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Design of Smoke Sensor for Continuous Online Quantitative Detection

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Abstract

In order to solve the problems of traditional smoke sensors which include disposable detection, high false alarm rate and low response speed, a new smoke detection sensor used in the early fire is proposed in this paper. Infrared photoelectric detection circuit is designed based on the light extinction principle to detect smoke concentration. Based on the analysis of fluid dynamics, the detection cavity and the miniature centrifugal fan are designed not only to realize the rapid and continuous detection, but also to reduce the error of the next detection. The quantitative detection model of smoke concentration is established with the method of smoke equivalent, which is verified through experiments. According to the multiple quantitative values, the control system can judge the level of smoke concentration and control the corresponding alarm circuit to warn users. The result shows that the error of the quantification standard deviation is below 3.47 percent, which indicates the designed smoke sensor in this paper can realize the continuous online quantitative detection under the unsaturated state of smoke concentration.

Keywords: *light extinction principle, detection cavity, continuous online detection, smoke equivalent, quantitative*

1. Introduction

Fire not only damages buildings and constructions but also imperils human lives and properties. Therefore, it is very important to take precautions against fire [1]. Smoke, which is the sign of fire and accompanied with fire, is an important physical phenomenon in fire process [2]. Due to diffusion of the smoke, it is relatively easy to be detected, and the detection of smoke in the pre-warning of the fire is very important. Among various kinds of parameters, the smoke concentration is one of primary importance in early fire detection [3]. So we can judge whether fire occurs through the smoke concentration detection. With the development of the theoretical basis, some of the new technologies are gradually used in fire smoke detection, therefore, smoke sensors can be divided into traditional smoke sensors and non-traditional smoke sensors. Traditional smoke sensors include photoelectric smoke sensor and ion type smoke sensor etc [4]. Many of them include problems of disposable detection, high false alarm rate, slow response speed and no specific quantization. Non-traditional smoke sensors are as follows: Toreyin [5] established markov model of fire color through the color and motion features of fire smoke and flame flicker information to identify whether the fire occur. Fujiwara *et al.*, [6] made use of fractal coding method, and extracted and identified fire smoke according to the similarity of smoke itself. C. Simon *et al.*, [7] used the Bayesian classifier to identify smoke through the analysis of the color and texture feature of smoke and flame. However, these smoke sensors systems are complex, and the hardware costs are relatively high, and the detection area should be open in the process of detection.

In this paper, a smoke sensor is designed, which is composed of infrared photoelectric detection circuit, MCU control module, miniature centrifugal fan circuit

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and alarm module. Infrared photoelectric detection circuit is used to detect smoke concentration. The detection cavity and miniature centrifugal fan can quickly inhale and exhale smoke so as to realize the continuous detection and improve the detection accuracy. The quantitative detection model of smoke concentration is established with the method of smoke equivalent. Through the verification, the smoke sensor can realize the online continuous quantitative detection in the early fire.

2. Smoke Detection Method

2.1. Light Extinction Principle

When the smoke spread to the detection area, smoke particles can cause reflection, refraction and diffraction of light, etc. As a result, the intensity of the output light is less than the intensity of the incident light [8]. The diagram of light extinction principle is shown in Figure 1.

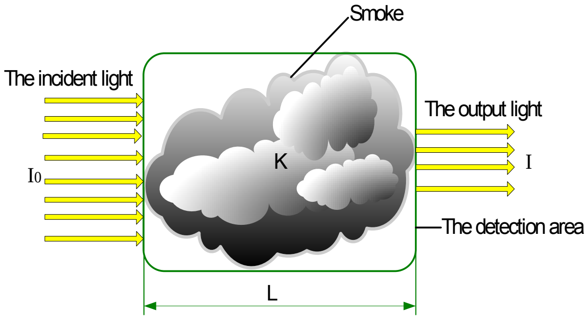

Figure 1. The Diagram of Light Extinction Principle

The process of smoke particles absorb optical radiation meets the Lambert-Beer law[9] as shown in Formula (1):

$$I = I_0 e^{-KL} \tag{1}$$

Where I_0 is the intensity of the incident light; I is the intensity of the output light; L is the thickness of the smoke and K is extinction coefficient. In theory, K has nothing to do with light intensity, so it can be established as shown in Formula (2):

$$K = xc \tag{2}$$

Where c is the smoke concentration, x is extinction coefficient of unit smoke concentration. x depends on many factors, including burning materials, the combustion condition and smoke particles distribution. In a certain range, x can be considered to be a constant. So, Formula (1) can be written as below:

$$I = I_0 e^{-xcL} \tag{3}$$

From Formula (3) we can know that the intensity of the output light I depends on the smoke concentration c and the thickness of smoke L. In this paper, L and I_0 are fixed, so there is a nonlinear relationship between I and c.

2.2. Hardware of Smoke Detection

The hardware of smoke detection consists of MCU control module, infrared emitting diode circuits, infrared photodiode circuit, amplifier circuit and A/D convert circuit.(Shown in Figure 2).

Based on the light extinction principle, 940nm infrared emitting diode and infrared photodiode are used in this paper to constitute the photoelectric smoke sensor to detect the smoke concentration. Output signal from MCU control module drives infrared emitting diode, so that given a certain wavelength of light. Infrared photodiode receives the light through the smoke, and generates the corresponding photocurrent signal. Because the photocurrent signal is microamp level, amplifier circuit is designed to amplify the photocurrent signal, and then to convert the amplified current into the corresponding voltage. MCU control module obtains the AD value of the corresponding voltage through the process of A/D converter circuit. In this paper, The AD value of the corresponding voltage can be considered to be the value of smoke concentration.

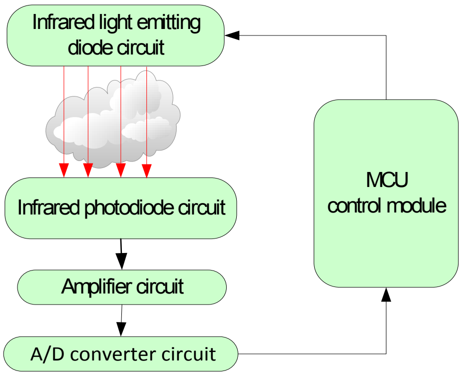

Figure 2. The Structure of the Hardware

3. Smoke Sensor Structure Design

3.1. Detection Cavity Design Principle

In fluid dynamics, Bernoulli's principle[10]states that for an inviscid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy. Bernoulli's principle can be derived directly from the law of conservation of mass which is Newton's 2nd law actually.

A common form of Bernoulli's equation is shown in Formula (4):

$$\frac{1}{2}\rho v^2 + \rho gh + p = C \tag{4}$$

Where v is the fluid flow speed; g is the acceleration due to gravity; h is the elevation of the point above a reference plane; p is the pressure at the chosen point; ρ is fluid density; and C is a constant.

Formula (4) can be rewritten as:

$$p_0 + \rho gh = C \tag{5}$$

$$p_0 = p + q \tag{6}$$

$$q = \frac{1}{2}\rho v^2 \tag{7}$$

Where p_0 is the total pressure; q is dynamic pressure; p is static pressure.

In this paper, the fluid is air, and the change in the ρgh term along the streamline is so small that it can be ignored. So Formula (5) can be presented in the following simplified form:

$$p + q = C \tag{8}$$

Obviously, if the flow speed v increases, the dynamic pressure q increases, and the static pressure p decreases.

In addition, the flow of the pipe can be calculated by the following formula:

$$Q = S \times v \tag{9}$$

Where Q is the flow; S is the cross-sectional area of the pipe; and v is the flow speed.

Based on Formula (4)-Formula (9), we can know that when the providing flow Q is constant, two assumptions can be made: if the cross-sectional area of the pipe S decreases, the flow speed v increases, the dynamic pressure q increases and the static pressure p inside the pipe decreases; if the cross-sectional area of the pipe S increases, the flow speed v decreases, the dynamic pressure q decreases and the static pressure p inside the pipe increases.

3.2. Detection Cavity

In order to detect smoke rapidly, detection cavity is designed on the basis of the basic principle of fluid dynamics. Figure 3 is the structure of detection cavity. Smoke detection cavity is composed of detection cavity, infrared emitting diode component, infrared photodiode component, upper interface component and lower interface component. The middle protrude rectangular part is photoelectric detection area, which is composed of infrared emitting diode component and infrared photodiode component, and the distance between infrared emitting diode component and infrared photodiode component is L. The lower detection cavity is designed to be anti-Y channel, so the smoke which come from the inlet can quickly spread to the detection area and can be rapidly detected. The upper detection cavity is designed to be Y channel in order to slow down the speed of smoke flow and avoid affecting the flow of smoke at the outlet of detection cavity.

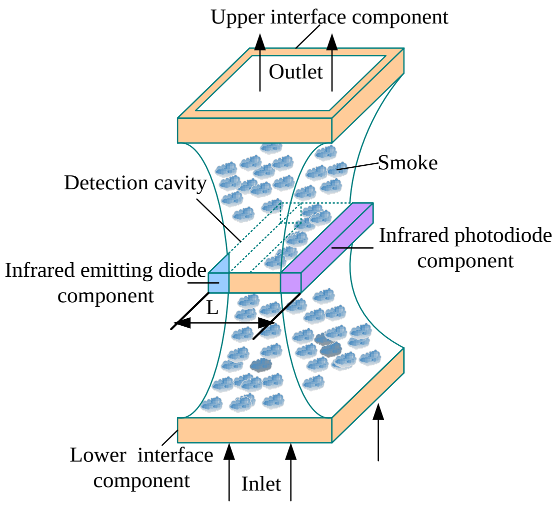

Figure 3. Structure of Detection Cavity

3.3. Simulation of Distribution of Smoke Flow Velocity in Detection Cavity

To provide a detailed distribution of smoke flow velocity in detection cavity, a simulation software--COMSOL Multiphysics (version 4.3) is used in this paper. Figure 4 is the simulation of distribution of flow velocity. We assume that the initial flow velocity is 3m/s. when smoke spread to the middle part of detection cavity (the cross-sectional area is the smallest), the flow velocity is 55m/s which is the largest. When smoke spread to outlet, the flow velocity becomes 3m/s again. It can be seen that the structure of detection cavity is feasible.

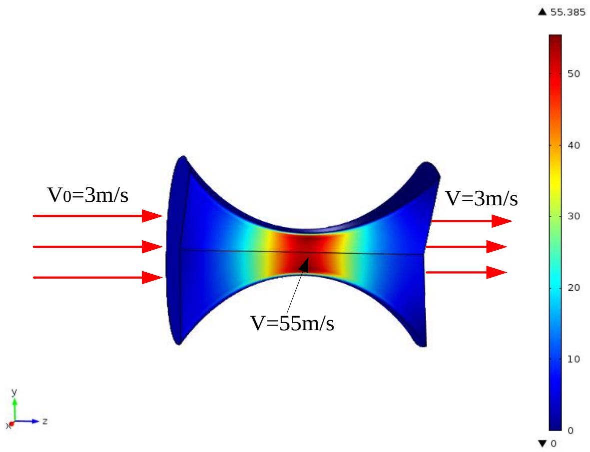

Figure 4. Simulation of Distribution of Flow Velocity

3.4. Smoke Continuous Detection Mechanism

In order to detect the smoke concentration continuously, this paper adopts the miniature centrifugal fan. It can not only inhale quickly new smoke in the current environment, but also can discharge the original smoke in detection cavity.

When miniature centrifugal fan works, centrifugal force is generated in the process of rotation of the fan impeller, which can discharge air in detection cavity. After the air in the impeller is discharged, negative pressure is generated, and then the outside smoke is pressed into the impeller under the effect of atmospheric pressure. The smoke can keep flowing in the detection cavity as the impeller keeps rotating. On the one hand, smoke can be detected continuously; on the other hand, it can make sure that no remaining smoke will interfere with the next detection.

3.5. Avoid Light Mechanism

This paper designs a Z optical maze which is made of black and opaque materials. Figure 5 is the structure of Z optical maze. Before outside light enters into the detection cavity, it has already occurred reflection and scattering many times in the outlet/inlet of Z optical maze, so the intensity of outside light can be reduced effectively. Besides, the cross-sectional area of the outlet and inlet of Z optical maze is as small as possible in order to effectively reduce interference of the outside light and reduce the error of detection.

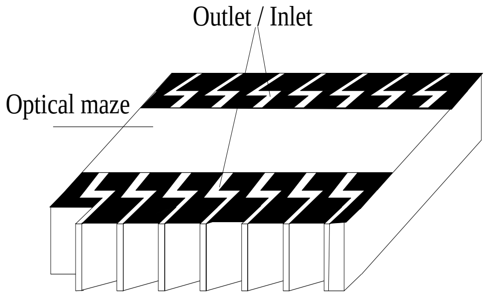

Figure 5. Structure of Z Optical Maze

3.6. Structure and Detection Process of Smoke Sensor

Smoke sensor in this paper mainly includes the upper and lower optical maze, detection cavity, miniature centrifugal fan, control module, power module, reset button, beeper and indicator light. Figure 6 is the structure of smoke sensor.

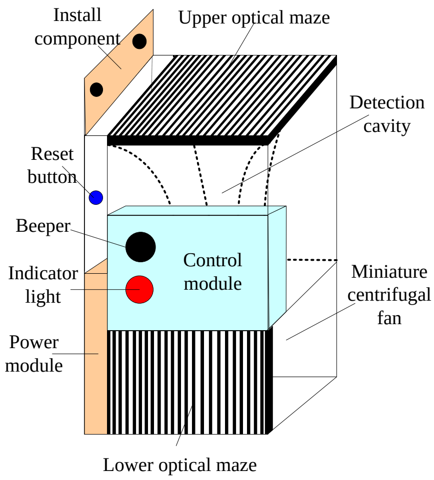

Figure 6. Structure of Smoke Sensor

The control module starts the miniature centrifugal fan, so smoke can be inhaled into the lower detection cavity from the lower optical maze, and spread to photoelectric detection area at the fastest speed. The control module obtains the AD value of the amplified voltage through the process of A/D converter circuit. Based on the collected smoke concentration quantification value, the control module could judge the level of smoke concentration and control the corresponding alarm circuit to warn the users. After the detection, the smoke can be discharged from the upper optical maze with the use of the miniature centrifugal fan. When the miniature centrifugal fan keeps working, the smoke concentration can be detected continuously without interference. Figure 7 is the detection process of smoke sensor.

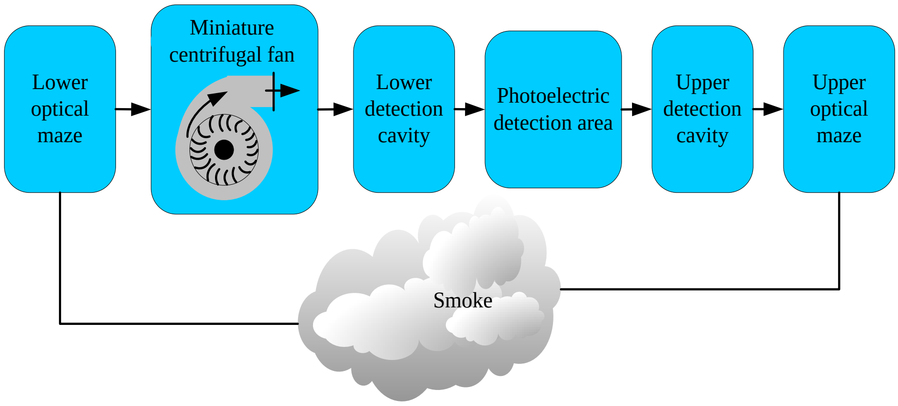

Figure 7. Detection Process of Smoke Sensor

4. Experiment and Analysis

4.1. Experimental Materials and Method

The experimental equipment is composed of the experimental box (30cm long × 15cm high × 15cm wide), glass, smoke sensor, PC, burning material, smoke production base and the base. In the center of the bottom of the experimental box, there is a rectangular opening which is the same size as the smoke production base. In the process of experiment, the rectangular opening should be closely together with the smoke production base, and the base also should be closely combined with the bottom of the experimental box after the burning material is lit. The smoke concentration can be detected by smoke sensor which is installed at the left side of the experimental box. In order to ensure the sealing of the experimental box, the experimental box is made of sealing materials, and all the interfaces are coated with the sealing glue, the bottom of the box and the base are also stuck with soft plastic. We can observe experiment situation through the glass. At the same time, we can save the smoke concentration sampling values through PC. Figure 8 is the structure of experimental equipment.

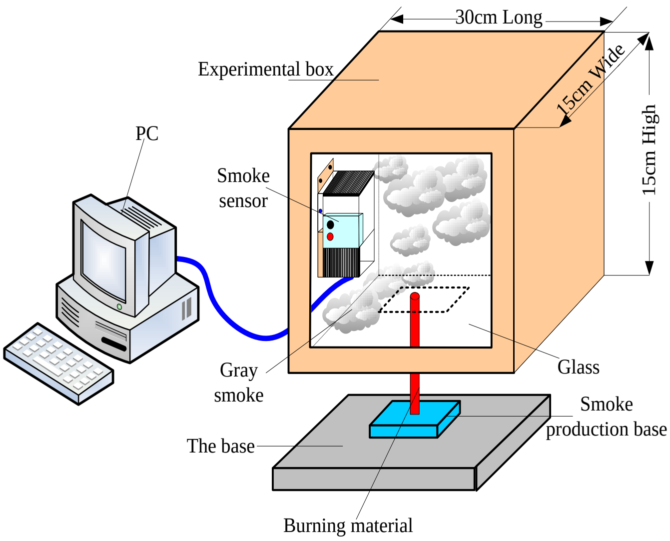

Figure 8. The Structure of Experimental Equipment

In this paper, the smoke is grey smoke. In order to ensure the quantitative production of the gray smoke, the burning materials are processed into 3 mm in diameter, 50 mm long cylinders. In the process of the experiment, the burning materials should be placed vertically in the center of the smoke production base so as to reduce the error.

4.2. Quantitative Detection Model

To facilitate quantitative analysis, smoke equivalent method is adopted to do experiments in this paper. (Shown in Formula (10)).

$$s = t \times n \times s' \tag{10}$$

Where s is the smoke equivalent value; t is burning time; n is burning material number; s' is the smoke production volume of one burning material per unit time. In this paper, we define that when s' is a constant , t=20sec and n=1, then s=1.

At first, one burning material is lit and placed in the experimental box. The control module collects AD value of smoke equivalent (s=1 to 48) and transmits data to PC every 20 seconds. Above steps are repeated 54 times and the corresponding AD values are saved in PC.

In this paper, the least square method [11] is proposed to analyze and process the data and to establish the smoke quantitative detection model. According to the first four groups of data (s=1 to 24), the quantitative detection model of smoke concentration is established as follows.

$$y = -11.2543 x + 3166.971 \tag{11}$$

$$R^2 = 0.99037 \tag{12}$$

Where y is the smoke concentration sampling value, x is smoke equivalent value, R^2 is the correlation coefficient.

The correlation coefficient R^2 is up to 0.99, which indicates the fitting curve has a good correlation with the experimental data. Figure 9 shows that there is a linear relationship between smoke concentration sampling value and smoke equivalent value. Along with the increase of smoke equivalent value, smoke concentration increases, and AD sampling value gradually decreases, which proves that the smoke concentration can be quantified.

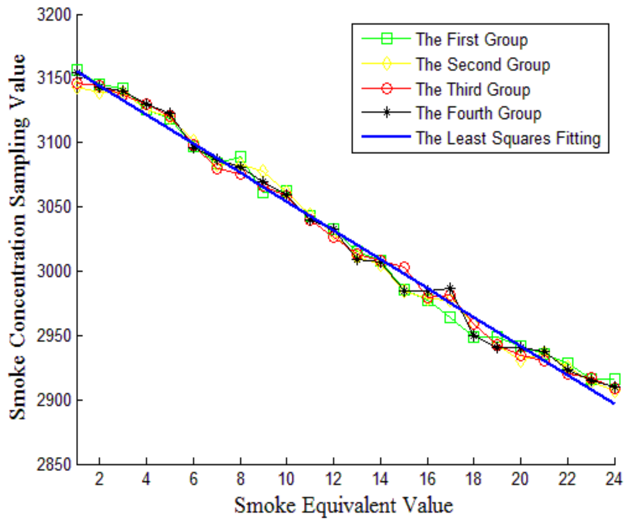

Figure 9. Smoke Quantitative Detection Model

4.3. Verification and Analysis of Quantitative Detection Model

This paper uses the remaining 50 groups of experimental data to verify the validity of the above quantitative detection model. The standard deviation could reflect the discrete degree of dataset in some extent. First, the standard deviations of each group (s=1 to 24) is calculated by using the Formula (13):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{24} (y_i - y_i')^2}{24}} \tag{13}$$

Where σ is the standard deviation; y_i is the smoke concentration quantitative value of each group; y_i' is the smoke concentration quantitative value of above detection model; and i is smoke equivalent value.

As shown in Figure 10, the range of the standard deviations of 50 groups is from 6.480800 to 8.661847. According to the smoke concentration quantitative data of 50 groups, the maximum is 3156, and the minimum is 2907. Then the error of the standard deviation of each group can be calculated by using the Formula (14):

$$e = \frac{\sigma}{mx - mi} \times 100\ \% \tag{14}$$

Where e is the error of standard deviation; mx is the maximum; mi is the minimum.

After calculation, the range of the error of the standard deviation of 50 groups is from 2.602731% to 3.478653%. The error is small, which means that smoke sensor can realize quantitative detection of smoke concentration.

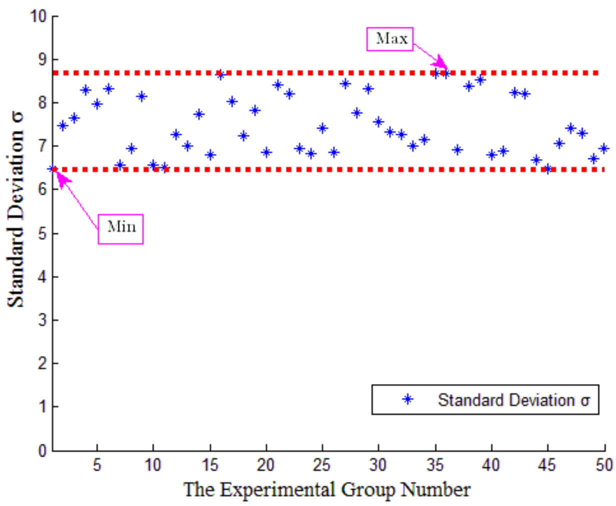

Figure 10. Statistical Chart of Standard Deviation

Figure 11 is the data fitting curve (s=1~48) of one burning material. It can be seen that it's a nonlinear curve, and when smoke equivalent value reaches a certain value, the smoke concentration in the experimental box gradually reaches the saturated state.

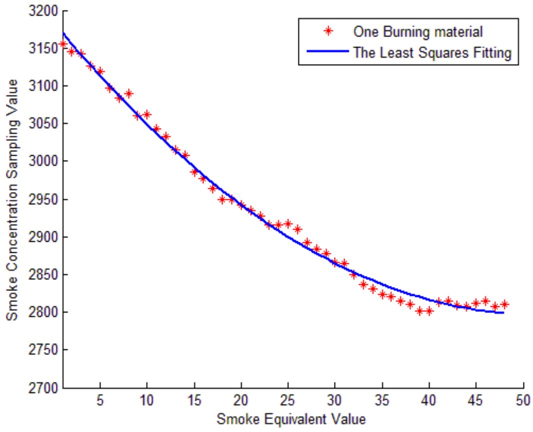

Figure 11. Data Fitting Curve of One Burning Material

It should be noted that data of the above quantitative detection model was collected under unsaturated state. Therefore, the conclusion is that the smoke sensor can realize the quantitative detection when the smoke concentration is under unsaturated state.

In order to continue to study the quantitative regularity of the smoke under the condition of saturated and unsaturated, two, three, and four smoke production materials are used respectively to perform the experiment under the same experimental conditions.

As shown in Table 1, the parameters of the fitting equation are calculated by using the least square method. We can see that the fitting curve has a good correlation with the experimental data under unsaturated state.

Table 1. Parameters of Liner Fitting Equation

Parameter	Burning material number		
	Two	Three	Four
Slope	-10.2935	-8.6654	-7.1283
Intercept	3115.329 7	3082.137 7	2961.6080
Correlation coefficient R^2	0.96724	0.96503	0.91825

Figure 12-14 are the data fitting curves of two, three and four burning materials. It can be seen that the degree of quantitative data fitting curve of the smoke concentration is more obvious with the increase of smoke equivalent value. It is in accordance with the theory that the smoke concentration and the intensity of the output light have a nonlinear relationship.

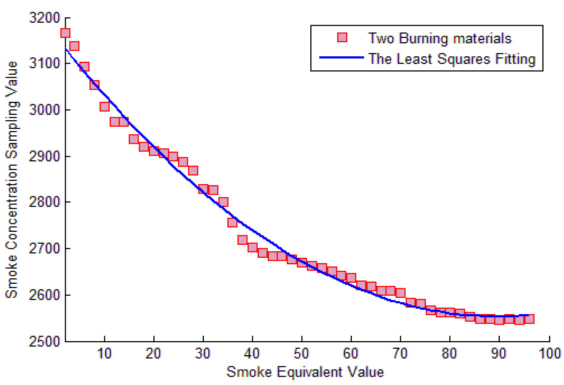

Figure 12. Data Fitting Curve of Two Burning Materials

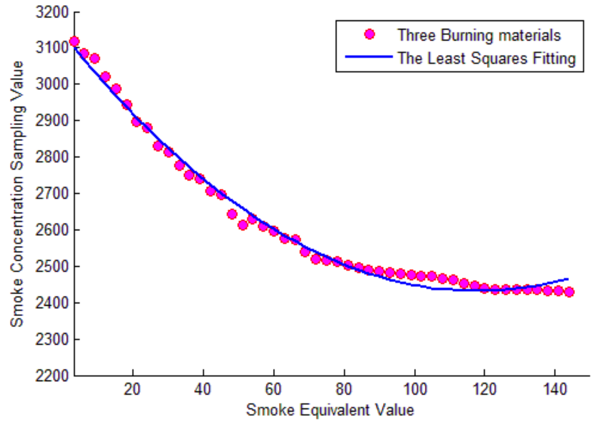

Figure 13. Data Fitting Curve of Three Burning Materials

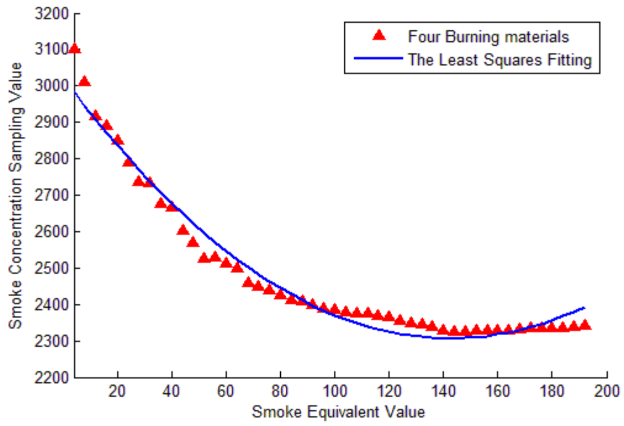

Figure 14. Data Fitting Curve of Four Burning Materials

5. Conclusion

In this paper, a new type of smoke sensor is proposed. Photoelectric detection circuit is designed to detect smoke concentration. Detection cavity and the miniature centrifugal fan are designed to achieve cycle detection and reduce the error of detection. The quantitative detection model is established with the method of smoke equivalent value. The result shows that this smoke sensor can rapidly and continuously detect the smoke concentration, and realize the online quantitative detection under the unsaturated state. It is an effective and low-cost method in fire prevention.

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