

# Current Status of Detection Technologies for Indoor Hazardous Air Pollutants and Particulate Matter

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## ABSTRACT

The application of modern gaseous pollutant detection techniques to monitor harmful gases and particulate matter in the indoor environment can effectively control air pollution and reduce accidents. Accurate, timely and economical monitoring of indoor concentrations of harmful gases and particulate matter in industrial production processes is still a great challenge. In recent years, there has been a gradual increase in research on detection methods for harmful gases and particulate matter.

A number of researchers have published reviews of research on detection methods for hazardous gases, which are generally organized in terms of the detection of specific hazardous gases. In order to provide a more comprehensive overview of the latest research advances in detection methods for hazardous gases and particulate matter, this paper provides a categorized summary of research on detection methods for nitrogen dioxide, sulfur dioxide, hydrogen sulfide, formaldehyde, methane, and particulate matter. Through a comprehensive analysis of various detection methods, this paper discusses the current research progress of detection technology of indoor harmful gases and particulate matter, which is of great significance for timely and accurate monitoring of harmful gases and particulate matter in the environment for judging the content of pollutants in the air and controlling atmospheric pollution.

**Keywords:** Nitrogen dioxide, Sulfur dioxide, Hydrogen sulfide, Formaldehyde, Methane, Particulate matter

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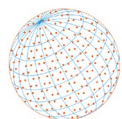
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## 1 INTRODUCTION

The atmosphere is indispensable for human production and life. In recent years, with the concept of 'low carbon, environmental protection and energy saving', people have started to pay more attention to the atmospheric environment. With the development of industrial progress, a variety of harmful gases and particulate matter are widely present in indoor spaces such as production workshops. Harmful gases in the environment are often difficult to detect, and if they are not monitored and handled properly, they can easily cause various acute poisoning accidents and chronic poisoning damage caused by harmful gases and particulates in the air. Therefore, timely monitoring of hazardous gases and particulate matter in the operating space environment is an important prerequisite for preventing environmental pollution and protecting human life and health. Based on the atmospheric hazardous gases and particulate matter and their respective detection methods, this paper reviews the current research progress of indoor hazardous gas and particulate matter detection technology, introduces its detection principles, research status, advantages, and disadvantages, and provides an outlook on its future development direction.



## 2 POLLUTION STATUS OF INDUSTRIAL HAZARDOUS GASES AND PARTICULATE MATTER

The atmosphere is a gas environment with nitrogen and oxygen as the main components and a variety of components together. Among them, harmful gases usually refer to gases that are harmful to human health in general or under certain conditions, or hazardous to operational safety, including toxic gases, combustible gases, and asphyxiating gases. Common harmful gases include nitrogen dioxide, sulfur dioxide, hydrogen sulfide, formaldehyde, methane, etc.

In the field of air pollution prevention and control, countries around the world are now generally aware of the importance of controlling harmful gases and particulate emissions and have developed a series of relevant standards. The World Health Organization, the European Union, the United States, and others have all set relevant control standards for harmful gases in the atmosphere. Therefore, the application of modern gas pollutant detection technology to accurately monitor the content of harmful gases and particulate matter in the environment promptly to determine the content of pollutants in the air and control air pollution is of great significance.

There are a number of sources of hazardous gases and particulate matter pollution in the workplace of industrial enterprises. Both short-term exposure to high concentrations of hazardous gases in the environment and long-term exposure to low concentrations of hazardous gases in the environment can threaten the health and lives of workers (Fuller and Suruda, 2000; Basham, 2001; Mathieu-Nolf, 2002; Leiva G *et al.*, 2013; Zhang and Pang, 2013; Chen *et al.*, 2018b; Soltanpour *et al.*, 2022).

The industrial workspace environment is relatively confined, in which the airflow is poor and the harmful gases and particles are not easily detectable. If they are not monitored and properly handled promptly, it is very possible for safety accidents to occur and result in casualties (Ozmen and Aksoy, 2015). Therefore, the detection of harmful gases and particulate matter in operating spaces is of great importance in reducing industrial production accidents and improving the living standards of residents.

## 3 DETECTION TECHNOLOGY AND RESEARCH PROGRESS OF HARMFUL GASES

At present, hazardous gas detection methods mainly include sample collection-based spectrophotometry, chromatography, mass spectrometry, Fourier infrared spectroscopy, and other laboratory detection methods, as well as on-site rapid detection methods based on sensors, gas detectors, quick detectors, and other instruments, which are shown in Fig. 1. This paper focuses on the detection technologies for NO<sub>2</sub>, H<sub>2</sub>S, SO<sub>2</sub>, HCHO, and CH<sub>4</sub> gases. The general content is shown in Fig. 2.

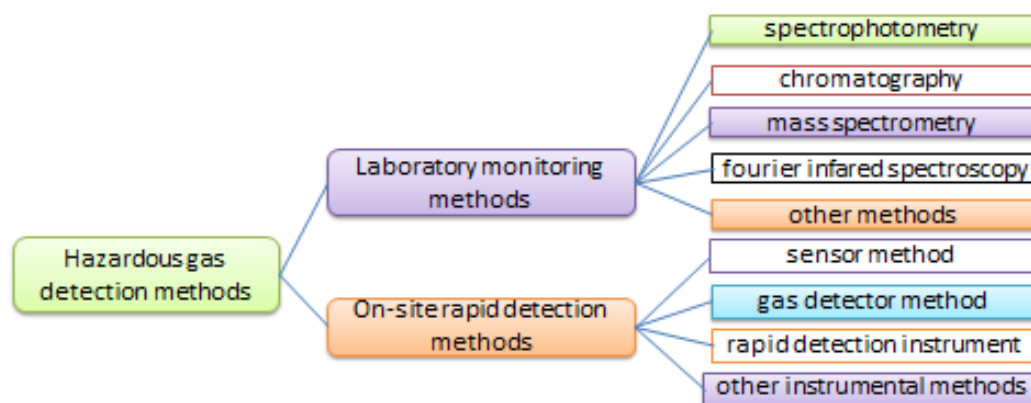


Fig. 1. Current main methods for harmful gases detection.

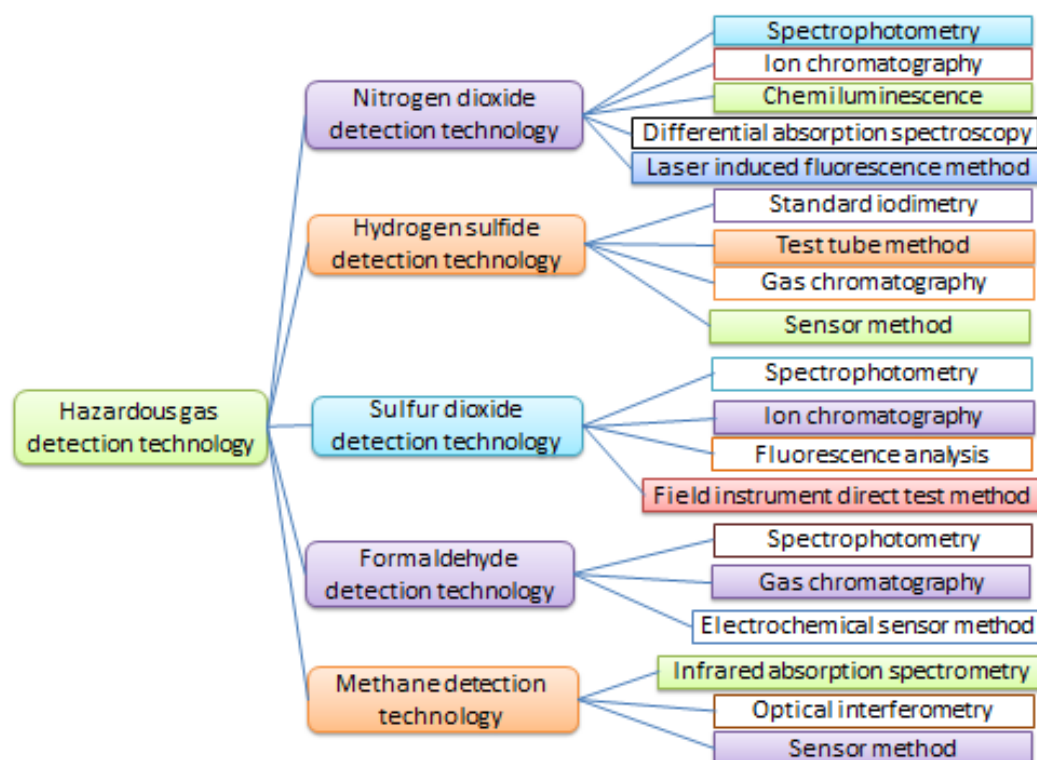
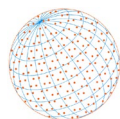


Fig. 2. Hazardous gases and their detection techniques reviewed in this paper.

### 3.1 Nitrogen Dioxide Detection Technology

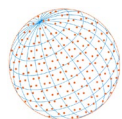
Nitrogen dioxide is a typical air pollutant, and its emission can aggravate atmospheric pollution and lead to the formation of disasters such as acid rain and photochemical smog. In addition, nitrogen dioxide entering the human body may affect the respiratory system and cardiovascular function, leading to respiratory disorders as well as heart failure, hypertension, and other diseases (Möller *et al.*, 2013; Coogan *et al.*, 2017; Strassmann *et al.*, 2021).

According to the different detection principles, nitrogen dioxide detection techniques can be divided into two categories: one is the indirect detection techniques including spectrophotometry, ion chromatography, sensor method, fluorescence spectrometry, chemiluminescence, and other methods, and the other is the direct detection techniques including differential absorption spectrometry, laser-induced fluorescence, optical cavity decay spectrometry and other detection methods. Among them, the direct detection technique is based on the Lambert-Beer absorption law for the detection of nitrogen dioxide, and the indirect detection techniques are usually used to convert nitrogen dioxide into nitrite ions by solution absorption or reduce it to nitric oxide by using reducing agents, and then use detection techniques and equipment for qualitative and quantitative detection methods.

#### 3.1.1 Spectrophotometric method

The principle of spectrophotometric determination of nitrogen dioxide is that nitrogen dioxide is first converted to nitrite, and aromatic amines are diazotized with nitrite under acidic conditions, and then coupled to form azo dyes, and the absorbance size of the sample is proportional to the concentration of nitrogen dioxide, so that the concentration of nitrogen dioxide can be calculated (Flamerz and Bashir, 1981; Nair and Gupta, 1981; Sunita and Gupta, 1984; Buteau *et al.*, 2018).

The standard method for the detection of nitrogen dioxide is the naphthylenediamine hydrochloride spectrophotometric method. Kaveeshwar *et al.* (1992) used *o*-nitroaniline as an adsorbent to diazotize the absorbed nitrite ion and coupled it with 1-amino-2-naphthalenesulfonic acid in an acidic medium. The red-violet dye with maximum absorption at 540 nm was obtained, and the nitrogen dioxide detection concentration was 0.03 mg m<sup>-3</sup>. Salem *et al.* (2011) used



concentrated hydrochloric acid to acidify nitrite ions to produce peroxyxynitrite oxidant, and 2,2-azido-bis(3-ethylbenzothiazoline)-6-sulfonic acid diammonium salt (ABTS) as the reducing colorant to determine the concentration of nitrogen dioxide in the air. The experimental results showed that the method was more accurate and more reliable compared with ion chromatography, and the sensitivity was improved by one order of magnitude.

The naphthylenediamine hydrochloride spectrophotometric method for the determination of nitrogen dioxide has high accuracy and good linearity, but the method has more operational steps, the chemical reagents involved are toxic and harmful to humans, and the test results are easily affected by the reaction time, light, temperature, and other conditions.

### 3.1.2 Ion chromatography

The working mechanism of ion chromatography is ion exchange. Separation, characterization, and quantification are performed according to the different affinities of the anions on the anion analysis column. NO<sub>2</sub> sampling is carried out by triethanolamine absorbent or solid adsorption tubes to convert NO<sub>2</sub> in the air into NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup>, and the amount of NO<sub>2</sub> in the air is calculated by measuring the amount of NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup>.

Peng *et al.* (2007) used a 5% triethanolamine solution as the absorbent solution to absorb nitrogen dioxide in mainstream cigarette smoke, which was directly determined by ion chromatography without a pretreatment process. The experimental results showed that the method has good linearity in the range of 0.5–10 mg L<sup>-1</sup>, and the detection limits of NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup> were 0.04 mg L<sup>-1</sup> and 0.05 mg L<sup>-1</sup>, respectively.

Ion chromatography is characterized by high precision, high sensitivity, simple operating procedures, and low detection limits. And is suitable for the simultaneous determination of a wide range of anions. However, the detection of ion chromatography usually takes several minutes to ten minutes, and the detection time is long, so real-time indoor monitoring cannot be realized.

### 3.1.3 Chemiluminescence method

Chemiluminescence detection of nitrogen dioxide is based on the determination of NO by chemiluminescence assay: nitric oxide reacts with ozone in a chemiluminescent reaction to produce excited state nitrogen dioxide molecules. The concentration of nitric oxide can be measured by using a photomultiplier tube to receive the light emitted by the nitrogen dioxide when it returns to the ground state which is proportional to the concentration of nitric oxide.

Qi *et al.* (2010) designed and fabricated an on-line NO<sub>2</sub> chemiluminescence detector based on the chemiluminescence reaction of NO<sub>2</sub> with luminal solution. The linear range for NO<sub>2</sub>, measurement is  $5.0 \times 10^{-11}$ – $8.0 \times 10^{-8}$  (V/V, volume ratio, same hereinafter), peak response time < 1 s, time resolution is 1 s, and detection limit is  $5.0 \times 10^{-11}$  (V/V). The instrument is characterized by a simple structure, small size and low cost.

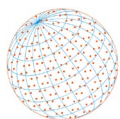
With the advantages of high measurement accuracy, short response time, high sensitivity, and good stability, the chemiluminescence method has become the quantitative analysis method of NO<sub>x</sub> recommended by the State Environmental Protection Administration. However, while converting NO<sub>2</sub> to NO, other nitrogen-containing compounds in the air may also be converted to NO, thus making the measured NO<sub>2</sub> values high.

### 3.1.4 Differential Optical Absorption Spectroscopy

Differential Optical Absorption Spectroscopy (DOAS) is a technique based on characteristic absorption spectroscopy to identify information such as the type and concentration of trace gases by analyzing the characteristic absorption of atmospheric trace gases in the ultraviolet and visible wavelengths, using the narrow-band absorption properties of gas molecules.

Al-Jalal *et al.* (2019) developed an experimental setup based on differential optical absorption spectroscopy technology for the detection of low concentrations of nitrogen dioxide gas in an absorption cell, using white LEDs as the light source. The experimental results showed a total acquisition time of 5 s and a detection limit of 0.4 mg m<sup>-3</sup> per meter of path length.

Due to the different ability of gas molecules to absorb light, the sample does not require any treatment when air is detected using differential absorption spectroscopy, and interference from



other gases in the atmosphere can be avoided. The differential absorption spectroscopy technique is sensitive and suitable for all types of trace gases with significant absorption cross sections in the UV and visible spectral regions and is particularly suitable for the detection of highly reactive substances such as NO<sub>2</sub>, and the concentration of several trace gases can be determined simultaneously, thus reducing the time required for measurement.

Differential absorption lidar (Sa *et al.*, 2017) is a method based on differential optical absorption spectroscopy, which has high spatial resolution and sensitivity, fast scanning speed, and can accurately measure a wide range of NO<sub>2</sub>. However, the application of differential absorption lidar technology is somewhat limited due to the high requirements and costs of the laser part.

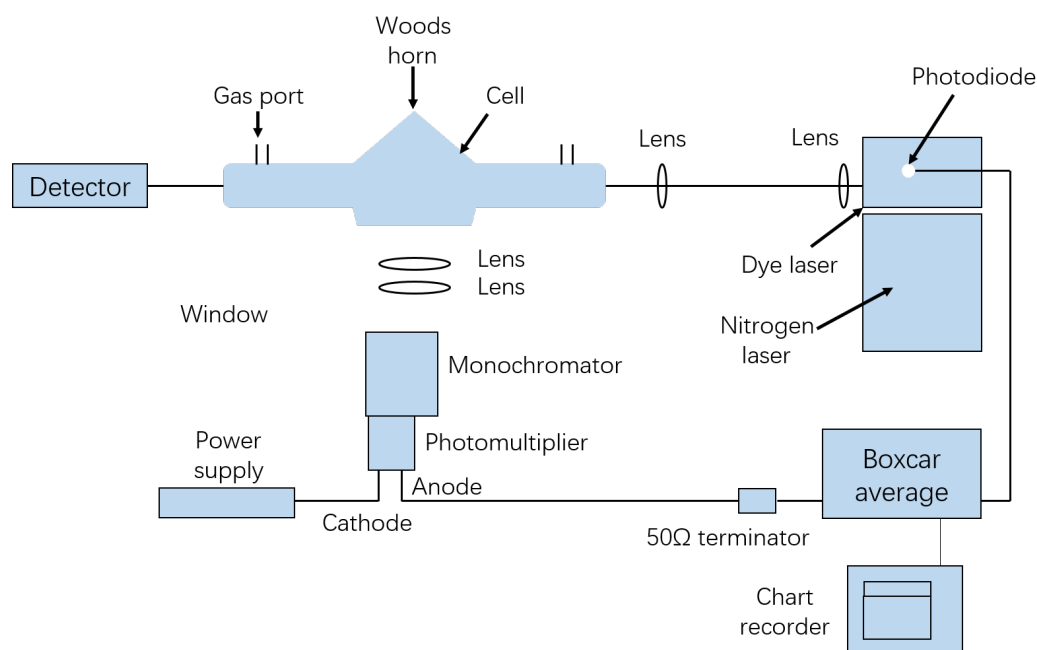
### 3.1.5 Laser-induced fluorescence method

Laser-induced fluorescence (LIF) is based on the principle of using a laser of a specific wavelength to excite NO<sub>2</sub> to the excited state, collecting the fluorescence signal of NO<sub>2</sub> molecules re-excited, and then determining the concentration of NO<sub>2</sub> based on the fluorescence signal, as shown in Fig. 3. Laser-induced fluorescence is a direct NO<sub>2</sub> detection method with good selectivity, high sensitivity, and fast response time, and has been widely used (George and O'Brien, 1991). Suzuki *et al.* (2011) used a GaN diode laser (NICHIA, NDHV310APB) at a wavelength of 410 nm as a fluorescence excitation source. The GaN output was modulated by a diode current-controlled switch with a pulse width of 700 ns, a repetition frequency of 100 kHz, and an average laser intensity of 10 mW. NO<sub>2</sub> fluorescence was detected using a photomultiplier tube (PMT) (Hamamatsu, R928). A long-pass filter (CVI, LPF-600) was placed in front of the PMT to avoid detection of the chamber and Rayleigh scattered light. Peripheral air was drawn into the fluorescence cell using a rotary pump (Edwards, RV12). The intracell pressure monitored by a capacitance manometer (MKS Baratron 122A) was typically 3 Torr. The sample flow rate in the fluorescence cell was 100 sccm (standard liters per minute). The lowest detection limit of the instrument was 0.39 ppbv over a 60 s sampling time.

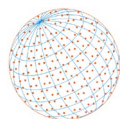
The above detection methods are summarized in detail by the author, mainly including the detection limits and the advantages and disadvantages of the technical applications, as shown in Table 1.

## 3.2 Hydrogen Sulfide Detection Technology

Hydrogen sulfide is a colorless, acidic, and highly toxic gas that can cause impairment of the



**Fig. 3.** Experimental arrangement for the NO<sub>2</sub> studies using the laser-induced fluorescence technique (Anastasi and Hancock, 1988).

**Table 1.** Detection limits and features of NO<sub>2</sub> detection technology.

NO <sub>2</sub> detection technology	Features	Detection limit
Spectrophotometric method	High accuracy and good linearity, more operational steps, involving chemical reagents that are toxic and harmful to humans, and test results are easily affected by reaction time, light, temperature and other conditions	0.03 mg m <sup>-3</sup> (Kaveeshwar <i>et al.</i> , 1992)
Ion Chromatography	High precision and sensitivity, simple operation steps, low detection limit, but long detection time	The detection limits of NO <sub>2</sub> <sup>-</sup> and NO <sub>3</sub> <sup>-</sup> were 0.04 mg L <sup>-1</sup> and 0.05 mg L <sup>-1</sup> , respectively (Peng <i>et al.</i> , 2007)
Chemiluminescence method	High measurement accuracy, short response time, high sensitivity and good stability. The measured value of nitrogen dioxide may be high	5.0 × 10 <sup>-11</sup> (V/V) (Qi <i>et al.</i> , 2010)
Differential Optical Absorption Spectroscopy	No need to handle the sample, high sensitivity, and it can avoid the interference of other gases in the atmosphere	0.4 mg m <sup>-3</sup> (Al-Jalal <i>et al.</i> , 2019)
Laser-induced fluorescence method	Good selectivity, high sensitivity, fast response time	0.39 ppbv (Suzuki <i>et al.</i> , 2011)

human sense of smell in small amounts and is highly lethal in higher concentrations. In China, almost all the exploited oil fields contain different amounts of hydrogen sulfide gas. If the content of hydrogen sulfide in oil and gas wells exceeds the safety threshold, once the well blowout develops out of control, it will cause catastrophic consequences.

### 3.2.1 Standard iodometric method

The principle of the standard iodine volume method for determining hydrogen sulfide is that a zinc acetate solution produces a zinc sulfide precipitate by absorbing hydrogen sulfide gas, and the remaining liquid is titrated and tested with an iodine solution to measure the amount of hydrogen sulfide in the air. Boumrijel *et al.* (2019) performed H<sub>2</sub>S sampling by absorbing industrial gases into a cadmium acetate absorption solution. The formed cadmium sulphide (CdS), as a result of a chemical reaction, was analyzed by turbidimetry. A methodical validation study of the proposed method was performed according to the requirements of ISO 17025 standards. The proposed method was demonstrated to be precise, linear and accurate over a concentration range of 6.91–92.16 mg L<sup>-1</sup>. Detection and quantification limits were equal to 5.09 mg L<sup>-1</sup> and 6.91 mg L<sup>-1</sup>, respectively. The turbidimetry method was applied successfully to the industrial gaseous effluents and can be considered as an economical alternative to the iodometric method.

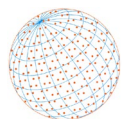
The standard iodine measurement method is mostly adopted in drilling fields because of its simple operation and wide measurement range. The disadvantage is that the stability of iodine and sodium thiosulfate solution is poor, and the measured data in a laboratory environment is relatively different from the actual data.

### 3.2.2 Detection tube method

The detection tube is mainly composed of glass tubes, protective glue, indicator glue, and cotton plugs. The principle of measuring hydrogen sulfide in the detector tube is that when the gas sample containing hydrogen sulfide passes through the detector tube containing the indicator gel, a color change column is generated, and the length of the color change area of the column is proportional to the H<sub>2</sub>S content in the gas. The amount of hydrogen sulfide in the gas sample can be derived from the number indicated by the color change column.

The detector tube method is suitable for samples that do not require high accuracy of measurement results and only need to give an approximate result of the hydrogen sulfide content in the sample. However, due to its simplicity, the test tube method still has great potential for use in the detection of hydrogen sulfide in the coal chemical industry.





### 3.2.3 Gas chromatography

The principle of gas chromatography for the determination of hydrogen sulfide gas is that the sample gas is collected into the gas chromatograph, separated by the column, and then the chromatogram of the time of hydrogen sulfide gas flowing out of the column is measured by the detector. The concentration of hydrogen sulfide gas is measured according to the peak height and peak area size.

For the determination of hydrogen sulfide gas by gas chromatography, different detectors are selected if the concentrations measured are different. TCD thermal conductivity detector can measure constant amounts of hydrogen sulfide gas, FPD flame photometric detector can detect small amounts of hydrogen sulfide, and SCD sulfur chemiluminescence detector is suitable for the detection of trace amounts of H<sub>2</sub>S. [Tambani et al. \(2013\)](#) used four different methods, Eschka, infrared, thermal conductivity detection (TCD), and ultraviolet fluorescence detection (UV), to determine total sulfur in solid fuels. The experimental results showed that the results of TCD and the IR method (standard method) for high-sulfur coal samples were determined with similar accuracy. [Rapagna et al. \(2012\)](#) conducted a continuous catalytic steam gasification run of almond shells in the temperature range of 808–813°C (maintained by an electric furnace) and analyzed the volumetric composition of the product gases by means of IR, UV, and TCD equipment for on-line detection of CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>, NH<sub>3</sub>, and H<sub>2</sub>S. The measured NH<sub>3</sub> and H<sub>2</sub>S in the dry gas were 60–80 ppmv and 10–15 ppmv, respectively.

[Zhang et al. \(2009\)](#) performed the qualitative and quantitative analysis of six sulfides, including hydrogen sulfide, methyl mercaptan, and ethyl mercaptan, contained in oil and gas using gas chromatography equipped with a capillary column and an FPD detector. The results showed that the natural logarithm of the peak height of the response of the detector for the above six sulfides showed a good linear relationship with the natural logarithm of the sulfide concentration. [Han \(2012\)](#) used sulfur chemiluminescence detection-wide-bore quartz capillary column gas chromatography to detect 11 volatile sulfides, including methyl mercaptan, ethyl mercaptan, carbonyl sulfide, hydrogen sulfide, and carbon disulfide, in the exhaust gas. The experiment was performed with an Agilent 7890A gas chromatograph and a Sievers 355 sulfur chemiluminescence detector. The results showed that the detection limits of the above sulfides were in the range of 0.03–0.1 mg m<sup>-3</sup> when the injection volume was 0.2 mL. Compared with the conventional FPD flame photometric detector, the detection method has better selectivity and higher sensitivity.

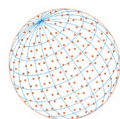
FPD has the following disadvantages: non-linear response with a narrow linear range; hydrocarbon compounds produce a quenching effect, resulting in inaccurate detection results; and is not sensitive enough for carbon disulfide. While the SCD has high sensitivity, good linearity, low detection limit, and no response to hydrocarbon compounds, which is not interfered with by most sample matrices and avoids the interference of co-fluxed hydrocarbons to sulfide peaks, which makes up for the shortcomings of FPD.

The prerequisite for the accurate detection of hydrogen sulfide gas is the reliability of the standard gas. However, on the one hand, the quality form of standard gas prepared by different standard gas manufacturers is also different due to the instability and low concentration of hydrogen sulfide gas. The same concentration of standard gas with the same method may not give the same results, which is also a major problem in the detection of hydrogen sulfide by gas chromatography.

### 3.2.4 Sensor method

Existing hydrogen sulfide gas sensors have their advantages and disadvantages. The current hydrogen sulfide gas sensors mainly include electrochemical hydrogen sulfide gas sensors, metal oxide hydrogen sulfide gas sensors, and optical hydrogen sulfide gas sensors.

Electrochemical hydrogen sulfide sensors are based on the principle of limiting currents, using the limiting diffusion current generated by the gas passing through the sensitive material in proportion to the concentration of hydrogen sulfide gas to measure the magnitude of the gas concentration. [Yu et al. \(2002\)](#) used sulfuric acid pretreated Nafion membrane as a solid electrolyte sensor for H<sub>2</sub>S gas detection and gold catalyst as an alternative electrode to improve the selectivity for H<sub>2</sub>S. The results showed a gas measurement range of 1 to 100 ppm, a detection limit of 0.1 ppm, and a response time of 9 s. Electrochemical hydrogen sulfide sensors currently dominate the market



**Table 2.** Advantages and disadvantages of different H<sub>2</sub>S sensors.

H <sub>2</sub> S sensor type	Advantages	Disadvantages
Electrochemical H <sub>2</sub> S sensors	Low production cost and easy to operate	Highly influenced by temperature and other environmental factors, difficult to adapt to the harsh detection environment
Metal oxide H <sub>2</sub> S Sensors	Miniaturizable, easy material synthesis, low energy consumption, and low cost	Recovery time tends to be longer, less long-lived and less stable
Optical H <sub>2</sub> S sensors	High sensitivity, high accuracy, high stability, free from electromagnetic interference	Highly specialized operation, high price of analytical instruments, not suitable for mass production

because of the advantages of low production cost and simple operation. However, electrochemical hydrogen sulfide sensors are greatly influenced by environmental factors such as temperature and are difficult to adapt to harsh detection environments.

The metal oxide H<sub>2</sub>S gas sensor is based on the principle that the adsorption of hydrogen sulfide gas causes a change in the conductivity of the semiconductor, which results in a change in resistance. Then the change in resistance value is measured to detect the concentration of hydrogen sulfide gas. [Verma and Gupta \(2012\)](#) prepared porous CuO-SnO<sub>2</sub> lamellar p-n heterostructures by compounding p-type CuO with n-type SnO<sub>2</sub> and investigated their sensing response characteristics to 20 ppm H<sub>2</sub>S gas. The experimental results showed a high response of  $2.7 \times 10^4$  with a response time ( $t_{90}$ ) of s at a lower operating temperature of 140°C. The CuO layer on the surface of the sensing SnO<sub>2</sub> layer spills dissociated H<sub>2</sub>S gas molecules making the sensing responsiveness and response speed improved. Metal oxide hydrogen sulfide sensors have a good response and high sensitivity and are widely used due to their miniature ability, easy material synthesis, low energy consumption, and low cost, and are suitable for mass production. However, the recovery time is often long and has disadvantages such as a short life span and low stability. Although many attempts have been made to improve them by doping and other methods, the results are still unsatisfactory.

Optical sensors typically use optical conversion techniques to generate analyte signals. The design of an optical sensor depends on the interaction of light placed in front of an optical fiber and coating with the analyte so that the optical sensor can record experimental signals for quantitative and qualitative analysis by absorption and emission spectroscopy techniques. [Hu et al. \(2017\)](#) prepared Mn<sub>3</sub>O<sub>4</sub>/g-C<sub>3</sub>N<sub>4</sub> composites with catalytic luminescence, which can selectively and sensitively detect H<sub>2</sub>S. Optical hydrogen sulfide gas sensors have the advantages of high sensitivity, high accuracy, high stability, and immunity to electromagnetic interference, and can be used for detection in harsh environments such as high pressure, high temperature, and strong corrosiveness. However, the use of existing optical hydrogen sulfide sensors requires a high degree of operator expertise and the sensor analyzer is expensive, which makes it unsuitable for mass production.

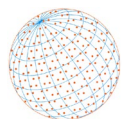
It is easy to see that the detection limit of hydrogen sulfide using a GC-SCD sulfur chemiluminescence detector is the lowest. A summary of the advantages and disadvantages of different hydrogen sulfide sensors is shown in [Table 2](#). The current methods and technologies can hardly meet the growing demand for fast, sensitive, efficient, and real-time detection of hydrogen sulfide gas. In the future, hydrogen sulfide gas sensors will develop towards fast response, high accuracy, high sensitivity, and high stability, combining new materials and technologies to further strengthen the performance of optical hydrogen sulfide sensors in all aspects.

### 3.3 Sulfur Dioxide Detection Technology

Sulfur dioxide, also known as sulfite anhydride, is a colorless gas with a strong, irritating odor. Sulfur dioxide is highly chemically active and can irritate the human respiratory tract and cause respiratory diseases ([Kochi et al., 2017](#); [Tomic-Spiric et al., 2021](#)). In addition, sulfur dioxide is an important precursor to the formation of secondary atmospheric pollution.

There are many methods for the determination of sulfur dioxide in ambient air, which can be divided into several categories such as ion chromatography, spectrophotometry, atomic absorption spectrometry, and field instrumentation detection.





### 3.3.1 Spectrophotometric method

The main spectrophotometric detection methods for sulfur dioxide are the formaldehyde buffer-para-rosaniline hydrochloride spectrophotometric method and potassium tetrachloromercurate-para-rosaniline hydrochloride spectrophotometric method. The formaldehyde absorption-para-rosaniline hydrochloride spectrophotometric method which is referred to as the formaldehyde method is suitable for the determination of low concentration of sulfur dioxide due to its sensitivity. The principle of the method is that sulfur dioxide is absorbed by a formaldehyde buffer solution to produce a hydroxymethanesulfonic acid addition compound. Sodium hydroxide is added to the solution to make the additional compound decompose, and the sulfur dioxide released after decomposition interacts with para-rose aniline and formaldehyde to produce a purple-red compound. The absorbance is measured at a wavelength of 577 nm using a spectrophotometer, and the sulfur dioxide content is proportional to the absorbance value.

*Oliveira et al. (2009)* developed a flow system based on the multi-commutation concept for the determination of free and total sulfur dioxide in table wines using gas diffusion separation and spectrophotometric detection. The system allowed the comparison of malachite green and pararosaniline chemistries, using the same manifold configuration. Free and total SO<sub>2</sub> were determined within the ranges 1.00–40.0 and 25.0–250 mg L<sup>-1</sup>, at determination throughputs of 25 and 23 h<sup>-1</sup>, respectively. Employing the malachite green reaction, detection limits of 0.3 and 0.8 mg L<sup>-1</sup> were attained for free and total SO<sub>2</sub>, respectively. Pararosaniline chemistry provided detection limits of 0.6 mg L<sup>-1</sup> for free SO<sub>2</sub> and 0.8 mg L<sup>-1</sup> for total SO<sub>2</sub>. Relative standard deviations better than 1.8 and 1.4% were obtained by the malachite green and pararosaniline reactions, respectively.

Although the sensitivity of tetrachloromercury potassium-para-rosaniline hydrochloride spectrophotometry is relatively high, the use of tetrachloromercury potassium is relatively low because of its toxicity. However, formaldehyde absorption-para-rosaniline hydrochloride spectrophotometry is not toxic, it is more demanding on the environment and cannot be used especially in summer.

### 3.3.2 Ion chromatography

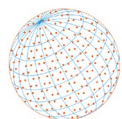
Ion chromatography has the advantages of low detection limit, easy operation, rapid determination, sensitivity, and accuracy. The determination of SO<sub>2</sub> by ion chromatography can be directly determined after the collection and filtration of the sample and quantified according to the peak area, which is fast, simple, and less interfering. The reagents used in ion chromatography are non-toxic and non-hazardous, which avoids bodily harm to the analysts and does not cause secondary pollution to the environment.

*Lin (2017)* used sodium hydroxide and hydrogen peroxide solution as the absorbent solution to convert sulfur dioxide and nitrogen oxides in the air into nitrate and sulfate and then determined by ion chromatography. If 10 mL of absorbing solution is used, the minimum detectable concentration of sulfur dioxide and nitrogen oxides is 0.007 mg m<sup>-3</sup> when the sampling volume is 30 L, which fully meets the demand for simultaneous determination of sulfur dioxide and nitrogen oxides in ambient air. *Yang et al. (2021)* developed a method for the detection of sulfur dioxide in workplace air by ion chromatography without derivatization using triethanolamine aqueous solution for absorption collection. The method is simple and the linearity of the experimental results is good. The SO<sub>2</sub> absorption sample can be stored at room temperature (25°C) and 37°C for at least 7 d, which can prevent SO<sub>2</sub> from being oxidized and achieve the direct detection of SO<sub>2</sub> in workplace air without derivatization.

### 3.3.3 Fluorescence analysis method

After being irradiated by ultraviolet light, certain substances are excited. When they return to the ground state from the excited state, the excess energy is emitted in the form of electromagnetic radiation, a process known as luminescence, and this light is called fluorescence. The characteristics and intensity of the fluorescence spectrum allow for qualitative or quantitative analysis of the substance.

*Matsumi et al. (2005)* detected sulfur dioxide gas in the atmosphere by UV laser-induced



fluorescence technique, and the sensitivity of the method was as high as  $0.005 \mu\text{g L}^{-1}$  within an integration time of 60 s. On the basis of the cross-sensitivity of the catalytic luminescence of formaldehyde, benzene, and sulfur dioxide on  $\text{Ti}_3\text{CeY}_2\text{O}_{11}$  nanoparticles, [Zhou et al. \(2017\)](#) determined the response of the concentrations of sulfur dioxide, formaldehyde, and benzene to the catalytic luminescence signal intensity at 420, 535, and 680 nm respectively, and then accurately measured the concentrations of sulfur dioxide, formaldehyde, and benzene based on the superposition characteristic of the luminescence signal intensity. This method enables the simultaneous determination and online analysis of sulfur dioxide, formaldehyde, and benzene in air. Due to the unique spectral characteristics of sulfur dioxide, other gas components in the atmosphere have no effect on the detection. [Li et al. \(2015\)](#) reported a novel approach to the rapid visual detection of gaseous sulfur dioxide ( $\text{SO}_2$ ) by manipulating the surface chemistry of 3-aminopropyltriethoxysilane (APTS)-modified quantum dots (QDs) using fluorescent coumarin-3-carboxylic acid (CCA) for specific reaction with  $\text{SO}_2$ . Upon exposure to different amounts of  $\text{SO}_2$ , the fluorescent color of the nanoparticle-based sensor displays continuously changes from red to blue. Most importantly, the approach owns high selectivity for  $\text{SO}_2$  and a tolerance of interference, which enables the sensor to detect  $\text{SO}_2$  in a practical application. Using this fluorescence-based sensing method, a visual detection limit of 6 ppb for gaseous  $\text{SO}_2$  has been achieved.

The fluorescence analysis method has the advantages of low detection limit, high sensitivity, rapidity, and simple instrumentation, which can be used for the real-time detection of sulfur dioxide to achieve accurate, rapid, and efficient detection of sulfur dioxide in the atmosphere. Although the selectivity and sensitivity of laser-induced fluorescence technique for sulfur dioxide gas are high, there are still some drawbacks such as expensive instrumentation, high cost, single excitation wavelength, and non-adjustable excitation wavelength. If the selectivity of the fluorescence sensor for the target molecule can be improved, the interference in the determination process can be reduced, and the detection cost can be lowered, it is expected that the low-cost and highly selective detection of sulfur dioxide molecules can be realized.

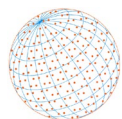
#### 3.3.4 Field instrument direct detection method

[Kim et al. \(2014\)](#) developed a prototype sensor node based on the Raspberry Pi architecture for monitoring ozone ( $\text{O}_3$ ), particulate matter, carbon monoxide (CO), nitrogen oxides ( $\text{NO}_2$ ), sulfur dioxide ( $\text{SO}_2$ ), volatile organic compounds, and carbon dioxide ( $\text{CO}_2$ ). The method is sensitive and accurate, allowing simultaneous monitoring of multiple atmospheric pollutants. Since the use of gas sensors for air quality monitoring consumes a lot of electricity, it is crucial to choose the right type of sensor and improve energy efficiency. [Liu et al. \(2021\)](#) investigated the sensing characteristics of a novel metal-doped  $\text{WO}_3$  sensor in  $\text{SO}_2$  gas at different operating temperatures. The sensor response to  $\text{SO}_2$  gas was measured at different concentrations from 100 ppb to 16 ppm. The detection limit of the 1 wt% Pt- $\text{WO}_3$  sensor was very low at 100 ppb with a sensitivity of 4.1 at the optimum operating temperature of  $160^\circ\text{C}$ . The sensor response was better compared to other  $\text{SO}_2$  gas sensors.

The field instrument direct detection method for the determination of  $\text{SO}_2$  avoids the operator's exposure to toxic substances, the transportation and preservation of reagents when testing outside, and the tedious experimental process. Moreover, it can realize real-time monitoring, a convenient and rapid detection process, and the detection results are sensitive and accurate. Therefore, the field instrument direct reading method will be a major trend in the future development of  $\text{SO}_2$  detection.

### 3.4 Formaldehyde Testing Technology

Formaldehyde, a colorless gas with a strong irritating odor, is a typical volatile pollutant that easily evaporates at room temperature and is also one of the main pollutants in the indoor environment ([Salthammer et al., 2010](#); [Wolkoff, 2013](#)). At present, a lot of research work has been done and many effective detection methods have been established at home and abroad for the detection of formaldehyde content in indoor air. The detection methods for indoor air formaldehyde mainly include spectrophotometry, gas chromatography, electrochemical sensor method, etc.



### 3.4.1 Spectrophotometric method

Spectrophotometric detection of formaldehyde mainly includes AHMT (4-amino-3-benzyl-5-mercapto-1,2,4-triazolium) spectrophotometric method, acetylacetone spectrophotometric method, phenol reagent spectrophotometric method.

Formaldehyde in the air reacts with a certain concentration of AHMT solution under alkaline conditions by condensation. After oxidation by potassium periodate, the amount of formaldehyde in the air can be determined according to the color shade of the resulting purple-red compound. Kawamura *et al.* (2005) developed a novel handheld formaldehyde sensor using a well-described reagent, 4-aminohydrazino-5-mercapto-1,2,4-triazole (AHMT). When the filter was exposed to HCHO gas at a rate of 400 mL min<sup>-1</sup>, the AHMT reagent on the filter reacted with HCHO, causing it to change color. The color change is recorded by measuring the intensity of reflected light from a photodiode. The filter color intensity increased with sampling time in a concentration range of 0.04–1 ppm HCHO, and also the filter gave no response in the absence of HCHO. The limit-of-detection (LOD) of 0.04 ppm HCHO within a sampling time of 3 min was achieved. Thus, this method could be used to detect HCHO at the WHO standards (0.08 ppm) within 3 min.

AHMT spectrophotometric method has the advantage of higher sensitivity and better selectivity. Moreover, most of the aldehydes and atmospheric nitrogen dioxide, and sulfur dioxide do not interfere with the detection results. The disadvantage of the method is that the standard solution and the sample solution must be consistent with the time of chromogenic reaction, otherwise, it will lead to inaccurate detection results.

The principle of the acetylacetone spectrophotometric method for the determination of formaldehyde is that formaldehyde gas in air is absorbed by water and reacted with acetylacetone in a pH 6 solution of acetic acid-ammonium acetate buffer medium in a boiling water bath to produce a stable yellow compound, which can be quantified colorimetrically at 413 nm wavelength.

Huang *et al.* (2007) reported that the detection limit of formaldehyde in this method can reach 0.014 mg m<sup>-3</sup>. Acetylacetone chromogenic agent is stable and the main advantage of this method is better reproducibility and selectivity. The disadvantage is the low sensitivity. In addition, it is difficult to achieve rapid detection because of the interference of sulfur dioxide in the air and the need for a long reaction time to generate a stable chromogenic substance.

The main principle of the phenol reagent spectrophotometric method for the determination of formaldehyde is that formaldehyde in the air reacts with phenol reagent to form zine, which is oxidized by ferric ions under acidic conditions to form blue-green compounds, and then the colorimetric quantitative analysis is carried out.

Xue and An (2011) investigated several variables affecting the experimental results in the determination of formaldehyde concentration in air by phenol reagent spectrophotometry, including the concentration of phenol, the dissolution conditions of the chromogenic acid, the wavelength of the incident light, and the temperature and time of color development. As a result, the detection limit of formaldehyde was 0.015 mg L<sup>-1</sup> and the minimum detection concentration was 0.025 mg m<sup>-1</sup> (based on 3 L of sampling air) under the best method.

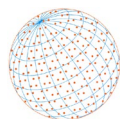
The advantage of the phenol reagent spectrophotometric method for the detection of formaldehyde is its high sensitivity. The disadvantage is that the reaction is easily affected by temperature, and the color development is incomplete when the room temperature is lower than 15°C. And the presence of acetaldehyde, propionaldehyde, and other substances will interfere with the detection results.

The advantages and disadvantages of the above three spectrophotometric methods for formaldehyde detection are shown in Table 3.

### 3.4.2 Gas chromatography

The main principle of gas chromatography for the measurement of formaldehyde is that formaldehyde in the air is adsorbed on a stretcher coated with 2,4-dinitrobenzotrile under acidic conditions, and formaldehyde reacts with 2,4-dinitrobenzotrile to form a chemically stable formaldehyde hydrazone. After elution by carbon disulfide and separation on an OV column, it is detected by a hydrogen flame ion detector and quantified by peak height.

Dugheri *et al.* (2018) developed a highly sensitive online automated pre-enrichment gas chromatographic method for the analysis of formaldehyde and 10 other carbonyl compounds in

**Table 3.** The advantages and disadvantages of three kinds of formaldehyde detection spectrophotometric methods.

Types of spectrophotometric methods	Advantages	Disadvantages	Detection limit
AHMT spectrophotometric method	Higher sensitivity and better selectivity	Require the standard solution and the sample solution color development reaction time must be the same	0.04 ppm (Kawamura <i>et al.</i> , 2005)
Acetylacetone spectrophotometric method	Stable acetylacetone color developer, good repeatability and selectivity	Lower sensitivity, longer reaction time, difficult to achieve rapid detection	0.014 mg m <sup>-3</sup> (Huang <i>et al.</i> , 2007)
Phenol reagent spectrophotometric method	Higher sensitivity	The reaction is susceptible to temperature, and the presence of acetaldehyde, propionaldehyde and other substances can interfere with the test results	0.015 mg L <sup>-1</sup> (Xue and An, 2011)

the air. A large volume injection and a programmed ramp-up evaporation injector were used during the experiment, and the effects of parameters such as maximum injection volume, program temperature, evaporation transfer time and temperature, carrier gas flow rate, and packing type on the detection results were investigated. The absolute detection limit and method detection limit were improved after optimization.

The advantage of this method is that the aldehydes and ketones in the air can be separated, and the presence of sulfur dioxide and nitrogen oxides does not interfere with the detection results. When the sampling volume is 20 L, the minimum detected mass concentration is 0.01 mg m<sup>-3</sup>, and the detection range is 0.02–1.0 mg m<sup>-3</sup>. However, the price of the instrumentation used is high, which makes it difficult to be widely promoted.

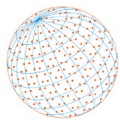
### 3.4.3 Electrochemical sensor method

When formaldehyde gas passes through the sensor, the formaldehyde concentration signal is converted into a current signal by the action of electrolyte and external voltage, and then the concentration of formaldehyde is displayed by amplification and a digital processing circuit.

A novel electrochemical sensor for formaldehyde determination was developed by Zhou *et al.* (2009). The results show that Pt/Pd nanoparticles have good catalytic activity for the oxidation of formaldehyde, and the formaldehyde sensor based on Pt-Pd/Nf/GCE electrode has a wide linear range, good reproducibility and high sensitivity for formaldehyde detection. He *et al.* (2013) prepared a novel and sensitive electrochemical sensor for formaldehyde detection based on platinum nanoparticles (Pt-NPs) and l-alanine-modified glassy carbon electrodes at room temperature and explored the effects of scanning speed, electrolyte type, acidity, and other conditions on the catalytic oxidation of formaldehyde. The results showed that the sensor has strong electrocatalytic activity for the oxidation of formaldehyde.

A novel silver-doped WO<sub>3</sub> sensing material was prepared by a hydrothermal method combined with a wet immersion method by Yu *et al.* (2018). The phase composition and micro-morphology of the resulting samples were characterized by x-ray diffraction (XRD) and field emission scanning electron microscopy (SEM) techniques. The results showed that the anti-vibration performance of the silver-doped WO<sub>3</sub> is about 3.5 times higher than that of the pure WO<sub>3</sub> after exposure to formalin, and exhibits a high response of 10.3–100 ppm HCHO at an operating temperature of 250°C, which is superior to that of the pure WO<sub>3</sub> at an operating temperature of 350°C of 6.5 ppm. The response/recovery time is shortened to 3 s/3 s.

With the development of optical and electrochemical analysis technology, the development of simple sampling instruments with high sensitivity, good selectivity, and unaffected by temperature, humidity, and coexisting gas interference is one of the hot spots for future field instrument analysis.



### 3.5 Methane Detection Technology

Methane is a type of greenhouse gas and a major component of gas. Accurate detection of methane concentration is important for effective prevention and early warning of gas disasters. Infrared absorption spectroscopy, optical interferometry, and other detection methods have their advantages and disadvantages in the application process, and the scope of application is also different.

#### 3.5.1 Infrared absorption spectrometry

Gas molecules with different structures absorb light at different wavelengths, resulting in the attenuation of light energy at specific wavelengths, thus producing the corresponding absorption spectrograms. From the absorption spectra of CH<sub>4</sub> in the mid-infrared and near-infrared regions, NDIR and TDLAS were derived, respectively.

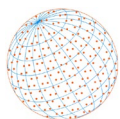
*Kim et al. (2018)* implemented and characterized a small NDIR-based sensor with a volume of 4 cm × 4 cm × 2 cm and a response time (T<sub>90</sub>) of less than 30 seconds in order to tune a methane sensor for industrial field applications. It can detect low concentrations below 5000 ppm and measure up to the detection limit of 50 ppm using the NDIR method with long life and high accuracy. A TDLAS laser gas detection system for CH<sub>4</sub> gas was developed by *Huang et al. (2021)*. The system adopts a VCSEL laser as the core light source, which has the advantages of small size and low power consumption. The experimental results show that the system is suitable for methane concentration measurement in the range of 90 ppm–600 ppm with an error of less than 10%. The minimum detection limit is 90 ppm. The system is highly stable and the measurement results are accurate. *Chen et al. (2018a)* designed an infrared methane detection system based on wireless WiFi technology for the current problems of poor real-time and low accuracy of methane gas detection in home life and industrial production. The detection part uses a methane sensor developed by the undifferentiated infrared method, and the wireless communication part uses a WiFi serial module, and combines with a cell phone app to realize remote real-time detection of methane gas concentration. This detection system improves the real-time and measurement accuracy of methane detection, effectively prevents explosion accidents caused by human negligence, and has a certain application value.

#### 3.5.2 Optical interference method

The principle of the optical interference method for methane detection is based on the different refractive indices of CH<sub>4</sub> and air, and the different distances of light movement in the two different gas media, forming the optical range difference, which causes the original interference pattern to shift. The offset is related to the change in refractive index, which has a certain relationship with the CH<sub>4</sub> concentration. That is, a good linear relationship is shown between the offset and CH<sub>4</sub> concentration.

The optical interference methane detector has the advantages of high stability and reliability and wide measurement range, but the existing devices all adopt the manual reading method with low automation and cannot be connected to the coal mine monitoring system. *Lin et al. (2015)* proposed a detector improvement method based on measuring the light intensity of interference fringes. By improving the optical path design, the uniqueness of the correspondence between the methane volume fraction and the light intensity variation was ensured. Interference fringes were collected using photoelectric elements, and the methane volume fraction was obtained based on the light intensity variation of the interference fringes. Considering the influence of external environmental factors, temperature and air pressure compensation models were established, and finally the validity of the compensation models and the stability of the designed system were verified. A new method for respiratory methane monitoring by all-optical photoacoustic spectrometry based on distributed feedback laser diode and fiber optic acoustic sensor was proposed by *Mao et al. (2017)*. The CH<sub>4</sub> absorption line at 1650.96 nm was chosen to avoid the interference of high CO<sub>2</sub> and H<sub>2</sub>O concentrations at atmospheric pressure. The lowest detection limit of 64 ppb (signal-to-noise ratio = 3) was achieved in a simulated breath sample (4% CO<sub>2</sub> and 6% H<sub>2</sub>O (100% relative humidity at 37°C)).





### 3.5.3 Sensor method

Gas sensors have important applications in industry, especially thanks to their ability to transmit signals remotely and efficiently and to enable real-time detection, which plays an important role in the monitoring of hazardous gases.

[Hong \*et al.\* \(2017\)](#) prepared ZnO nanosheets and nanospheres of gas-sensitive materials and sensing elements based on the hydrothermal method and tested their detection characteristics for CH<sub>4</sub>. The experimental results showed that the gas sensor fabricated based on ZnO nanosheets exhibited better gas-sensitive performance than the nanosphere sensor for CH<sub>4</sub>, and the optimal operating temperature for 50 μL L<sup>-1</sup> CH<sub>4</sub> was reduced by about 60°C, while it showed higher linearity and long-term stability for low (1 μL L<sup>-1</sup>–20 μL L<sup>-1</sup>) CH<sub>4</sub> concentrations.

The optical method has a wide measurement range, not only for online monitoring to prevent the occurrence of hazards but also suitable for real-time monitoring in the field, which has a high sensitivity and low cost. [Yang \*et al.\* \(2018\)](#) designed a laser-based photoacoustic methane sensor, optimizing various parameters including gas flow rate, modulation frequency, and modulation depth. The sensor uses a cost-effective DFB near-infrared laser diode as the excitation light source. The device is simple and cost-effective and can meet the needs of atmospheric environment detection and industrial process control. [Zhao \(2020\)](#) developed an infrared methane sensor based on non-dispersive infrared spectroscopy using the main absorption peak of methane gas molecules at 3.3 μm. The results showed that compared with methane sensors based on thermal radiation infrared light source or laser detection principle, the power consumption of infrared methane sensor based on dual narrow band light emitting diode was reduced by more than 70%, which can meet the technical requirements of low power consumption for portable and wireless applications.

It is easy to see that the detection limit of methane gas is the lowest when the optical interference sensor is applied to detect methane gas. Fiber optic methane sensors have the advantages of high sensitivity, fast response, large dynamic range, immunity to electromagnetic interference, and corrosion resistance. Using long-range near-infrared low-loss optical fiber transmission medium and extended multiplexing technology, online continuous monitoring and telemetry of environmental gases can be achieved, which has been used in coal, chemical, petroleum, and other industrial sectors.

## 4 DETECTION TECHNOLOGY AND RESEARCH OF ATMOSPHERIC PARTICULATE MATTER

As one of the major pollutants in the atmosphere, atmospheric particulate matter has a significant impact on human production and life, human health, and the global climate. Recent studies in the medical field have shown that short-term and long-term exposure to particulate matter, especially fine particulate matter, may cause cardiopulmonary damage and increase the risk of cardiovascular death in humans, and may also have adverse effects on kidney function ([Losacco and Perillo, 2018](#); [Rasking \*et al.\*, 2022](#); [Liang \*et al.\*, 2022](#)). Therefore, appropriate particle detection technologies are needed to monitor and analyze particle concentrations in industrial workspaces to safeguard the health of workers and prevent further atmospheric pollution.

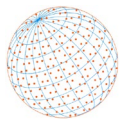
With the further development of the field of atmospheric environmental science, the detection methods regarding atmospheric particulate matter are becoming more and more diverse. In general, atmospheric particulate matter concentration detection methods can be divided into two categories: individual concentration detection and mass concentration detection.

### 4.1 Individual Concentration Detection

The individual concentration method is currently one of the most recommended methods for detecting ultrafine particles by domestic and international scholars. Individual concentration is the concentration value expressed as the number of particles per unit volume of air, in particles cm<sup>-3</sup> or particles L<sup>-1</sup>.

The instruments currently used to detect the number of atmospheric particles concentration are mainly divided into segmentable counters including Electronic Low-Pressure Impact Instrument (ELPI), Ferrari Cup Electrostatic Meter (FCE), and non-segmentable counters including Condensation





Particle Counter (CPC). The segmentable counter can detect and display the number of particles in each segment range and the trend of the concentration in real time (Tritscher *et al.*, 2013). The non-segmentable counter can detect the concentration and its trend of all particles in the applicable range in real-time, but the disadvantage is that it can't detect the particle size graded counting.

Xing *et al.* (2015) investigated the exposure characteristics of Fe<sub>2</sub>O<sub>3</sub> nanoparticles (NPs) released from a plant and showed that the detection of individual concentration is more sensitive and can more accurately reflect the trend of the exposure level of ultrafine particulate matter compared to the mass concentration, and is, therefore, more suitable for the exposure detection of ultrafine particulate matter.

#### 4.2 Mass Concentration Detection

Light scattering meters can realize online monitoring of atmospheric particulate concentration, with the advantages of convenient operation, strong stability, and noise almost zero, more suitable for application in public places of hygiene or production sites dusty occasions.  $\beta$ -ray absorption meter has the advantages of high accuracy, durability, and stability of the measurement results, and it can realize both automatic continuous measurement and intermittent measurement.

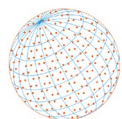
Yang *et al.* (2014) designed a PM<sub>2.5</sub> detection sensor based on the photoelectric sensor principle in their study of haze detection equipment. The sensor adopts the convective detection method, using a semiconductor laser with a wavelength of 650 nm and a power of 10 mW as the light source, and completes the detection of the mass concentration of particulate matter after circuit processing. The experimental study proved that the sensor has the advantages of accurate measurement, short response time, and precise measurement results.

### 5 SUMMARY AND OUTLOOK

In order to realize the timely detection of indoor hazardous gases and particles, on the one hand, under the premise of ensuring accurate detection results, the detection process should be as fast as possible, and it is best to realize the real-time monitoring of the above gas pollutants, because many hazardous gases and particles are not easily detected in the working environment, and if they can not be monitored in a timely manner and handled appropriately, they are very prone to safety accidents. On the other hand, the detection method should be as simple as possible, with fewer operational steps, and try not to involve chemical reagents that are toxic and harmful to the human body. In addition, the drugs and materials used in the testing process should be as inexpensive as possible, so that they can be produced in large quantities at low cost.

In the detection of nitrogen dioxide, as shown in Table 1, among several detection methods, the laser-induced fluorescence method, with good selectivity, high sensitivity, and fast response speed, seems to be a better method for detecting nitrogen dioxide and has been widely used. However, the detection process is more demanding on the laser, so attention should be paid to the maintenance of the laser. As for the detection of hydrogen sulfide gas, the standard iodometric method, detector tube method, and gas chromatography method are not accurate enough, and several sensors for detecting hydrogen sulfide gas concentration have their advantages and disadvantages, as shown in Table 2. If the detection environment is not harsh, an electrochemical hydrogen sulfide sensor is a better choice. Sensors also play an important role in the detection of hydrogen sulfide, formaldehyde, methane, and particulate matter. It is easy to see that the use of gas sensors not only allows for online monitoring to prevent hazards but is also suitable for on-site real-time monitoring with high sensitivity.

In addition to the respective problems faced by each detection method, the detection of hazardous gases and particulate matter in general can be improved in the following ways. (1) The test results should have a high degree of accuracy. On the one hand, it is not easily affected by conditions such as light and temperature. On the other hand, interference from other gases in the atmosphere should be avoided during detection. (2) From the point of view of resource conservation and pollutant management, the chemicals used in the testing process should not be toxic or harmful so as not to cause environmental pollution. (3) The time required for the experimental process should be as short as possible, and real-time monitoring of gaseous pollutants should



ideally be achieved. (4) Several studies have reported that the application of sensors to detect gaseous pollutants in indoor environments has been increasing. We can make the sensor smaller, more selective, and more stable by further research. (5) Detection methods that meet the ultimate industrial application need to be characterized by low cost. Therefore, the detection of gaseous contaminants requires that the internal materials and structure of the sensor be adapted and improved to meet these performance requirements.

In recent years, in the context of the rapid development of information technology and automation technology, the detection of gaseous pollutants involved in atmospheric environmental testing work is basically based on laboratory analysis and manual sampling. The detection of gaseous pollutants is moving towards the direction of intelligence, automation and networking, and the scope and field of detection is becoming more and more extensive. In the actual detection of various types of detectors used in the work also presents multi-functional, automation, high quality, integration, intelligence and systematization and other characteristics. In the future, the focus of gaseous pollutant detection should tend to be in areas such as industrial pollution emissions. The content of the test will also be more detailed. For example, it will include temperature, moisture content, flow detection and so on.

## ACKNOWLEDGMENTS

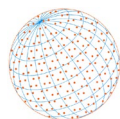
This work was supported by the National Natural Science Foundation of China [22278248] and the Scientific Innovation Program of Shenzhen City, China, under basic research program [JCYJ20220530141011026].

## DISCLAIMER

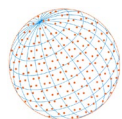
The authors declare no conflict of interest with this study.

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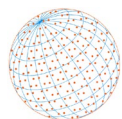
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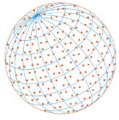
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