Development of a Multi-component Infrared Gas Sensor Detection System

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Abstract. A multi-component infrared gas sensor detection system is designed based on the principle that the gas under test absorbs infrared radiation of a specific wavelength, periodic infrared radiation signals pass through the chamber to reach multiple sets of filters. The infrared sensitive component extracts an electrical signal to filter and zoom which having the same period as the light source. And in a period of signal acquisition repeatedly, which achieved the effect of improving the reliability of signal acquisition, Enhanceing the capability of anti-jamming, Reduce the response time of the sensor, etc.

1. Introduction

As we all know, the safety problem of coal mine has become the focus of the industry, and the Harmful or suffocating gases commonly encountered in mine production are CH4, SO2, CO, C2H2, CO2, and the like. When these gases exceed a certain concentration, it will inevitably cause varying degrees of danger, that is, the need for real-time and accurate detection of these gases at the same time. There are many commonly used gas detection methods, such as the methods based on infrared absorption, Raman spectrum, photoacoustic spectrum, catalytic combustion, semiconductor conductivity change, thermal conductivity and other principles. Infrared absorption is a non-contact real-time monitoring gas detection technology, and has been more and more widely valued and applied. The patented of "dual-light source and dual-sensor infrared multi-gas detection sensor" (CN101105449) provides a dual-light source and dual-sensor infrared gas detection sensor, whose optical path structure is complex and requires the focus of the reflector. In addition, the manufacturing of the gas chamber is also complex and has poor practicability. Zheng wen-xian's study on multi-component gas sensing technology in underground coal mine based on non-spectrophotometric infrared only uses the peak value of the signal for calculation, which is low sensitivity [1]. Kang kai's study on the infrared multi-component gas detection system based on single-chip microcomputer, which the collected electrical signals have not been filtered or amplified [2]. Through consulting relevant literature and market survey, it is found that the structure and optical system of some sensor gas chambers are complex, which leads to complex manufacturing process, high cost, difficult maintenance, and difficult to realize the measurement of multi-component gas. Some of them gas chamber structure and detection methods are not conducive to the full exchange of gas between the gas chamber and the environment, resulting in long measurement response time and unreliable gas detection in the environment. Most of the sensors has lots of shortcomings such as only output the electrical signal converted by the infrared...
detector and have no subsequent signal processing. This paper presents a practical and efficient multicomponent infrared sensor detection system.

2. Principle of infrared radiation absorption
When the infrared light source passes through the corresponding gas, its characteristic frequency spectral line light energy will be absorbed by the gas. For example, the infrared absorption spectra of CO\textsubscript{2}, CH\textsubscript{4} and C\textsubscript{2}H\textsubscript{2} are shown in figure 1.

![Relative Absorption Carbon dioxide INFRARED SPECTRUM](image1)
![Relative Absorption Mathane INFRARED SPECTRUM](image2)
![Relative Absorption Acetylene INFRARED SPECTRUM](image3)

(a) CO\textsubscript{2}  (b) CH\textsubscript{4}  (c) C\textsubscript{2}H\textsubscript{2}

**Figure 1.** The infrared absorption spectrum of gas

The characteristic absorption wavelength of CO\textsubscript{2} gas is 3.43\mu m\textsuperscript{-1}, the characteristic absorption wavelength of CH\textsubscript{4} gas is 4.26\mu m\textsuperscript{-1}, and the characteristic absorption wavelength of C\textsubscript{2}H\textsubscript{2} gas is 13.6\mu m\textsuperscript{-1}. The absorption of infrared radiation by gas follows the Lambert-Beer law [3].

\[
\frac{I}{I_0} = e^{-Lc}
\]  

(1)

The process of converting infrared radiation signals absorbed by infrared detectors into electrical signals is quite complicated, this paper takes the infrared single-light source dual-detector as an example, and the relationship between the electrical signal output and the energy of infrared radiation is as follows:

\[
u_r = R_1I_0
\]  

(2)
\[ u_m = R_2 I \tag{3} \]

When the concentration \( c = 0\% , I_0 = I \), so

\[ \frac{u_{m0}}{u_{r0}} = \frac{R_1}{R_2} = R \tag{4} \]

Where: \( u_r \) is the output electrical signal of the reference detector; \( I_0 \) is the initial energy of infrared radiation; \( u_m \) is the output electrical signal of the measuring detector; \( I \) is the energy of infrared radiation absorbed by the gas; \( R_1, R_2 \) are the voltage response rates of the infrared detectors. According to (1), (2), (3) and (4), the relationship between the signal detected by the sensor and the gas concentration is:[4]

\[ \frac{u_m}{u_r} = \frac{u_{m0}}{u_{r0}} e^{-kLC} \tag{5} \]

Where: \( u_m/u_r \) is the output voltage ratio of the measuring detector and the reference detector; \( u_{m0}, u_{r0} \) are the output voltage of the detector and the reference detector when the measured gas concentration is 0; \( K \) is the gas absorption coefficient; \( L \) is the thickness of radiation passing through the gas layer; \( C \) is the concentration of measured gas.

3. System design

![Figure 2. A frame diagram of a multi-unit infrared gas sensor detection system](image)

The radiant light emitted by the light source is the spectrum of visible light to infrared wavelengths of incandescent light. After generating periodic radiation waves driven by periodic voltages, which through the air chamber, the spot formed by multiple reflections directly illuminates the sensitive surface of the infrared detector, and the light path is not adding any gathering or dividing optical device. The infrared detector is composed of several infrared sensors, one infrared sensor receiving wavelength is \( 3.90 \mu m \), narrowband interference filters are mounted on the sensitive surface of the remaining infrared sensing element, which has the capable of receiving infrared radiation of a wavelength corresponding to the narrowband interference filter. The infrared detector converts the received periodic radiation light into an electrical signal of the same period and transmits it to the signal processing circuit, namely the narrow-band band-pass filter amplification circuit. Then connected to the microcontroller, and displayed after analog-to-digital conversion. At the same time, alarmed when the detected gas concentration is higher than the set value. The overall design of the system is shown in Figure 2.
4. System hardware design

4.1 The circuit of Light source modulation and drive
After the radiant light wave is reflected by the sidewall of the gas chamber and absorbed by the gas to be tested, which irradiated on the photosensitive surface of the infrared detector, and converted into an electrical signal. The specific circuit is shown in figure 3.

![Figure 3. the circuit of the light source modulation drive](image)

The periodic control signals generated by the single-chip microcomputer pass through the resistor R46, the audion VT10 and the field-effect tube IRF220 successively, and the driving light source will emit radiation light waves periodically; When the FET is turned on, the source current value is set by adjusting the resistor R48, thereby determining the intensity of the radiant light wave generated by the light source; When the FET is turned off, the source current value is set by adjusting the resistor R49, thereby determining the modulation depth of the light source. The transistor can protect the FET from damage and can prevent the interference between the control signal and the light source.

4.2 The circuit of the photoelectric conversion
Lithium tantalate crystal (lithium tantalate) is a very thin plate capacitor as the key component of the infrared detector. Lithium tantalate is a thermoelectric crystal, which the polarity at both ends will be reversed when heated. The specific circuit is shown in figure 4.

![Figure 4. The conversion process of pyroelectric infrared detector](image)

Figure 4 shows the various stages of the conversion from infrared radiation to electrical signals [5]. The radiant flux in the pyroelectric element is absorbed and causes a change in temperature, and the temperature change changes the charge density on the electrode, thereby forming an electrode. The equivalent circuit is shown in figure 5.

![Figure 5. The equivalent circuit of temperature change](image)
4.3 The circuit of signal processing
The infrared sensitive component receives the radiated light wave signal and converts it into an electrical signal of the same period, but its signal is weak, which needs to be filtered and amplified. The specific circuit is shown in figure 6.

![Circuit Diagram](image)

Figure 6. The circuit of narrowband bandpass filter amplifier

The output of the infrared sensitive component is connected to the positive input of the operational amplifier, by adjusting the parameters of the resistors R10, R11, C16, and C17, and then the center frequency, bandwidth, amplification factor, and quality factor Q of the narrowband bandpass filter amplifier circuit are controlled. The transmission function of the narrowband band-pass filter amplifier circuit is:

$$H(s) = 1 + \frac{s}{R_1C_{15} + s\left(\frac{1}{R_{10}C_{15}} + \frac{1}{R_{11}C_{16}} + \frac{1}{R_{10}R_{11}C_{15}C_{16}}\right)}$$  \hspace{1cm} (6)

Take the light source with a frequency of 4 Hz as an example, the center frequency of the narrowband band-pass filter amplifier circuit is 4 Hz. The bandwidth should be as narrow as possible to filter out interference signals that are not 4 Hz. The bandwidth is as narrow as possible to filter out interference signals that are not 4 Hz, such as \(f_w = 8 \text{Hz}\). In order to prevent the generation of self-oscillation of the amplifying circuit and drastically reduce the amplitude-frequency characteristic below the bandwidth, the quality factor of the filter \(Q < 1\). Then, in the case where the center frequency, bandwidth and quality factor \(Q\) does not change, which requirements of the amplification factor of the narrowband bandpass filter amplifier circuit can be realized by adjusting the resistors R10 and R11.

4.4 The circuit of signal acquisition
The output signal of each sensitive component in the infrared detector is processed into a sine wave after being processed by the narrowband bandpass filter amplifier circuit. In this paper, the pattern of \(n\) samplings in one cycle is designed, which is the same as the pattern of sampling \(n\) cycles in terms of time. Sampling at any point in the wave of the sinusoidal function is equivalent to the sampling at the peak value, thus, the reliability of signal acquisition and anti-interference capability are improved, and the sampling time is shortened, saving the time of delay and waiting of the single chip microcomputer (MCU), improving the operational efficiency of the program, and shortening the response time of the sensor. \(N\) samples can be taken in a sine wave, and the following formula can be used for calculation:

$$u_m = \frac{\sum_{i=1}^{n} U_m \sin wt_n}{\sum_{i=1}^{n} U_r \sin wt_n} = \frac{U_m}{U_r}$$  \hspace{1cm} (7)

\(u_m\) is a gas absorption under test after the infrared radiation energy of analog sine wave measured values, \(u_r\) is the test after the gas does not absorb the infrared radiation energy of analog sine wave reference, \(U_m\) is the peak value measured \(u_m\), \(U_r\) is the peak value reference \(u_r\); \(u_m / u_r\) represents the value of the gas concentration to be measured, which is the peak ratio of the measured value to the sine function waveform of the reference value; \(n\) is the number of sampling
times in a cycle, and the value ranges from 128 to 1024; Generally, comparing to the pattern of one sampling in one cycle, the pattern of n samplings in one cycle is the same as that of sampling n cycles in terms of time, sampling at any point in the wave of the sinusoidal function is equivalent to the sampling at the peak value, thus, the reliability of signal acquisition and anti-interference capability are improved, and the sampling time is shortened. According to the measured data in (7), the concentration of the measured target gas can be obtained by using (5).

5. System software design
The periodic radiation wave generated by the light source heats the gas in the air chamber periodically, which promotes the gas in the air chamber to expand and contract periodically, thereby realizing the rapid gas exchange between the gas in the air chamber and the external environmental gas, forming the "breathing gas chamber". When the periodic control signal causes the current in the light source to be changed from large to small then amplified and filtered, the single-chip microcomputer opens the analog-to-digital conversion channel to separately collect data for the temperature, the voltage of each point, and the output of the sensitive component of the infrared detector. The data is obtained by 128 samplings, and finally the calculated concentration c is obtained. The target gas concentration is finally displayed by pressing the button. The software flow chart design is shown in Figure 7.

6. Experimental results and conclusions
Calibrate the device while the concentration of CO$_2$, CH$_4$ and C$_2$H$_2$ is 2% one by one, the calibrated device measures three groups of standard mixed gases to be measured at different temperatures. The experimental data results are shown in Table 1.

![Figure 7. The flow chart of main program](image)

| T(℃) | CO$_2$(2%) | error | CH$_4$(2%) | error | C$_2$H$_2$(2%) | error |
|------|------------|-------|------------|-------|----------------|-------|
| 32   | 1.94       | 0.06  | 1.96       | 0.04  | 1.93           | 0.07  |
| 20   | 1.70       | 0.30  | 1.82       | 0.18  | 1.75           | 0.25  |
| 10   | 1.45       | 0.55  | 1.65       | 0.35  | 1.52           | 0.48  |
| 3    | 1.27       | 0.73  | 1.37       | 0.63  | 1.25           | 0.75  |
The multi-component infrared sensor detection system designed in this paper can measure the gas of different concentrations quickly and achieves the desired effect in stability and sensitivity. However, from a large number of experimental data, the measurement data error is large because of the change in the actual ambient temperature, that is, the lack of temperature compensation. Therefore, the next step is to use wavelet transform for noise elimination or support vector machine or other theories to more accurately analyze the factors affecting the temperature of multi-component mixed gas in the actual environment, and establish the corresponding temperature compensation model, so as to obtain more accurate gas concentration value.

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