Detection of Carbon Monoxide in Automobile Exhaust Based on Photoacoustic Spectroscopy

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Abstract: To enable the detection of carbon monoxide (CO) in automobile exhaust, this study designs and implements a CO detection system based on photoacoustic spectroscopy. By optimizing the excitation light source, photoacoustic cell, signal processing unit, and data acquisition module, the key challenges of sensitivity, stability, and signal-to-noise ratio in real-time monitoring are effectively addressed. Experimental results demonstrate that the system performs excellently within the concentration range of 120 ppm to 1200 ppm, with a maximum relative error not exceeding 1.8%. These results verify the system's high sensitivity and accuracy. The system shows significant potential for widespread application, providing reliable data support for automobile exhaust monitoring.

Keywords: Photoacoustic Spectroscopy; Automobile Exhaust; Carbon Monoxide Detection; Photoacoustic Effect

1. Introduction

With global warming, ozone hole, photochemical smog pollution and frequent occurrence of various extreme weather, etc., the serious situation of environmental problems has become a hot issue of global concern. With the rapid increase in the number of automobile production, the pollution of the ecological environment by exhaust emissions from automobiles has become more serious.[1] According to the statistical yearbook of the Ministry of Environmental Protection, in 2022, the emission of four pollutants from motor vehicles nationwide, namely carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons (HC), will be accounted for to reach 14,662,000 tons, of which 7,430,000 tons of CO will be discharged, which is the most important component of pollutants emitted by the exhaust of automobiles. CO is the product of incomplete combustion of organic compounds, and it is a kind of CO is a product of incomplete combustion of organic compounds, and is a highly toxic and undetectable gas, which is not easy to be detected because it is colorless, odorless, and irritant, and is not easy to be detected by people, and has been called the “silent killer”.[2] At present, the technologies that can be used to monitor CO gas include gas chromatography, non-dispersive infrared technology, sensor array technology and photoacoustic spectroscopy.[3] Among them, gas chromatography cannot realize real-time detection of CO gas; non-dispersive infrared technology has low detection accuracy and sensitivity; and sensor array technology has poor accuracy and stability, and the results of the measurement are not accurate.[4] Photoacoustic Spectroscopy (PAS) is a technique based on the principle of photoacoustic effect, which uses the change in the intensity of the acoustic signal produced by the gas molecules after absorbing a specific wavelength of light irradiation to quantitatively measure the concentration of gases.[5] The technique is characterised by high selectivity, sensitivity and fast response, and is therefore widely used in many fields such as chemical, pharmaceutical, agricultural and industrial. In view of its superior performance, this paper designs an all-optical photoacoustic spectroscopy-based carbon monoxide detection system in vehicle exhaust.[6] In this paper, the absorption spectral characteristics of carbon monoxide are firstly discussed in depth based on the basic theory of photoacoustic spectroscopy gas detection. Subsequently, a laser is selected as the excitation light source, and an optimised photoacoustic cell structure is designed for the experimental requirements to enhance the sensitivity and accuracy of the gas detection system. On this basis, combined with the system design and optimisation, it seeks to achieve high sensitivity and high selectivity detection of gases such as carbon monoxide. Through the design and implementation of this system, it is expected to provide a reliable technical solution for environmental monitoring and vehicle exhaust safety detection.

2. Research Foundation

Photoacoustic Spectroscopy (PAS) is an indirect spectroscopic detection technique based on an optical method for acoustic detection, an absorption spectroscopy technique without background noise, which combines the photoacoustic effect with optical detection techniques to achieve a highly sensitive, non-contact analysis of the sample. The principle of photoacoustic spectroscopy is the photoacoustic effect [7], when a carbon monoxide molecule absorbs light energy of a specific wavelength, it causes a localized temperature increase and generates ultrasonic signals. By detecting these ultrasonic signals through the all-optical technique, the concentration of carbon monoxide in the exhaust gas can be quantitatively analyzed, and its corresponding workflow is shown in Figure 1.

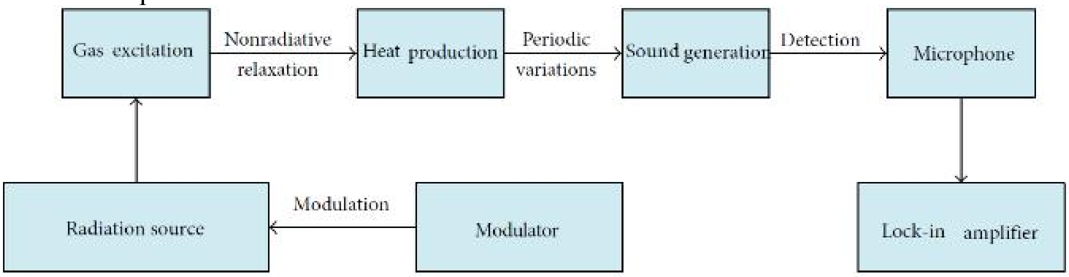

Figure 1. Workflow of Photoacoustic Effect

In addition, the structure of the photoacoustic system is relatively simple and does not require a complex optical path calibration process. The photoacoustic spectroscopy gas detection system generally consists of four parts, namely, a light source, a photoacoustic cell, an acoustic wave sensor and a photoacoustic signal acquisition and processing unit. Infrared light source after wavelength modulation or intensity modulation, to produce a periodic light source, the light is collimated and incident to the photoacoustic pool, the gas in the pool absorbs the light energy to produce heat energy caused by the expansion of the gas in the pool, when the intensity or frequency of the light source undergoes a periodic change, the thermal energy in the photoacoustic pool also undergoes a periodic change to form a periodic pressure wave. The acoustic detector is used to measure the photoacoustic pressure wave, extract the signal of the same frequency as the frequency of the modulated light source, and use certain signal processing methods to calculate the intensity of the photoacoustic signal, and ultimately calculate the concentration of the gas to be measured.

The generation of photoacoustic signals involves two key processes: the generation of thermal energy and the formation of acoustic waves. The article presents an expression for the thermal energy produced due to non-radiative transitions, derived through an analysis based on the particle number density in a simple two-level system after the gas absorbs light. Under typical conditions, for lower modulation frequencies $\omega << 10^6 s^{-1}$, the fundamental equation describing the thermal energy generated by light absorption, which serves as the theoretical basis for photoacoustic research, can be expressed as[8,9]:

$$H_0 = N\sigma I_0 \quad (1)$$

N represents the molecular number density in the two-level system, σ is the absorption cross-section of the molecules, and I_0 denotes the incident light intensity. The thermal source generated by light absorption can be considered as the source of acoustic waves within the gas, and the sound waves produced inside the photoacoustic cell due to light absorption primarily depend on the following two factors:

(1) If the modulation frequency ω of the incident light is lower than the lowest resonant frequency of the photoacoustic cell, no

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resonant modes will exist within the resonance tube. The amplitude of the acoustic wave is given by:

$$A_0(\omega) = \frac{i\alpha(\gamma-1)\mathrm{JI}(r,\omega)dV}{V_\omega\left[1+\frac{i}{\omega\tau_T}\right]} \quad (2)$$

(2) τ_T represents the thermal conduction time from the gas to the cell wall, and is given by the expression $\tau_T = \frac{R_2 c_r}{2.04k}$, where k is the thermal conductivity of the gas and C_r is the specific heat capacity at constant volume of the gas.

(3) When the modulation frequency ω of the incident light is equal to a specific acoustic resonance frequency ω_j, the amplitude of the acoustic wave corresponding to the resonance mode j inside the cavity can be expressed as

$$A_j(\omega) = \frac{Q_j}{\omega_j}(\gamma-1)/V_c\int_{P_j}^{*}(r)H(r,\omega)dV \quad (3)$$

The term $\frac{\omega_j}{Q_j}$ represents the half-width at half-maximum (HWHM) of the resonance mode. Equations (2) and (3) reflect the intrinsic relationship between the photoacoustic signal intensity and the structure and operating mode of the photoacoustic cell. These expressions are considered the theoretical foundation for the design of photoacoustic cells under typical conditions.

The carbon monoxide molecule has a unique infrared absorption spectrum, and its absorption peaks are mainly distributed in the wave number range from 2000cm^{-1} to 2200cm^{-1}, corresponding to a wavelength of about 4.5 μm to 5 μm. In this range, the CO molecule can absorb part of the energy in the infrared spectrum, leading to the appearance of the absorption peaks in the infrared spectrum. Therefore, when light at these wavelengths is irradiated into the CO gas, the light energy is converted into heat energy, resulting in a localized temperature increase and a strong expansion effect, which enhances the photoacoustic signal. Photoacoustic spectroscopy can be used to determine the concentration of CO gas by analyzing the intensity and frequency of the sound waves.[10]

3. Design of Inspection System Based on Photoacoustic Spectroscopy

In this paper, a detection system based on photoacoustic spectroscopy is designed for detecting carbon monoxide in automobile exhaust, as shown in Figure 2. The design of the system is centered around the characteristic absorption spectral lines of carbon monoxide, focusing on the problems of high sensitivity, stability and real-time monitoring. The main components of the system include an excitation light source, a photoacoustic cell, a signal processing unit, and a data acquisition and analysis module, aiming at realizing fast and accurate measurement of carbon monoxide concentration in automobile exhaust.

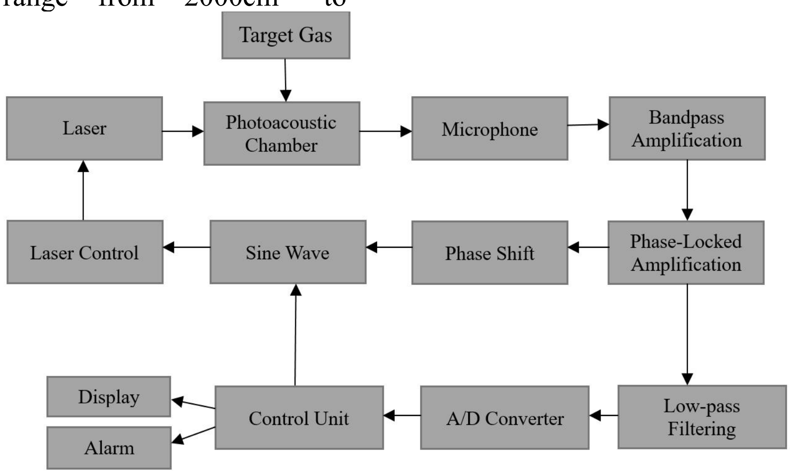

Figure 2. Photoacoustic Spectrum Gas Detection System

Firstly, based on the characteristics of carbon monoxide absorption spectrum, a vertical cavity surface emitting laser (VCSEL) was selected as the excitation light source. With excellent wavelength stability and narrow spectral bandwidth, the vertical-cavity surface-emitting laser can effectively excite the photoacoustic effect of carbon monoxide molecules at their characteristic absorption wavelengths. By controlling the center frequency of the laser, it accurately matches the absorption spectral lines of carbon monoxide, thus enhancing the detection sensitivity of the system for carbon monoxide.

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Secondly, in the design of the photoacoustic cell, in order to ensure the full interaction between light and gas sample, the system adopts a highly efficient photoacoustic cell structure design. The reasonable design of the photoacoustic cell ensures that the light beam can pass through the gas sample uniformly, and at the same time reduces the loss of photoacoustic signal. In terms of signal processing, the system is designed with several key circuits to optimize the acquisition and processing of photoacoustic signals. Specifically, a bandpass filter circuit is designed to filter out noise signals at non-target frequencies, and a lock-in amplifier circuit is used to enhance the weak photoacoustic signals. In addition, a phase-shift circuit is used to optimize the phase of the signal, a low-pass filter circuit is used to further eliminate high-frequency noise, and an analog-to-digital converter circuit converts the analog signal to a digital signal for further data analysis.

3.1 Selection of Light Source

The light source is the excitation source in the photoacoustic spectral detection system, and the radiation characteristics of the light source are directly related to the detection sensitivity of the photoacoustic system and the type of gas that can be detected. According to the radiation characteristics, the light source can be divided into two categories of incoherent light source and coherent laser light source. Commonly used non-coherent light sources are: incandescent light source, arc lamp source, high pressure xenon lamp. Most of the incoherent light sources are broadband light sources, whose radiation range can continuously cover most of the region of the infrared band, but their radiation intensity is generally weaker, lower resolution, so that the improvement of system detection sensitivity is limited. Therefore, the choice of high-power and excellent characteristics of the light source can improve the signal-to-noise ratio of the system. The following are a few influencing factors for the selection of light source: firstly, the output wavelength of the light source should be matched with the absorption spectral lines of the gas to be measured, and the spectral lines with larger absorption intensity should be preferred to improve the sensitivity. At the same time, cross-interference with other gas spectral lines should be avoided. The light source should have good tunability and wide tuning range to meet the measurement needs of different gases. In addition, stability is key, especially under temperature changes, the light source needs to have a temperature control system to ensure that the output wavelength is stable. Lifetime, low noise, size and ease of maintenance also need to be considered. In short, the selection of a light source should balance performance and cost to ensure that the inspection system operates efficiently, accurately and consistently.

According to the data given in the HITRAN database, the absorption spectra of CO, H_2O and CO_2 molecules near 2.33μm were simulated by software and systematically analyzed, and finally the spectral line located at 6380.3013cm^{-1} was chosen as the sensing target for CO measurement, as shown in Figure 3., which has a strong absorption and can ensure a high sensitivity of the measurement; moreover, the spectral line is relatively independent and there is no other interference nearby. This spectral line has strong absorption, which can ensure high measurement sensitivity; and this spectral line is relatively independent, and there are no absorption lines of other interfering components in the vicinity. In this paper, we choose DFB semiconductor laser, made of InGaAsP material, its center wavelength is 1567.32nm, the maximum output power of 20mW. 25°Cambient temperature conditions for the test, the radiation wavelength of the deviation within 1nm.

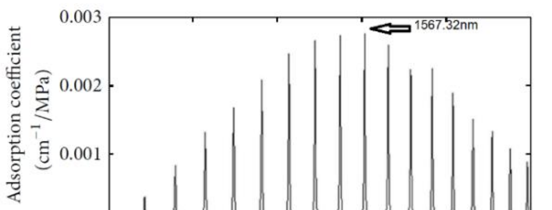

Figure 3. Near-infrared Spectra of CO

3.2 Design of Photoacoustic Cell

The photoacoustic cell is a key component of photoacoustic spectroscopy, and its working principle is based on the local temperature changes induced by light absorption, which subsequently generates an acoustic signal. The process begins when a laser or other light

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source illuminates a gas or liquid sample. When the frequency of the incident light matches the absorption characteristics of certain molecules within the sample, these molecules absorb the light energy and undergo transitions to higher energy levels. This light absorption process leads to the conversion of a portion of the absorbed energy into heat, resulting in a local temperature rise that induces a rapid thermal expansion, which in turn generates a pressure wave and ultimately produces an acoustic wave.

Within the photoacoustic cell, the generated acoustic waves propagate according to the geometry and size of the cavity, forming specific resonance modes. The design of the resonance cavity can significantly enhance the intensity of the acoustic signal. When the modulation frequency of the laser pulse matches the resonance frequency of the photoacoustic cell, the amplitude of the acoustic wave is substantially increased, thereby improving the detection sensitivity. The acoustic signal is typically detected by piezoelectric sensors or microphones, which convert it into an electrical signal. This signal is then amplified and analyzed by a signal processing system to extract information regarding the concentration of target substances or other physical properties of the sample.

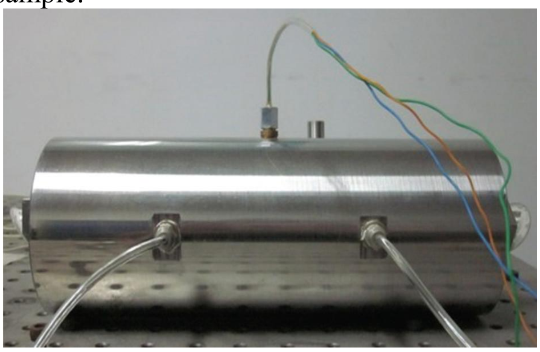

Figure 4. Structure of Photoacoustic Cell

In the gas photoacoustic spectroscopy detection system, the performance of the photoacoustic cell determines the sensitivity of the photoacoustic detection system. The photoacoustic cell can be divided into two types, resonant and non-resonant, according to different working methods. Among them, the resonant photoacoustic cell means that the modulation frequency of the incident light and the acoustic resonant frequency of the resonant cavity are the same, in which case the photoacoustic cell itself plays the role of an audio amplifier, which helps to improve the sensitivity of the photoacoustic spectral detection system. As shown in Figure 4, this paper adopts a first-order longitudinal resonant photoacoustic cell, whose length and radius of the resonant cavity are 120mm and 3mm, and the length and radius of the buffer chamber are 60mm and 30mm, respectively.

3.3 Signal Acquisition and Data Processing

In a photoacoustic spectroscopic gas detection system, the signal acquisition and data processing stages are essential for ensuring high sensitivity, accuracy, and reliability of the measurements. These stages play a pivotal role in extracting weak photoacoustic signals from noisy environments and transforming them into usable data for further analysis. The overall performance of the system depends significantly on how well the signal acquisition and data processing steps are executed, as they directly impact the quality and precision of the detected gas concentrations, such as carbon monoxide (CO).

3.3.1 Signal acquisition phase

The first step in the signal acquisition phase is to capture the acoustic signals produced by the photoacoustic effect inside the photoacoustic cell. Due to the inherently weak nature of the photoacoustic signals, especially in gas detection, it is crucial to use highly sensitive sensors such as microphones or piezoelectric sensors. These sensors convert the mechanical vibrations (acoustic signals) generated by the pressure waves into electrical signals. However, because these signals are usually quite faint and susceptible to interference from various environmental and system noises, additional signal enhancement techniques are necessary.

One of the most effective methods for improving signal detection is the use of lock-in amplifier technology. The lock-in amplifier is employed to selectively extract the target signal from the noisy background by synchronizing its reference signal with the modulation frequency of the laser. This technique is particularly valuable for suppressing noise components that do not match the modulation frequency of the laser, thereby enhancing the signal-to-noise ratio (SNR). By amplifying only the frequency components that correspond to the modulated laser signal, the lock-in amplifier significantly reduces the impact of low-frequency noise, thermal noise, and other interference sources. In addition to the lock-in amplifier, the system incorporates a band-pass filter to further improve signal quality. The band-pass filter is designed to allow only signals within a certain frequency range (corresponding to the optical-acoustic signal) to pass through, effectively filtering out noise from other sources that fall outside this range. This step is critical in ensuring that the system responds primarily to the optical-acoustic signal while ignoring irrelevant noise. To further enhance signal quality, a low-pass filter is introduced to remove any remaining high-frequency noise that may arise from sources such as electrical interference or other environmental factors. This filter ensures that the acquired signal is both smooth and free from high-frequency components, which could distort the subsequent data analysis.

3.3.2 Analog-to-digital conversion and data processing

Once the signal is amplified and filtered, the next step is to convert the analog signal into a digital form suitable for processing. This is achieved through an analog-to-digital converter (ADC), which samples the continuous analog signal and converts it into discrete digital values. To ensure high precision in the detection process, the system employs a high-resolution ADC, capable of capturing even small fluctuations in the signal that may correspond to minute changes in gas concentration.

The digital signal obtained from the ADC is then subjected to a Fourier transform, which converts the time-domain signal into a frequency-domain representation. This transformation allows the system to analyze the frequency components of the signal more efficiently and helps to isolate the characteristic frequency of the target gas—in this case, carbon monoxide. The frequency domain analysis is critical for selectively identifying the target gas amidst other potential interferences, as different gases absorb light at distinct wavelengths, corresponding to specific resonance frequencies. By extracting the target frequency, the system can improve its selectivity and accuracy in detecting the presence of CO. Additionally, to ensure the integrity of the signal throughout the processing stages, the system includes a phase-shifting circuit. This circuit adjusts the phase of the signal to account for any phase discrepancies that may occur during signal processing. The phase shift correction ensures that the signal remains consistent and aligned throughout the entire detection and analysis process, minimizing errors that could arise from phase misalignments. Further data processing is performed using data filtering and smoothing algorithms to remove any residual noise that may persist after the initial filtering steps. These algorithms help to refine the signal and improve the overall stability of the measurement results. By smoothing the signal, the system reduces fluctuations that could lead to false readings, thereby increasing the reliability of the concentration measurements.

3.3.3 Real-time monitoring and feedback

The ultimate goal of the signal acquisition and data processing stages is to enable real-time monitoring of carbon monoxide concentrations in environments such as automobiles, where CO levels can fluctuate rapidly. Through continuous data analysis, the system provides real-time feedback regarding the concentration of CO, enabling timely alarms to be issued when abnormal concentrations are detected. These feedback mechanisms are essential for ensuring the safety of individuals in vehicles, as elevated CO levels can be hazardous. In conclusion, the signal acquisition and data processing stages in a photoacoustic spectroscopic gas detection system are vital for ensuring that even faint photoacoustic signals can be accurately detected, processed, and analyzed. By utilizing advanced techniques such as lock-in amplifiers, band-pass and low-pass filters, high-resolution ADCs, Fourier transform, phase-shifting circuits, and noise reduction algorithms, the system can provide precise and reliable measurements of carbon monoxide concentrations. These capabilities make the system highly effective for real-time environmental monitoring, ensuring both safety and accuracy in gas detection applications.

4. Analysis of Results

To validate the testing accuracy of the CO detection system designed based on photoacoustic spectroscopy, it is first necessary to test the wavelength of the

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selected laser and the resonance frequency of the photoacoustic cell. Regarding the laser's wavelength characteristics, based on the test results, an appropriate adjustment factor must be applied to the obtained data, with a specific value of 0.44 nm/mA. Under standard atmospheric pressure and at 25°C, the resonance frequency of the photoacoustic cell was measured to be 1,607 Hz.

After obtaining the optimal parameters of the system, a series of measurements of CO gas were carried out using the constructed experimental system under the optimal conditions. Before the experiment, the photoacoustic cell was flushed with high purity nitrogen and pumped to vacuum, and then the sample gases with different concentrations of CO were fed into the photoacoustic cell for measurement after a set of homemade humidification system. In this paper, 10 groups of 120ppm-1200ppm CO gases were configured using the gas distribution device, and the experiments were conducted in the same environment as the calibration experiments. Table 1 shows the comparison between the CO gas concentration shown in the experiments and the values of the gas distribution concentration, and the maximum relative error of the signal value is not more than 1.8%, meeting the actual measurement requirements.

Table 1. Comparison between Dispensing Concentration and Displayed Concentration

No.	Dispensing Concentration(ppm)	Displayed Concentration(ppm)	Relative Error (%)
1	120	121	0.8
2	150	152	1.3
3	200	203	1.5
4	320	326	1.8
5	520	525	0.9
6	770	778	1.0
7	1200	1209	0.7

5. Conclusion

In this study, based on photoacoustic spectroscopy technology, we successfully designed and realized a high sensitivity carbon monoxide detection system for automobile exhaust gas. By optimizing the excitation light source, photoacoustic cell, signal processing unit and data acquisition module, we effectively solved the key problems of sensitivity, stability and signal-to-noise ratio in real-time monitoring. The experimental results show that the system has excellent detection performance in the concentration range of 120 ppm to 1200 ppm, and the maximum relative error is no more than 1.8%, which verifies its high sensitivity and accuracy. However, there is still room for improvement, such as enhancing the ability to suppress ambient noise and improving the overall stability of the system. In addition, the detected gases can be expanded and the detection range can be increased to meet a wider range of application requirements in the future. With the advancement of sensor technology and data processing algorithms, further improvement of detection accuracy and response speed will become an important development direction. The photoacoustic spectroscopy detection system developed by this institute shows a wide range of application prospects and can effectively improve the real-time monitoring capability of carbon monoxide in automobile exhaust, providing reliable data support for environmental protection and public health.

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