

A Novel Thermal Sensor for Gas Flowmeter Measuring

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Abstract: Thus far, the thermal gas flow sensor is commonly based on the constant current principle. However, the constant current thermal sensor suffers the zero drift because of the tolerance of manufacture. And the accuracy and the response time of constant current thermal sensor cannot fulfill the application with high accuracy requirement. The paper presents a novel thermal sensor for gas flow measuring, which is based on the constant power techniques. Experiment results demonstrate that the novel constant power thermal sensor is of high accuracy, short response time and small zero drift.

Keywords: Gas flow control, Thermal sensor, Constant power driver

1. Introduction

Mass Flow Meter (MFM) accurately measures mass flow rates, Mass Flow Controller (MFC) accurately measures and controls mass flow rates despite gas volume fluctuated due to pressure or temperature changes. Which is widely applied in the fields as: semiconductor and IC fabrication, special materials science, chemical industry, petrolic industry, pharmaceutical industry, environmental protecting and vacuum system researching, etc.. The typical applications include: microelectronic process equipment such as diffusion, oxidation, epitaxy, CVD, plasma etching, sputtering, ion implantation, vacuum deposition equipment, optical fiber melting, micro-reaction equipment, mixing & matching gas system, capillary flow control system, gas chromatograph and other analytical instruments.^[1-2]

By the key part of the mass flow controller, which measures the flow accurately, the mass flow controller can control the gas according to the command. The thermal method for sensor is dominated now because of the low cost, high accuracy and small coefficient of the pressure and temperature. The principle of the thermal sensor is that the capability of gas to pick up heat is only the function of the gas molecule.

2. Principle of the Thermal Sensor

MFC can be separated into 4 main components: a bypass, a sensor, an electronic board and a regulating valve. The construction of thermal mass flow controller is presented in Figure1

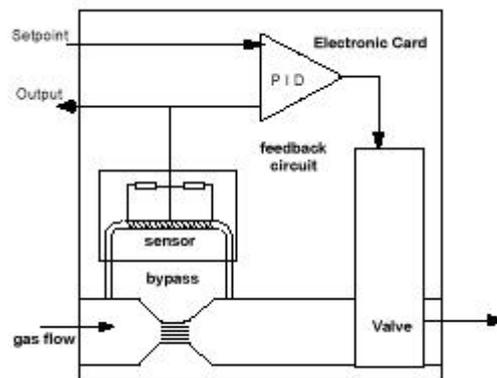


Fig.1 Construction of the mass flow controller

The flow is divided between a heated sensing tube (the sensor), where the mass flow is actually measured, and a flow restriction or bypass, where the majority of flow passes. The sensor is designed to deliver an output voltage almost proportional to the gas flow circulating thru it which is due to the bypass design proportional to the total flow circulating thru the mass-flow meter or controller. The electronics board amplifies and linearizes the sensor signal so the output of the electronics board named “readout” gives a signal proportional to the total flow circulating thru the mass flow controller. Then the electronic compares the readout to the desired set point. This comparison generates an error signal that feeds the regulating valve. The difference is used to drive the control valve. The control valve will proportionally open or close until the output is equal to the set point.

The thermal sensor includes capillary tube wound with two heated sensor resistances, measuring the change in temperature distribution created by the gas flowing inside this tube. The coils of the heating resistances are made with a thermal sensitive wire so that the temperature differences due to the flow are directly converted into resistances change. Ideally, for zero flow, the upstream and downstream temperature will be equal. The voltage of wheatstone bridge will be zero. When the gas is flowing, the upstream region cools down whereas the downstream region heats up causing a temperature gradient along the length of the tube. Then the wheatstone bridge will give out the voltage which is ratio of the flow.

However, most of sensor coils are very difficult to be manufactured identically. Normally the constant current circuit is adopted as the sensor driver. Under the constant current, the temperature on the upstream coil is different with the one of the downstream even it is no flow. Moreover, the ambient temperature and the valve heat will disturb the wheatstone bridge voltage. Then temperature coefficient and response time of thermal sensor has to be considered for accuracy and it is difficult to be cancelled by the simple algorithm.

3. A Novel Thermal Sensor Method

A novel thermal sensor method based on the constant power driver is presented in this paper. The total power of sensor coil comes from the driver circuit and the heat of gas. All the power of sensor coil will be denoted as the temperature on the sensor coil. The constant power driver can keep the constant consume power of the sensor coil during the measurement. The circuit

schematic of sensor driver is shown in Figure 2. Because of the amplifier, the voltage ratio between the sensor coil and R3 has to keep the same value between R2 and R1 all the time. In this way, when the gas is flowing, the circuit will keep the temperature of sensor coils constant by increasing or decreasing the current into the sensor coils.

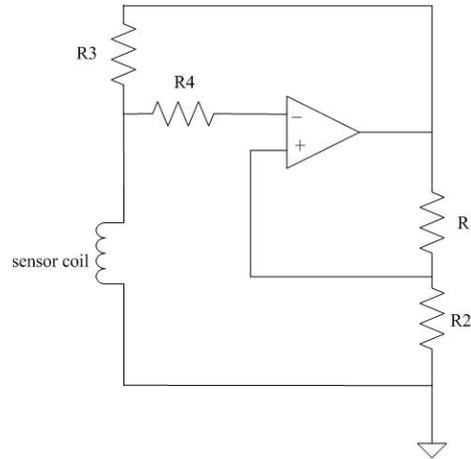


Fig.2 Schematic of the constant power sensor driver

Then according to the energy balance principle ^[3], the sensor voltage value ratio mass flow could be presented as follows:

$$\frac{U_{up} - U_{down}}{U_{up} + U_{down}} = \frac{2\dot{m}C_p(K_s + \dot{m}C_p)}{(K_s + \dot{m}C_p + \sqrt{K_s^2 - \dot{m}^2 C_p^2})^2} \quad (1)$$

Where

U_{up} : Voltage applied to the upstream sensor coil

U_{down} : Voltage applied to the downstream sensor coil

\dot{m} : Mass flow rate

C_p : Heat capacity of the gas at constant pressure

K_s : Thermal conductance of the heating elements

In Eq. (1), the mass flow rate is the function of the sensor value ratio, which is independent with the temperature. That means the temperature coefficient will be very small. But Eq(1) is too complicate to calculate the mass flow rate on time. Here, the simplified algorithm is presented. Normally, the typical value could be as follows: $U_{up} = U_{down} = 3V$, $I = 0.02A$, $C_p = 29.2J / mol \cdot K$, $T_s = 100^\circ C$, $T_a = 20^\circ C$

Where

T_s : Temperature on the sensor coil

T_a : Ambient temperature

According to the definition of the thermal conductance ^[3], K_s could be calculated as follows:

$$K_s = \frac{U_{up} \cdot I}{T_s - T_a} \quad (2)$$

Thus the mass flow rate could be calculated as follows:

$$\dot{m} \approx 83.33 \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} \tag{3}$$

Eq.(3) shows the relationship between mass flow rate with the voltage readout of the circuit. The value of the mass flow rate could be calculated by the microprocessor in the mass flow controller in time. Also the calibration procedure will be adopted to improve the accuracy of the sensor.

4. Experimental Results

The accuracy, response time and temperature coefficient are tested for new thermal sensor measuring method.

4.1 Accuracy Testing

Two prototypes (100sccm and 10000sccm) are selected to be tested for accuracy. The accuracy, repeatability and linearity specifications are calculated according to the SEMI standard [4]. Figure 3 and Figure 4 show the results.

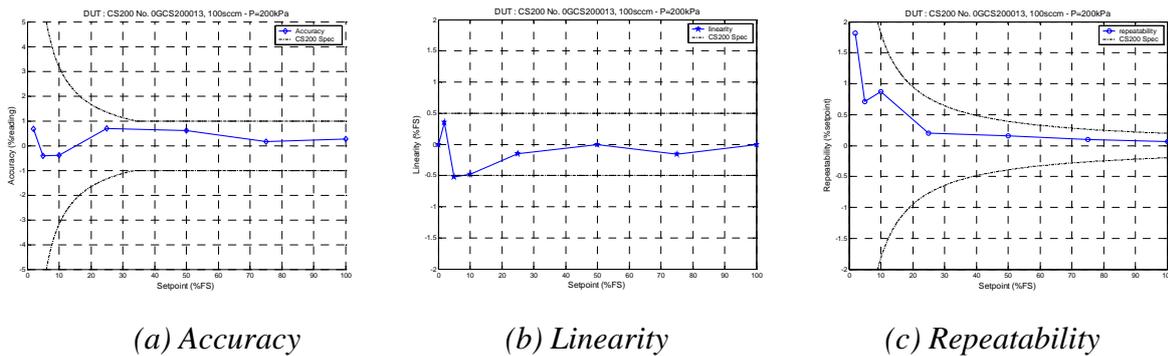


Fig. 3 Testing results of DUT 1(100sccm)

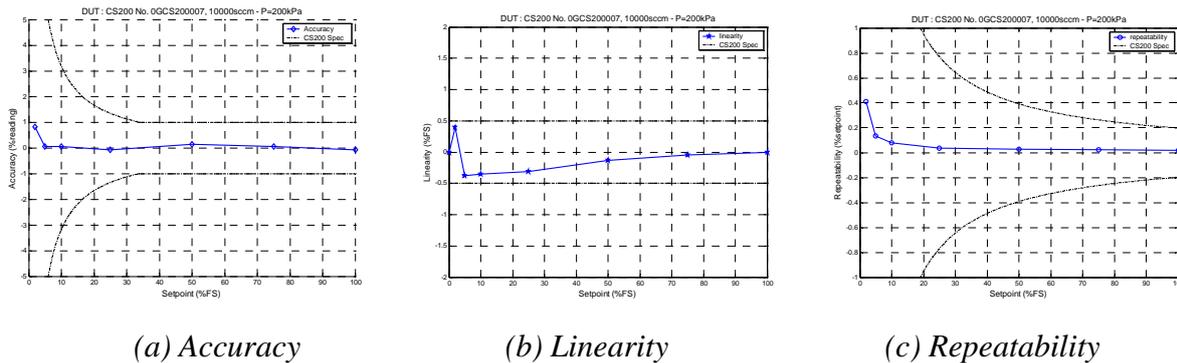


Fig.4 Testing results of DUT 2(10000sccm)

4.2 Response Time Testing

Step signal is select to test the response time of the sensor. The two order filter is also add to speed up the response time. Figure 5 shows the response time of the sensor under 2%FS, 10%FS, 25%FS, 50%FS, 75%FS and 100%FS respectively.

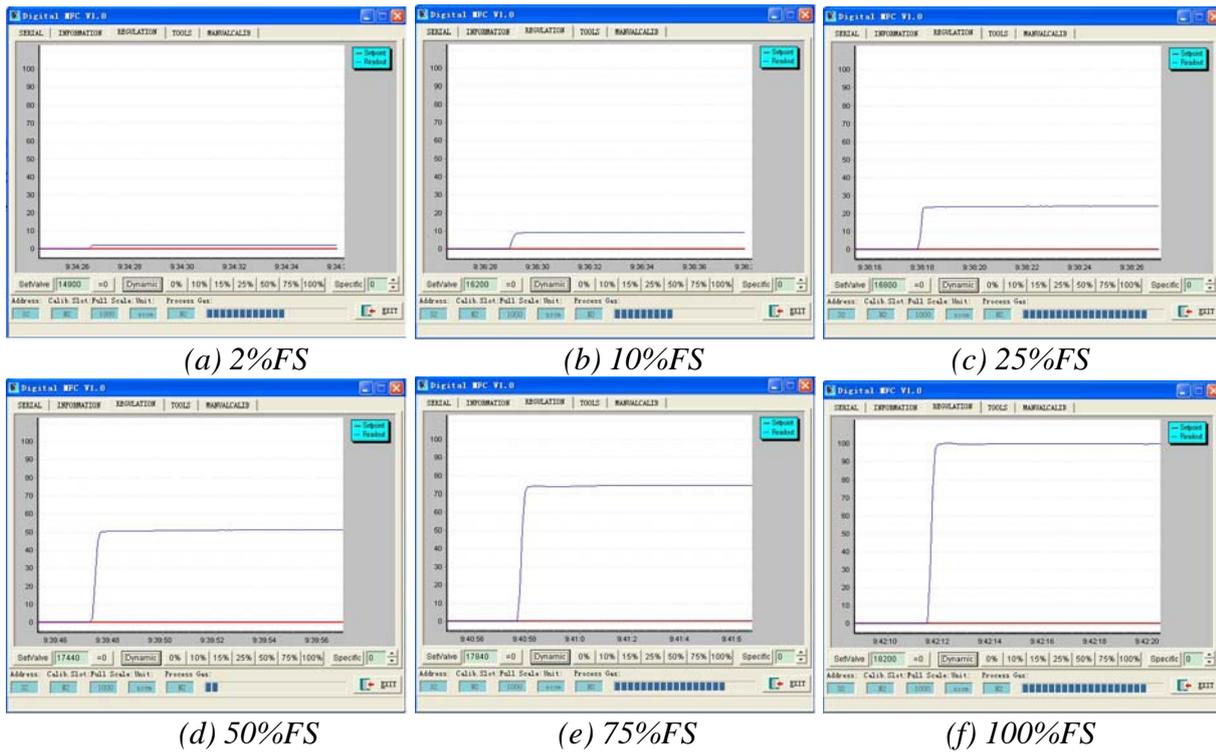


Fig.5 Response time of the sensor

4.3 Zero Drift Testing

The zero drift during the short period mainly comes from the tempco (temperature coefficient) of the sensor. The tempco k_0 (%FS/°C) could be calculated as follows^[5]:

$$k_0 = (\max - \min) / (T_{\max} - T_{\min}) \times 100 \tag{4}$$

Where:

T_{\max} : the max testing temperature

T_{\min} : the min testing temperature

max : the zero readout on the T_{\max}

min : the zero readout on the T_{\min}

The tempco of DUT1 and DUT1 are listed in the Table1. The zero readout under -5°C, 25°C and 50°C are recorded to calculated the tempco.

Table. 1 Zero Tempco of the novel thermal sensor

Temperature	-5°C	25°C	50°C	k_0 (%FS/°C)
DUT 1	0.0%FS	0.1%FS	0.5%FS	-0.0091
DUT 2	-0.2%FS	0.4%FS	0.0%FS	0.0109

4.4 Results Summary

The novel thermal sensor method shows the better performance. The accuracy could be 1%reading. And the response time from 2%FS to 100%FS show the same performance which are less than 300msec. And the tempco at zero flow could be 0.01%FS/°C which is dominant

improvement. The compare results between the novel thermal sensor method and the normal constant current thermal sensor method results are listed in the Table 2.

Table. 2 Compare of two methods

Items	Novel sensor method	Normal sensor method
Accuracy	$\leq 1\%$ reading	$\leq 1\%$ FS
Response time	≤ 300 msec	≥ 500 msec
Zero Tempco	$\leq 0.01\%$ FS/ $^{\circ}$ C	$\leq 0.05\%$ FS/ $^{\circ}$ C

5. Conclusion

A novel thermal sensor method is presented in this paper. The heat elements of the thermal sensor are kept the constant temperature by the constant power circuit. And based on that, the mass flow rate could be calculated simplify independent with the temperature changing. In this way, the wheatstone bridge is not necessary for the measurement circuit. The experiment results show the high accuracy, fast response time and low tempco. The mass flow controller with the novel thermal could be used in the semiconductor, fuel cell, vacuum industry etc.

Acknowledgment

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