]
p	= pressure	[kPa]
q_w	= heat generation rate	[W]
R	= module radius	[cm]
r	= radial coordinate	
r_w	= wire radius in Figure 1	[cm]
T	= temperature	[°C]
T_0	= inlet gas temperature	[°C]
T_1	= heater surface temperature	[°C]
v_z	= axial velocity	[cm/s]
v_{zav}	= average velocity	[cm/s]
v_{zm}	= maximum velocity	[cm/s]
Z	= distance between heater and sensor	[cm]
z	= axial coordinate	
Greek Letters		
á	= thermal diffusivity	[m^2/s]
ì	= viscosity	[kg/m s]
ñ	= density	[kg/m^3]

REFERENCES

[1]. Sakai, Y., Watanabe, T., Kamohara, S., Kushida, T. and Nakamura, I., "Simultaneous measurements of concentration and velocity in a CO2 jet issuing into a grid turbulence by two-sensor hot-wire probe," *Int. J. Heat and Fluid Flow*, **22**, 227 (2001).

[2]. Katsuki, A. and Fukui, K., "H2 selective gas sensor based on SnO2," *Sensors and Actuators B*, **52**, 30 (1998).

[3]. Afgan, N. H., Pereira, J. C., Leontiev, A. I. and Puzach, S. V., "Concept of porous wire anemometer," *Int. Comm. Heat Mass Transfer*, **24**, 411 (1997).

[4]. Hutchins, N. and Choi, K. S., "Accurate measurements of local skin friction coefficient using hot-wire anemometry," *Prog. Aerospace Sci.*, **38**, 421 (2002).

[5]. Vukoslavcevic, P. V. and Wallace, J. M., "The simultaneous measurement of velocity and temperature in heated turbulent air flow using thermal anemometry," *Measurement Sci. Tech.*, **13**, 1615 (2002).

[6]. Truzzi, G. E., Sarma, G. R. and Chokani, N., "Constant

voltage anemometer operated hot wire at subsonic speeds over wide overheats in unsteady flows," *Rev. Sci. Instrum.*, **73**, 4363 (2002).

[7]. Kim, Y. H. and Choi, J. J., "Measurement of Gas Concentration and Flow Rate Using Hot Wire,", *J. Cont. Auto. Sys. Eng.* (in Korean), **8**, 407 (2002).

[8]. Carnahan, B., Luther, H. A. and Wikes, J. O., "Applied Numerical Methods," John Wiley & Sons, Inc., New York, 451 (1969).

Table 1. Parameters for numerical analysis

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

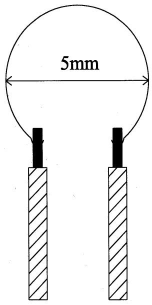

Figure 1. Description of a hot-wire.

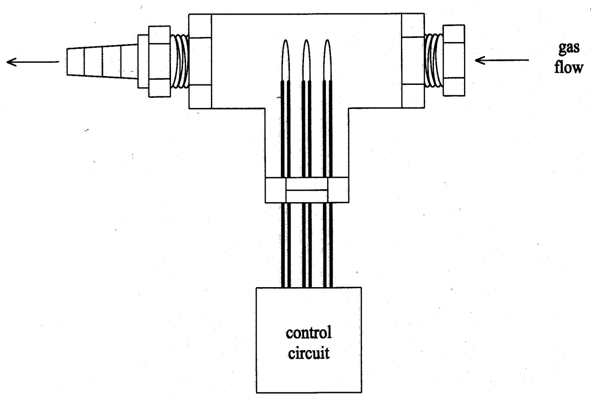

Figure 2. Schematic diagram of measuring module containing three wires. The first in gas flow is reference, the middle is heater and the last is sensor. The distance between two wires is 3 mm.

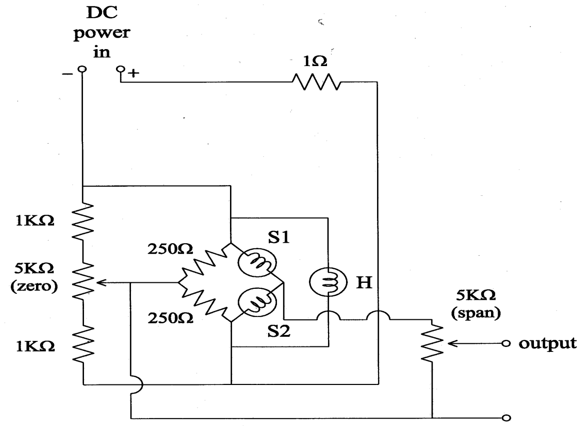

Figure 3. Schematic diagram of measurement circuit for hot-wire module. The symbol H is of heater and the S1 and S2 are of reference and sensor.

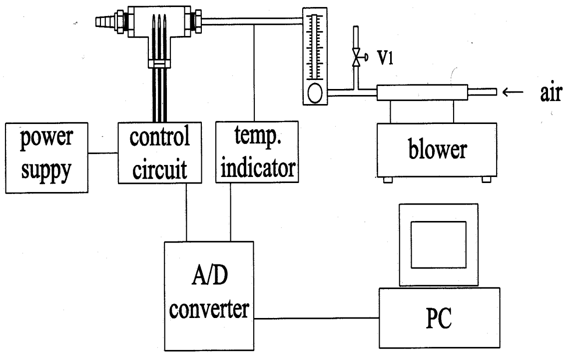

Figure 4. Schematic diagram of experimental setup

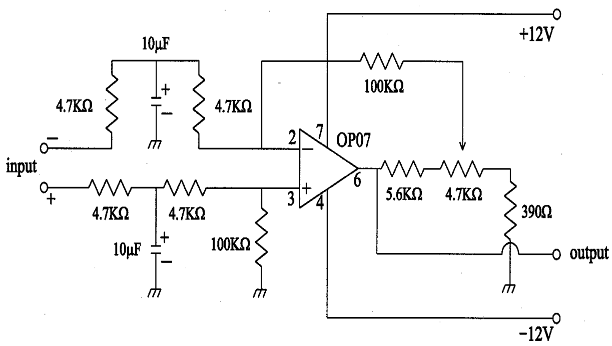

Figure 5. Schematic of amplification circuit.

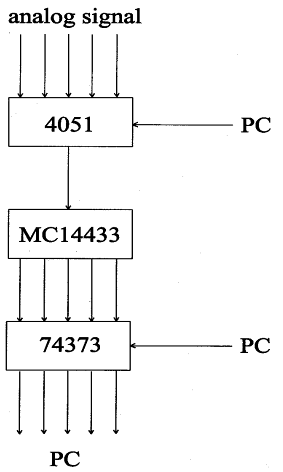

Figure 6. Diagram of an analog-to-digital converter.

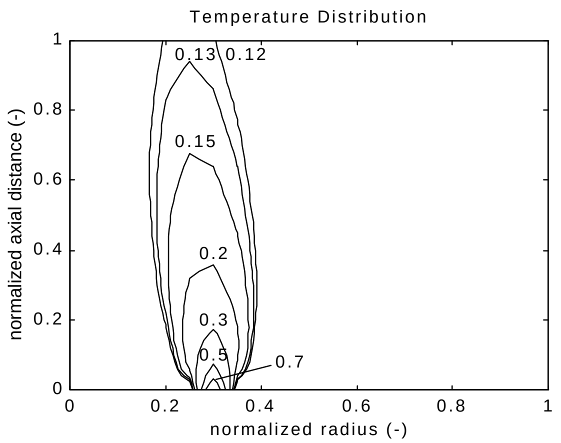

Figure 7. Normalized temperature distribution between heater and sensor wires at average gas velocity of 2.62 cm/s.

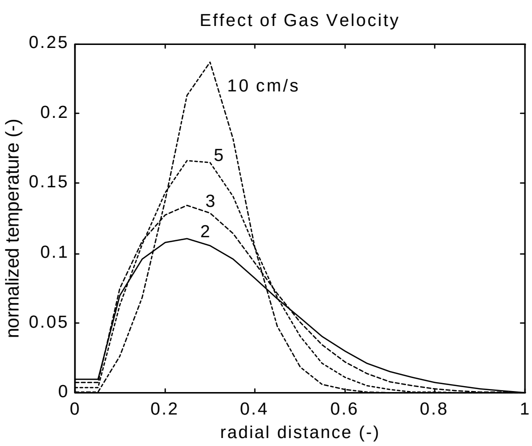

Figure 8. Effect of average gas velocity on the temperature at the axial location of sensor.

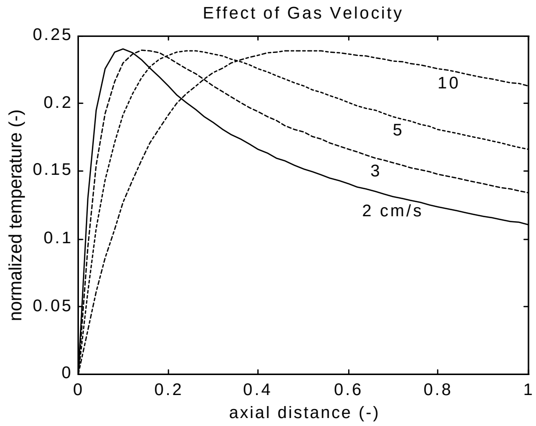

Figure 9. Effect of average gas velocity on temperature at the radial location of sensor.

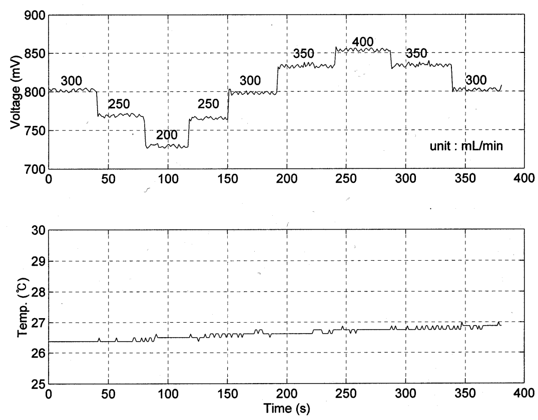

Figure 10. Variations of measurement signal and temperature with varying air flow rate.

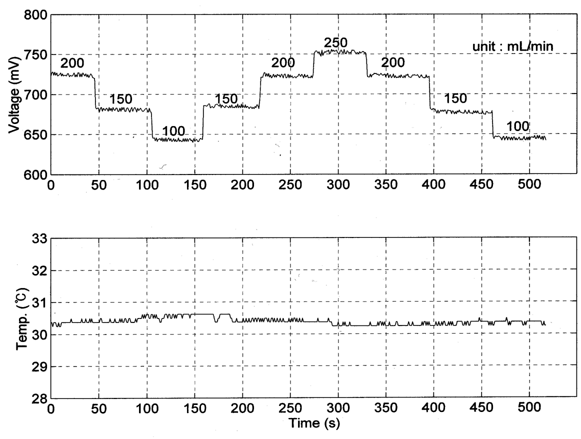

Figure 11. Variations of measurement signal and temperature with varying CO_2 flow rate.

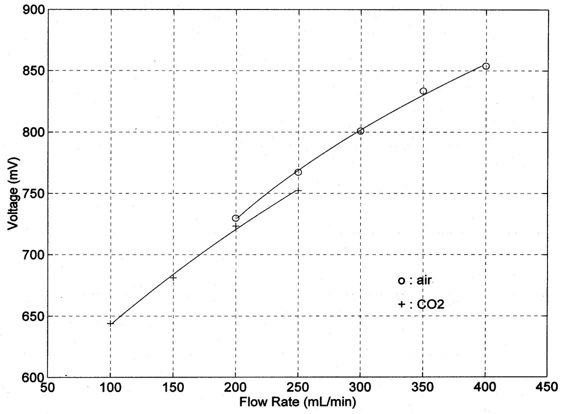

Figure 12. Relationship between gas flow and measure signal.

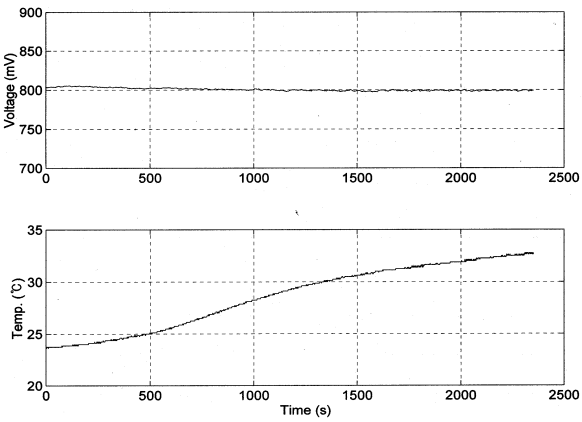

Figure 13. Variation of measured signal with increasing temperature.