

## DESIGN AND OPTIMIZATION OF THE MULTI-POINT THERMAL GAS MASS FLOWMETER

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**Abstract:** A multi-point thermal gas-mass flowrate measurement method is proposed. A meter with four sensing elements is developed. The temperature characteristics of the hot-film probe are analyzed at a specific temperature with self-heated effect and large current through the resistance. The relationship of resistance-characteristics is obtained under several currents. The arrangement of the four sensing elements is studied. According to the comparison of the testing results, the optimal disposition method, called Equal ring method, is selected. The polynomial curve fitting method is employed to calibrate the multi-point thermal gas-mass flowmeter. The gas flowrate is measured in terms of the output of the sensing elements array through curve fitting.

**Keywords:** thermal mass flowmeter, temperature compensation, curve fitting.

### 1. INTRODUCTION

The thermal gas-mass flowmeter is a new mass flowrate instrument based on the conventional hot-film flowmeter. It has wide application in the industries such as aero industry, energy, petroleum, metallurgy and medicine production. Currently, the thermal gas-mass flowmeter is still on the research stage, particularly for the large diameter and irregular pipe, in the domestic. The improvement of this technique is important for the development of the industries. [1, 2]

The purpose of this work is to develop a multi-point thermal gas-mass flowmeter based on the single-point thermal gas-mass flowmeter. The temperature characteristics of the hot-film probe are analyzed and the relationship of resistance-characteristics is obtained under several currents. Four sensing elements are installed in the pipe. The gas flowrate is measured according to the output of the sensing elements array.

### 2. TEMPERATURE CHARACTERISTICS

Generally, the configurations of probes are cylindrical hot-wires and hot-films deposited on cylindrical fibres. According to the achievements of relevant researches [3], platinum flat-film detector, which is called hot-film probe in

this paper, is employed here as heating elements, because this probe has the advantages of the small size, fast response to temperature changes, large temperature measurement range and good linearity and stability.

The output of the probe is influenced by the ambient temperature. The measurement results are related to the surrounding conditions when the hot-film probes run as the sensing elements of the flowmeters. In order to analyze the temperature characteristics of the hot-film probe quantitatively, experiments were carried out under different conditions. The experimental facilities are shown in Figure 1.

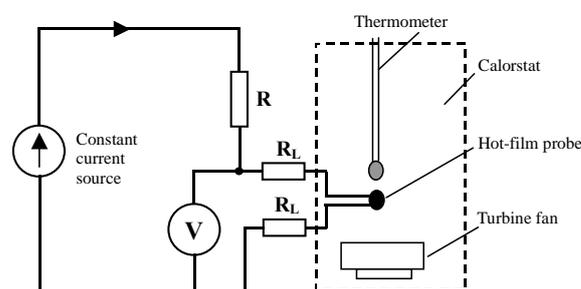


Fig. 1. The facilities for experiments of temperature characteristics

During the experiment, the constant current provides a steady current passing through the hot-film probe. The probe is placed in an adjustable calorstat. The different ambient temperatures are simulated by changing the temperatures of the calorstat. The standard thermometer is applied to measure the temperature and the voltage between the two sides of the probe is detected at the same time. A turbine fan is installed in the calorstat to simulate another condition. The forced convection occurs when the turbine fan opened and it does not occur when the turbine fan is closed. (In the following contents,  $U=0$  denotes that the turbine fan opened and  $U \neq 0$  denotes that the turbine fan is closed.)

The hot-film probe has two effects named non self-heated effect and self-heated effect. When the current passing through the probe is less than 1 milli-ampere, the probe is in the non self-heated effect. On the contrary, if the current passing through the probe is larger than 1 milli-ampere, the probe can be regarded as in the self-heated effect.

Generally, the conventional thermal mass flowmeter works under non self-heated effect. The experiments with non self-heated effect were carried out firstly. The results are shown in Figure 2.

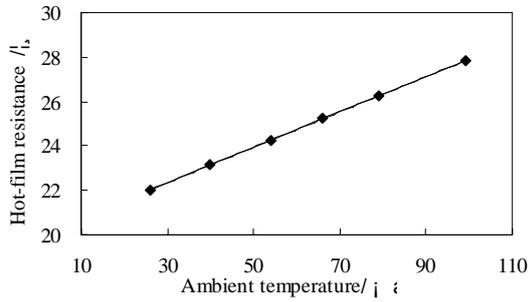


Fig. 2. Relationship of resistance-temperature in non self-heated effect

The relationship of resistance-temperature in non self-heated effect is obtained and given by:

$$R_t = 19.968(1 + 3.981 \times 10^{-3} \times t - 1.002 \times 10^{-7} t^2) \quad (1)$$

where  $R_t$  is the resistance of the hot-film probe and  $t$  is the ambient temperature.

In this work, the hot-film probe works under self-heated effect when the current is larger than 1mA. A certain operating temperature is achieved when the constant current passing through the probe. The gas flowrate measurement is conducted under this temperature. Figure 3 shows the test results as the same current ( $I=70\text{mA}$ ) passed through the probe under different conditions ( $U=0$  and  $U \neq 0$ ).

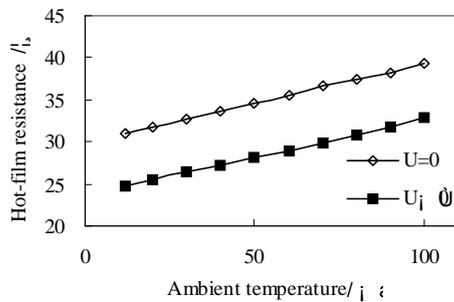


Fig. 3. Relationship of resistance-temperature in self-heated effect under different conditions

Figure 4 shows the test results when the probe is in the static situation ( $U=0$ ) under different current ( $I=50\text{mA}$ ,  $70\text{mA}$  and  $90\text{mA}$ )

Some useful conclusions can be drawn from the experimental results illustrated in Figure 3 and Figure 4:

(a) The resistance of the hot-film probe changes linearly according to the changes of the ambient temperature when the probe under a constant current higher than 1mA.

(b) There is the same amount of thermal dissipation as the ambient temperature changes. For example, the thermal dissipation of the probe used in this work is 31mW under forced convection.

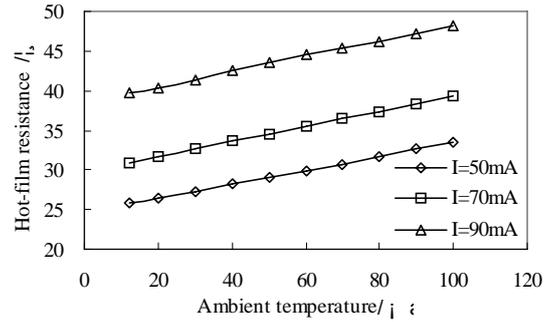


Fig. 4. Relationship of resistance-temperature in self-heated effect under different currents

(c) The operating temperature of the probe increases when the current grows. For example, the operating temperature ( $T_w$ ) is 77° when the current is 50mA, it is 142° when the current is 70mA, and it is 256° when the current is 90mA. So the operating temperature of the probe can be determined by the current passing through the probe.

The experimental results mentioned above indicate that there is a linear relationship between the resistance of the hot-film probe and the ambient temperature under a given current. This relationship provides significant information for the temperature compensation of the flowmeter.

### 3. THE TEMPERATURE COMPENSATION

#### 3.1. Circuit of the temperature compensation

The measurement principle of thermal mass flowmeter is based on heat dissipation of the sensing element, therefore the output signal of thermal flowmeter is not only sensitive to the gas mass flowrate but also to the ambient temperature. The temperature compensation should be employed to eliminate the impact of the variational ambient temperature. Generally, analytical correction and automatic compensation are often used for the temperature compensation [1, 4-6]. In this work automatic compensation method is applied. Figure 5 shows the circuit for the automatic correction.

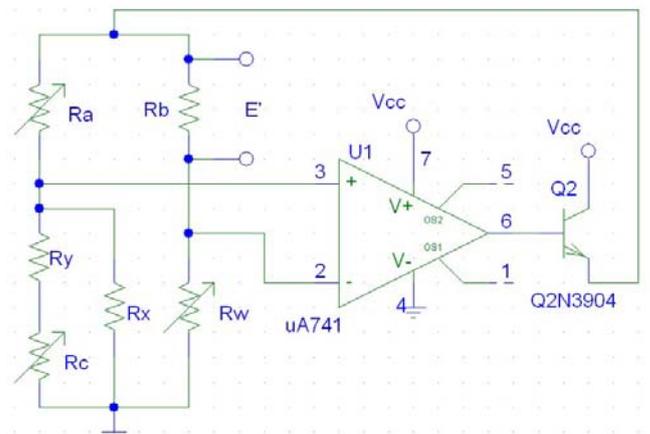


Fig. 5 Circuit of the automatic temperature compensation

**Table 1 Results of non-temperature compensation, analytical correction and automatic compensation ( $T_c=175^\circ\text{C}$ )**

Compensation method	Temperature Output signal (□) (V)		20		40		60		80	
	U=0	U≠0	U=0	U≠0	U=0	U≠0	U=0	U≠0	U=0	U≠0
Non-temperature compensation	0.299	0.662	0.196	0.492	0.096	0.372	-0.018	0.238		
Analytical correction	0.299	0.662	0.275	0.609	0.252	0.557	0.229	0.507		
Automatic compensation	0.286	0.650	0.248	0.634	0.231	0.612	0.229	0.585		

The compensation is implemented by placing a temperature-sensitive element in the Wheatston bridge. In Figure 5,  $R_c$  is a platinum resistance that has positive temperature coefficient. It works under non self-heated effect and only sensitive to ambient temperature.  $R_w$  is the hot-film probe as the sensor of the flowmeter that works with self-heated effect.

The design of automatic compensation circuit is according to the temperature characteristics of the hot-film probe. In order to make the output signals of the flow sensor insensitive to the environmental temperature, equation (2) should be satisfied in any situation theoretically:

$$\frac{R_a}{R_c} = \frac{R_b}{R_w} \quad (2)$$

where  $R_c' = \frac{(R_y + R_c)R_x}{R_y + R_c + R_x}$ .

If suitable parameters ( $R_x, R_y, R_c$ ) are selected, the ratio of  $R_c'$  with  $R_w$  will be constant at any temperature.

### 3.2. Analysis of temperature compensation results

Table 1 shows the experimental results of temperature compensation of the multi-point thermal gas-mass flowmeter.

The temperature drifts are analyzed for the performance evaluation of the temperature compensation methods. The temperature drifts of thermal mass flow sensor could be divided into zero-point drift and sensitivity drift [7]. The zero-point drift means the changes of output are caused by the variety of temperature in the static state. It could be expressed with TCR and given by:

$$TCR = \frac{E_{0T_1} - E_{0T_2}}{(T_2 - T_1)(V_{F.S} - V_0)} \times 100\% \quad (3)$$

where  $E_{0T_1}, E_{0T_2}$  are output values of thermal flow sensor at temperature  $T_1, T_2$  respectively;  $V_{F.S}$  is the full scale value of output; and  $V_0$  is zero-bias value under standard condition.

The sensitivity drift is caused by the change of temperature when the gas is flowing through the sensor in a given flowrate. It is denoted by TCS and expressed as:

$$TCS = \frac{(E_{QT_2} - E_{0T_2}) - (E_{QT_1} - E_{0T_1})}{(T_2 - T_1)(V_{F.S} - V_0)} \times 100\% \quad (4)$$

where  $E_{QT_1}, E_{QT_2}$  are the output values of thermal flow sensor in a given flowrate at the temperature  $T_1, T_2$  respectively.

**Table 2 Results of temperature compensation comparison**

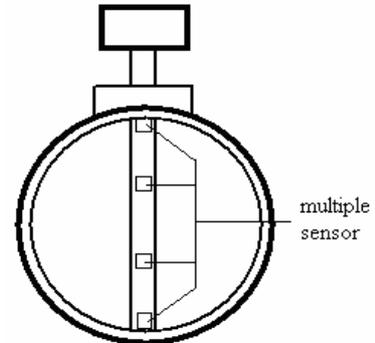
	[TCR]( $\times 10^{-4}$ )	[TCS]( $\times 10^{-4}$ )
Non-temperature compensation	35.2	-11.8
Analytical correction	7.8	-9.4
Automatic compensation	6.3	-0.89

Note: Full Scale output voltage of multi-point thermal gas-mass flowmeter is 1.5V.

Table 2 shows temperature compensation results of multi-point thermal mass flowmeter. The comparison with the analytical correction method indicates that the automatic compensation method has a good performance.

## 4. ARRANGEMENT OF THE SENSORS

Because the velocity field in the large diameter and irregular pipes is inhomogeneous, the single-point method can't be adopted in this situation [8, 9]. The multi-point thermal method may overcome the problem and improve the measurement accuracy.



**Fig. 6. Structure of the multi-point thermal gas-mass flowrate.**

Figure 6 illustrates the structure of the multi-point thermal gas-mass flowmeter, in which four sensing elements are installed symmetrically at the vertical diameter

of the pipe. The sensing element array is used to measure the mass flowrate at different sections of the pipe.

Three measuring points arrangements are studied in this work called Equal ring method, Chebyshev integral method and Log-linear method [10, 11]. The distance of each sensing element is shown in Table 3 when the center of the pipe is used as the base point.

**Table 3. The arrangements of measuring points**

Measurement method	$r_i$			
	$-r_2$	$-r_1$	$r_1$	$r_2$
Equal ring method	-25.98	-15	15	25.98
Chebyshev method	-26.64	-13.79	13.79	26.64
Log-linear method	-27.43	-12.57	12.57	27.43

## 5. CALIBRATION OF THE FLOWMETER

Because four sensing elements are applied, the output of the flowmeter is determined by the combination of the voltage at different position. The curve fitting method is applied to calibrate the output of the multi-point thermal gas-mass flowmeter. There are mainly three curve fitting methods for thermal gas-mass flowrate, called power laws fit, expended power law fit and polynomial curve fit, as mentioned in conference [12]. The polynomial curve fit is used in this work for the calibration. The equation can be expressed as:

$$Q = A + BE + CE^2 + DE^3 + FE^4 \quad (5)$$

where  $Q$  denotes the gas flowrate,  $E = \frac{1}{4} \sum_{i=1}^4 e_i$  □

$e_i$  ( $i = 1, 2, 3, 4$ ) is measurement voltage at different point and  $A, B, C, D, F$  are fitting coefficients.

The residual mean square (RMS) is applied to evaluate the performance of the different measurement methods. The RMS  $\varepsilon_u$  can be calculated by:

$$\varepsilon_u = \left[ \frac{1}{N} \sum_{i=1}^N (1 - Q_R / Q_C)^2 \right]^{1/2} \quad (6)$$

where  $Q_R$  is the measured mass flowrate,  $Q_C$  is the mass flowrate calculated by the calibration equation.

**Table 4. RMS  $\varepsilon_u$  in different measurement method**

Method	Equal area of ring	Chebyshev	Log-linear
$\varepsilon_u$	0.03514	0.03033	0.01497

The results in Table 4 show that the optimal measurement method is that the measurement points are arranged as log-linear function.

## 6. UNCERTAINTY ANALYSIS

The uncertainty of the multi-point thermal gas-mass flowmeter is determined by non-statistical means based on detailed knowledge about the instrumentation, calibration equipment and experimental conditions [13]. The uncertainties presented below are relative standard uncertainties  $u(y_i)$ , which is a function of the standard deviation of the input variance [14]:

$$u(y_i) = \frac{1}{y_i} \cdot S \cdot \left( \frac{\Delta x_i}{k_i} \right) \quad (7)$$

where  $S = \partial y_i / \partial x_i$  is the sensitivity factor and  $k_i$  is the coverage factor related to the distribution of the input variance (Gaussian, rectangular etc.).

The relative standard uncertainties of multi-point thermal flowmeter can be summarized in the table 5.

**Table 5. Analysis of uncertainties of multi-point thermal gas-mass flowmeter**

Source of uncertainty	Input variants	Typical value	Relative output variants	Typical value	Coverage factor	Relative standard uncertainty
	$\Delta x_i$	$\Delta x_i$	$\frac{1}{U} \Delta y_i$	$\frac{1}{U} \Delta y_i$	$k$	$\frac{1}{k} \frac{1}{U} \Delta y_i$
Calibrator	$\Delta U_{cal}$	0.5	$2 \cdot STDV(\Delta U_{cal})$	0.01	2	0.005
Linearisation	$\Delta U_{fit}$	1.5	$2 \cdot STDV(\Delta U_{fit})$	0.03	2	0.015
Temperature variations <sup>1)</sup>	$\Delta U_{cor}$	0.1	$2 \cdot STDV(\Delta U_{cor})$	0.002	2	0.001
Temperature variations <sup>2)</sup>	$\Delta T$	1□	$\frac{\Delta T}{273}$	0.004	$\sqrt{3}$	0.002
Ambient pressure	$\Delta P$	10kPa	$\frac{P_0}{P_0 + \Delta P}$	0.01	$\sqrt{3}$	0.006

$$\text{Relative expanded uncertainty: } U_r = 2 \sqrt{\sum \left( \frac{1}{k} \frac{1}{y} \Delta y_i \right)^2} = 0.034 = 3.4\%$$

1) Uncertainty due to changes in sensor overtemperature alone.

2) Uncertainty due to changes in air density with temperature alone.

## 7. CONCLUSION

The multi-point gas-mass flowmeter with four sensing elements is designed. The temperature characteristic of the sensing elements and the optimal measuring point arrangement are studied. Some conclusions can be drawn as:

(1) The relationship between the hot-film probe's resistance and the temperature has a good linear feature with the non self-heating effect (when the operating current  $\leq 1\text{mA}$ ). It still has a good linear feature under the different operating current (the current  $\gg 1\text{mA}$ ) and different operating conditions.

(2) The output of thermal mass flowmeter has the temperature drifting without temperature compensation. The automatic compensation method should be applied in the flowmeter to eliminate the drifting.

(3) The optimal arrangement of the measurement points was obtained. The calibration model, which related to the four measurement voltages at different points, was achieved. The measurement accuracy was improved by the multi-point thermal mass flowmeter.

## ACKNOWLEDGMENTS

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