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Study on Thermal Conductivity Methane Sensor Constant Temperature Detection Method

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Abstrak

Sensor metana konduktivitas termal dapat mendeteksi konsentrasi metana yang mengukur koefisien konduktivitas termal dari perbedaan metana yang diukur dari gas dasar. Sensor ini memiliki kelebihan pendeteksian berbagai gas, rentang pengukuran yang lebar, stabilitas, waktu hidup yang panjang, tetapi juga memiliki cacat, seperti akurasi deteksi yang buruk, sensitivitasnya terpengaruh suhu lingkungan dan suhu sensor, batasan cacat pada aplikasi yang luas dari sensor. Makalah ini menganalisis teori sensor metana konduktivitas termal dan metode pengukuran, mengusulkan metode deteksi suhu konstan sensor metana konduktivitas termal, dan secara eksperimental memvalidasi kelayakan kompensasi suhu lingkungan. Hasil penelitian menunjukkan bahwa metode ini secara efektif mengurangi efek dari suhu lingkungan pada akurasi pengukuran.

***Kata kunci**: konduktivitas termal, deteksi temperatur konstan, deteksi konsentrasi metana*

Abstract

The thermal conductivity methane sensor can detect methane concentration that measures the thermal conductivity coefficient of the measured methane different from the background gas. This sensor has advantages of detection of a variety of gases, large measuring range, stability, long working life, but also has defects, such as poor detection accuracy, sensitivity affected by ambient temperature and sensor temperature, the defect limits a wide applications of the sensor. This paper analyzes the theory of thermal conductivity methane sensor and method of measurement, proposes thermal conductivity methane sensor constant temperature detection method, and experimentally validates the feasibility of ambient temperature compensation. Experimental results show that the method effectively reduces the effect of ambient temperature on measuring accuracy.

***Keywords**: thermal conductivity, constant temperature detection, methane concentration detection*

1. Introduction

Each of the molecular structure and molecular weight of the gas is not the same; therefore, the thermal conductivity will change with the change of gas concentration. For the multi-component gas, heat capacity of the mixed gas will vary due to the different components [1-3] .The thermal conductivity sensor is based on the principle that it can achieve the gas composition analysis according to the heat capacity difference of mixed gas. Thermal conductivity sensor is an earlier gas sensors for gas detection, thermal conductivity of gas sensors are typically used for high concentrations of gas measurement, it has the following advantages:

1) The sensor has a large measuring range;
2) The sensor can detect a variety of gases, it not only detects flammable gas, but also detects inert gas;
3) The measured environment is unrestricted, the sensor can achieve gas detection in the aerobic or anaerobic conditions;
4) The sensor has a strong resistance against poisoning.

Many gas sensors do not have these excellent characteristics. But the thermal conductivity gas sensor has defects of low sensitivity and large temperature drift in application of gas detection that limits the applications of the sensor [4-6]. This paper proposes thermal

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gas-detection methods based on constant temperature detection, in order to reduce the effects of temperature drift and improve the sensitivity of the sensor.

2. The thermal conductivity gas sensor thermodynamic theory analysis

The working mechanism of thermal conductivity sensor needs going on the theoretical analysis to complete the method and the application research about thermal conductivity gas detection. Build static characteristic equation of thermal conductivity sensor based on basic theory of heat transfer, namely thermal balance equation.

Sensor operating current is set as I, the resistance set as r, the heat of sensor only comes from operating current heating power, that is $Q_{in} = I^2 r$ .Based on theory of heat transfer, there are three basic modes: heat transfer, heat radiation and heat convection[7-9]. On the technology craftsmanship of sensor, in order to reduce heat transfer of resistance wire axial, draw ratio of resistance wire is usually above 2×10^3 ~3×10^3, so the influence of heat transfer of sensor axial can be ignored[10]. When thermal conductivity sensor is working, the loss of heat convection caused by air flow also can be ignored because of the effective defense of sensor. So the main heat loss is heat transfer Q_{out1} and heat radiation Q_{out2} that can be expressed as:

$$Q_{out} = Q_1 + Q_2 \quad (1)$$

Q_{out1} is the loss heat of heat transfer, expressed as:

$$Q_1 = \frac{\lambda S dt}{dr} \quad (2)$$

In the formula above: λ is the gas thermal coefficient; t is the temperature; r is the radius of the sphere; S is the heat transfer area.

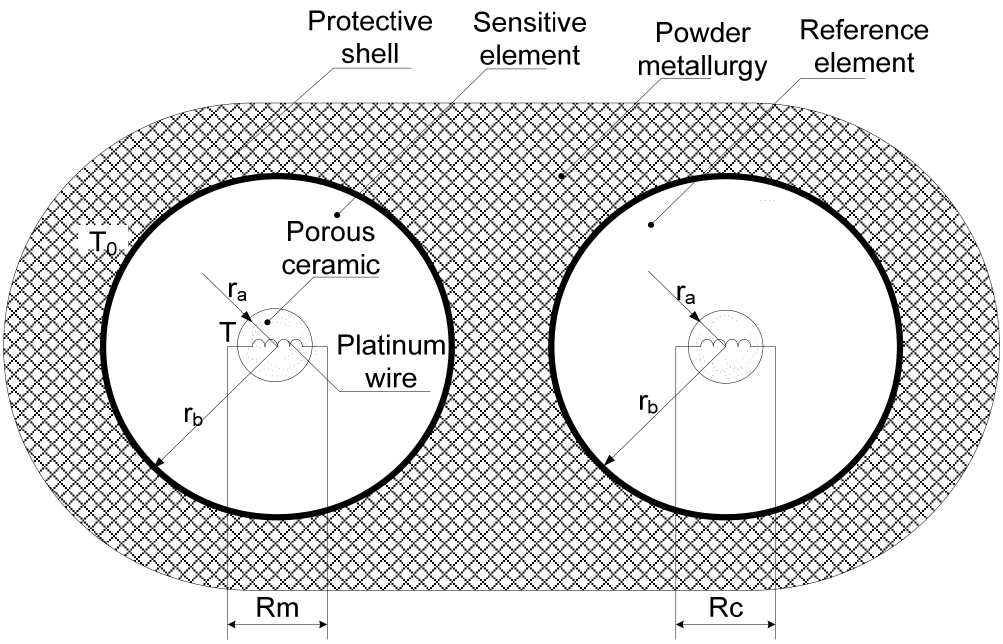

Figure 1. Schematic diagram of sensor sensitive ball and shell structure

The thermal conductivity type gas sensor used in this article is sensitive balls as shown in Figure 1, according to the structure of the ball; the following formula about heat losses of heat conduction can be obtained.

$$Q_1 = \frac{4\pi r^2 \lambda dt}{dr} \tag{3}$$

The above equation can be deformed as follows:

$$\frac{dr}{r^2} = \frac{4\pi\lambda dt}{Q_1} \tag{4}$$

Both sides of the equation are integrated at the same time, we can get:

$$\int \frac{dr}{r^2} = \int \frac{4\pi\lambda dt}{Q_1} \tag{5}$$

$$-\frac{1}{r} = \frac{4\pi\lambda t}{Q_1} + C \tag{6}$$

Where C is a constant of integration, determined by the boundary conditions. In Figure 1, the radius of the sensitive ball is r_a, and T is its temperature; the distance between the center of the sensitive ball to the outer wall of the sensor is r_b, and T_0 is its temperature. So, we can get:

$$\frac{1}{r_b} - \frac{1}{r_a} = \frac{4\pi\lambda(T - T_0)}{Q_1} \tag{7}$$

$$Q_1 = 4\pi\lambda(T - T_0) \Big/ \left(\frac{1}{r_b} - \frac{1}{r_a}\right) \tag{8}$$

Get $k = 4\pi \Big/ \left(\frac{1}{r_b} - \frac{1}{r_a}\right)$, K is a constant determined by the structure of the sensor, we can get:

$$Q_1 = \lambda k (T - T_0) \tag{9}$$

Q_{out2} is the loss heat of heat radiation, based on Stefan-Boltzmann's law, expressed as:

$$Q_2 = A\sigma S(T^4 - T_0^{\,4}) \tag{10}$$

In the formula above: A is radiation coefficien; σ is Stefan-Boltzmann constant, $\sigma = 5.6697 \pm 0.0297 \times 10^{-8}\,\mathrm{W \cdot m^{-2} k^{-4}}$.

when $Q_{in} = Q_{out} = Q_{out1} + Q_{out2}$ meets thermal equilibrium condition:

$$I^2 r = \lambda S(T - T_0) + A\sigma S(T^4 - T_0{}^4) \tag{11}$$

Ideal operating temperature of thermal conductivity sensor is at 400-500℃. In this paper, we adopt the constant temperature detection method; therefor the loss heat of heat radiation Q_{out2} is constant and far less than the loss heat of heat transfer Q_{out1}, that means Q_{out2} can be ignored. So heat-balance equation can be simplified to:

$$I^2 r = \lambda S(T - T_0) \tag{12}$$

Suppose that test gas is simple gas, and background gas is air. Volumetric concentrations of test gas and air in the gas mixture are C_m and C_c separately, thermal conductivities of test gas and air are λ_m and λ_c separately, thermal conductivity of gas mixture is λ_x. As $C_m + C_c = 100\%$, thermal coefficient of gas mixture can be achieved:

$$\lambda_x = \lambda_c C_c + \lambda_m C_m = \lambda_c(1 - C_m) + \lambda_m C_m \tag{13}$$

According to Figure 2, Heat-balance condition of the reference component and sensitive component is followed:

$$\begin{cases} I^2 R_c = \lambda_c S \Delta t_1 \\ I^2 R_m = \lambda_x S \Delta t_2 \end{cases} \tag{14}$$

In the formula above: λ_c is thermal conductivity of air; λ_x is thermal conductivity of gas mixture; R_c is resistance of the reference component; R_m is resistance of the sensitive component; Δt_1 is the temperature difference between the reference component and environment ℃; Δt_2 is the temperature difference between the sensor component and environment ℃.

So bring formula (13) into (14), we can get:

$$I^2 R_m = (1 - \frac{\lambda_c - \lambda_m}{\lambda_c} C_m)\lambda_c S \Delta t_2 = (1 - C)\lambda_c S \Delta t_2 \tag{15}$$

In the formula above, C is the relative coefficient of variation of gas mixture thermal conductivity:

$$C = \frac{\lambda_c - \lambda_m}{\lambda_c} C_m \tag{16}$$

The relation between resistance of the reference component and resistance of the sensor component with temperature:

$$\begin{cases} R_c = R_0(1 + \alpha t + \alpha \Delta t_1) \\ R_m = R_0(1 + \alpha t + \alpha \Delta t_2) \end{cases} \tag{17}$$

In the formula above:R_0 is the resistance of reference component when temperature is 0℃; t is environment temperature ℃; α is temperature coefficient of platinum resistance wire inside the sensor.

Voltage of the reference component and voltage of the sensitive component:

$$\begin{cases} V_m = IR_m = IR_0(1+\alpha t+\alpha\Delta t_1) \\ V_c = IR_c = IR_0(1+\alpha t+\alpha\Delta t_2) \end{cases} \quad (18)$$

Output of the bridge ΔV is:

$$\Delta V = \frac{V_c - V_m}{2} \quad (19)$$

According to formula (14), (15), (18) and (19), it can derive:

$$\frac{\Delta V}{V_c} = \frac{\alpha C \Delta t_1}{2(1+\alpha t_2)} \quad (20)$$

Bring formula(16) into the formula above, the expression between volume with concentration about methane gas is:

$$C_m = \frac{2(1+\alpha t_2)}{\alpha \Delta t_1} \bullet \frac{\lambda_c}{\lambda_c - \lambda_m} \bullet \frac{\Delta V}{V_c} \quad (21)$$

We can see from formula (21), the concentration of measured gas and the output of the bridge is in direct ratio, the concentration and the voltage of the reference component is in inverse ratio, and it also has direct relation with temperature coefficient of platinum resistance wire inside the sensor, environment temperature and the temperature of the sensitive component.

3. The thermal conductivity gas sensor constant temperature detection technology

Through the above theory analysis, the concentration of measured gas has relations with the temperature of the sensitive component. Conventional constant-current detection method supplies power for platinum resistance wire of the sensor by using of a constant-current source [11], when the ambient temperature changes or gas concentration changes, the temperature of the sensor can not guarantee constant, so that the temperature of sensitive component is unknown, unpredictable, this paper presents a constant temperature detection method. Figure 2 is the schematic diagram of thermal conductivity gas sensor constant temperature detection. In Figure 2, resistance R4, R5, Rm and Rc compose measuring bridge, the sensor is composed of R_m and R_c, Rm is sensitive component of the sensor, Rc is reference component of the sensor, which is used for environment compensation. R4 and R5 are the resistances of the other side of the bridge, the bridge picks up the measurement signal.

The key to achieve thermal conductivity sensor for temperature detection is how to ensure that the sensor is always working at predetermined temperature in the case of variety of environmental temperature and the detected gas concentration changes. This paper uses the variable current source technology to achieve constant temperature detection, by adjusting the current change heating power to ensure the temperature of sensor constant.

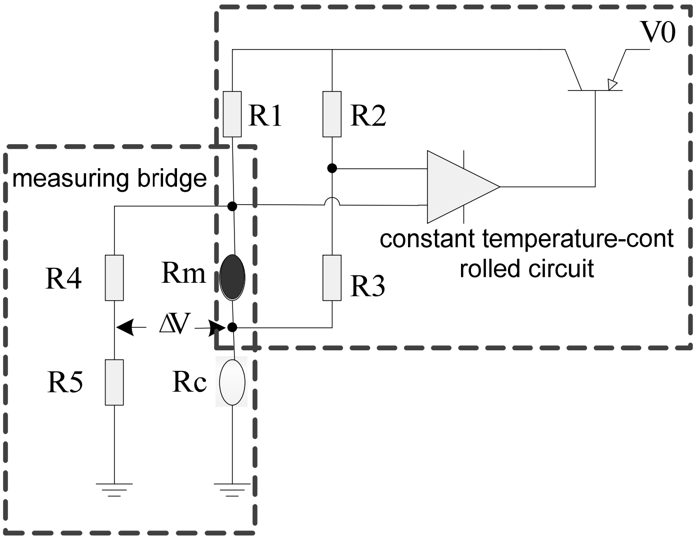

Figure 2. schematic diagram of thermal conductivity gas sensor constant temperature detection

In Figure 2, resistance R1, R2, R3 and sensor sensitive component R_m compose bridge, conditioning the closed-loop control circuit consisted of amplifiers and transistor .Bridge balance equation is:

$$\frac{R_1}{R_m}=\frac{R_2}{R_3} \tag{22}$$

In the formula above, the relationship between sensitive component resistance R_m and the temperature of sensitive component t_m is:

$$R_m = R_0(1+\alpha t_m) \tag{23}$$

When the concentration of measured gas is zero, the bridge is made to keep balance by adjusting the resistance value of the bridge arm, and so that the sensor is working at a predetermined temperature. The measured gases is detected , assuming that the thermal conductivity of the measured gas is greater than the thermal conductivity of air which make thermal conductivity of gas mixture increase and enhance heat transfer of gas, then the temperature of the sensor t_m becomes low, sensitive element resistance t_m reduces , bridge is unbalanced, current is coordinately regulated through the feedback link control amplifiers and transistor, making it increase ,so sensor temperature t_m and sensitive element resistance R_m increase, until the bridge rebuilt to a new equilibrium point.

As the bridge finally remains in equilibrium, the sensor resistance R_m is not changed, the sensor working temperature t_m is unchanged, the system is constant, and this is the most notable feature of the constant temperature detection [12].

Based on the theory of constant temperature measurement, sensor is set in a desired operating temperature by matching of resistances, and then the temperature sensors measure the current ambient temperature according to type (21) to compensate temperature, eliminating the effect of temperature on measuring sensitivity.

4. The application of the test results analysis

In order to verify the theoretical analysis and experimental results, a test experiment for sensor temperature compensation and sensor sensitivity experiment of wide range concentration are conducted.

Thermal conductivity sensor takes at 450℃ constant temperature through the constant temperature control circuit, 20% methane standard gas at 25 ℃ ambient temperature is used for sensor calibration. When operating ambient temperature is 0, 10, 20, 30 and 40℃, after calibration, the sensor takes a measurement without temperature compensation experiment by using 20% methane gas. Data without compensation is processed by the formula (20) for temperature compensation to obtain the experimental data shown in Table 1.

Table 1. Thermal conductivity gas sensor temperature compensation experimental data

temperature	uncompensated measurement value	compensated measurement value
0℃	23.1%	19.8%
10℃	22.3%	20.2%
20℃	20.9%	20.3%
30℃	19.1%	19.8%
40℃	18.0%	19.6%

The above table can be drawn that when ambient temperature reached 40℃, the maximum effect of ambient temperature is 3.1% methane equivalent without compensation, after the temperature compensation the residual value falls below 0.4%,this shows that the thermal conductivity gas sensor constant temperature detection method can effectively reduce the impact of temperature on the measurement accuracy.

Thermal conductivity sensor takes at 450℃ constant temperature through the constant temperature control circuit, after the temperature compensation, experiments are conducted at 25℃ ambient temperature. Dry air and concentration of 99.9% methane configures the following concentration methane standard gas: 0%, 50%, and 70%, the sensor is calibrated by using 50% concentration methane gas, measuring experiment with the configuration gas of each concentration. Experimental data are shown in Table 2.

Table 2. Gas sensor sensitivity experimental data

methane concentration	magnifying output voltage(mV)	measured value
0%	523.5	0%
30%	1453	30.5%
50%	2076	50.0%
70%	2686	68.4%
90%	3305	87.6%

By the data in the above table, within a wide range, output of the sensor is a linear relationship, within the range of 0% to 90%, maximum non-linearity error is 2.4%, so that the thermal conductivity gas detection method based on the constant temperature detection technology has high linearity, the reason is that the thermal conductivity of single-component gas is constant when the sensor operates in a constant-temperature state, the relationship between the thermal conductivity of mixed gas and gas concentration is linear.

In this paper, the gas detection method of thermal conductivity based on constant temperature detection technology effectively improves the detection accuracy of the system, solves the problem that the sensitivity of the sensor is affected by ambient temperature and creates conditions for achieving full scale measurement of gas concentration by using single thermal conductivity sensor.

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