

A Review of Air Pollution Monitoring Technology for Ports

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Abstract: As a prerequisite for pollution control, monitoring air pollutants is crucial. In recent years, all walks of life are developing toward intelligence, and the concept of intelligent ports is also the development direction of current port planning. A lot of work such as loading and unloading of port cargo and planning has now achieved intellectual development, and the monitoring of air pollutants in ports also needs to be developed towards intelligence. However, at present, there are not many air pollutant monitoring systems for ports. In order to find monitoring equipment and models that are better suited to the port environment, this paper focuses on the main components of air pollutants in ports (SO_2 , NO_x , PM, etc.) and their sources and describes the monitoring methods and principles for these pollutants in ports and on ships, respectively. Regarding monitoring methods, the current application of DOAS (Differential Optical Absorption Spectroscopy) equipment and the monitoring system based on various gas sensors have great development prospects and advantages, based on the monitoring system being more intelligent. At the same time, the use of the same monitoring principle for a variety of pollutants monitoring equipment to a certain extent can save the cost and efficiency of monitoring. In terms of monitoring mode, the combination of manual analysis and automatic analysis will be perfect for the port's air pollutant monitoring system. This mode can alleviate the embarrassment of the low life of the sensor-based monitoring system to a certain extent, and the data monitored by this mode will be more accurate.

Keywords: port pollution; ship emissions; monitoring system; intelligent port



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1. Introduction

Under the general trend of economic globalization, the shipping industry of various countries has become more and more developed. Today, the cargo throughput of major ports in the world has reached a large scale and is in a stage of steady growth, as shown in Table 1. Taking China as an example, its port cargo throughput ranks first in the world all year round [1]. With the rapid development of the port economy, the air pollution problem caused by ship transportation activities and the work of loading and unloading equipment has become increasingly serious.

In general, port pollution to the atmosphere mainly originates from two aspects; one is the solid dust pollution and exhaust gas pollution caused by loading and unloading equipment during the ship loading and unloading operations in the port, and the second is the fuel exhaust emissions during the ship's voyage [2]. The air pollution caused by the loading and unloading of ships in ports should not be underestimated [3]. During the operation of ports, the primary sources of air pollution vary from one type of port to another. There are many emission sources in the container port area, including container ships, loading bridges, front cranes, container trailers, tire cranes, etc. [4]. The dust pollution caused by these devices at work is large, and their fuel exhaust emissions also account for part of the port air pollution. Bulk cargo terminal air pollution mainly comes from the dust generated in overturning engine rooms, belt conveyors, storage, and ship loading. According to the relevant survey results, the current Chinese port air TSP (Total Suspended Particulate) generally exceeds the standard. The amount of dust in the center of the port area is larger; the degree of pollution is higher; and the amount of dust pollution in some

ports occupies 50% of the total amount of pollution [5]. However, this kind of pollution shows the characteristics of surface source pollution. The diffusion pattern is not strong, so only the closer to the port area has an impact on residential life [6]. Evidence suggests that particulate matter emissions from shipping cause about 60,000 premature deaths each year [7], most of which occur near densely populated coastlines in East Asia, South Asia, and Europe [8].

Table 1. Top 10 Ports in the World in 2022 (Based on Cargo Throughput).

Name of Port	Cargo Throughput	Growth Rate
Ningbo Zhoushan Port	1224.05 million tons	4.4%
Shanghai Port	769.7 million tons	8.2%
Tangshan Port	722.4 million tons	2.8%
Qingdao Port	630.29 million tons	4.3%
Guangzhou Port	623.67 million tons	1.8%
Singapore Port	599.64 million tons	1.5%
Suzhou Port	565.90 million tons	2.1%
Port Hedland	553.27 million tons	1.1%
Rizhao Port	541.17 million tons	9.1%
Tianjin Port	529.54 million tons	5.3%

On the other hand, ships, as the mainstream power of logistics and passenger transportation in the shipping industry, have the characteristics of large fuel consumption and high harmful emissions, and the increasingly serious ship pollution problems and port environmental pollution problems brought by them have been widely concerned [9]. After investigation, about 15% of global anthropogenic NO_x emissions and 4–9% of SO₂ emissions can be attributed to ships [10]. In Chinese regions such as the Pearl River Delta, Yangtze River Delta, and Bohai Sea, the contribution of ship emissions to SO₂ and NO_x can reach 14.1 and 11.6% [11–13], of which about 70% of ship emissions occur in the sea within 400 km from the coastline [14], and according to model simulations, sea and land winds can transport the ship emissions several hundred kilometers inland [15]. Therefore, even if the emissions from ships occur mainly at sea, their emissions can affect the air quality and people's health in coastal and inland cities.

In the case of increasingly serious air pollution in ports, the situation of air pollution control has become very serious. According to the survey, air pollution ranks eighth among the leading risk factors for death, accounting for 2.5% of all deaths in developed countries [16]. Several studies now clearly document the link between air pollution and a variety of human diseases. The most consistent associations were increased mortality and hospitalizations from cardiovascular and respiratory diseases. Short-term or long-term exposure to PM and NO₂ will greatly affect cardiovascular mortality and the incidence of coronary artery disease, while long-term exposure to SO₂ has been shown to be closely related to respiratory mortality [17]. The detailed health effects of these pollutants are shown in Table 2.

With the rapid development of shipping and global trade, air pollution from shipping and ports may cause extensive health burdens on surrounding residents. In order to reduce the health burden caused by port air pollution, IMO implemented more stringent emission control measures in 2012, which have reduced the impact of port air pollution to a certain extent. However, despite the corresponding emission control measures, the pollution emissions of the shipping industry as a whole are likely to increase as the demand for global trade and shipping increases (by 50% by 2050) [18].

Table 2. Common air pollutants and their impact on health.

Pollutant Type	Health Effects
SO ₂	It can increase the incidence of respiratory diseases, and the condition of patients with chronic diseases will deteriorate rapidly
NO ₂	Damage the airway and cause delayed pulmonary edema, adult respiratory distress syndrome, etc.
CO	Long-term exposure to low concentrations of CO will have varying degrees of impact on the cardiovascular system and nervous system and may cause hypoxemia
PM2.5 and PM10	Affects the ventilatory function of the lungs, which can lead to premature death in people with cardiopulmonary disease

To protect people's health and living environment, the management of air pollution cannot be delayed. The management of air pollutant emissions cannot be separated from air pollutant monitoring, which is the basis of all air pollutant management work. There are various types of air pollution in ports, and if they are to be treated, it is necessary to determine the type and amounts of pollutants through air monitoring so that targeted treatment measures can be taken for air pollutants. In turn, air pollutant monitoring is inseparable from monitoring equipment, which is a necessary means to obtain information on air pollutants. Generally, air pollution conditions are monitored by conventional air pollution monitoring systems equipped with stationary monitors. These monitoring stations are highly reliable, accurate, and capable of measuring a wide range of pollutants using conventional analytical methods [19]. With the development of the times, the monitoring technology for port air pollution is constantly updated and evolving toward intelligence. Information communication, i.e., ubiquitous sensor networks, cyber-physics, and embedded systems, provide a new approach to the development and application of environmental monitoring [20], and various new types of air monitoring systems are constantly being updated.

In this paper, we review various methods of air pollutant detection and the current research status of various types of monitoring equipment, focusing on the air pollutant monitoring equipment applicable to the port environment and the characteristics of these equipment, and make predictions on the future development trend with the research progress of air pollutant monitoring equipment.

2. Detection Methods for Air Pollutants in Ports

For ports, the main air pollutants differ in different periods. According to a survey by Xiuyan Yang [21], the air pollutants in ports at different periods are shown in Table 3.

Table 3. Main air pollutants and pollution sources in the port (Adapted from [21]).

Port Development Stage	Project Type	Air Pollution Sources	Main Pollutants
Construction Period	Construction work	Sand and gravel stockpiling, loading and unloading and mixing Dust from vehicle loading and unloading Road and site dust Cement unpacking and other dust	Dust

Table 3. Cont.

Port Development Stage	Project Type	Air Pollution Sources	Main Pollutants
Operation Period	Port transportation equipment	Construction machinery emissions Transport vessel emissions Loading and unloading machinery and vehicle emissions Evacuation vehicle emissions	SO ₂ , NO _x , CO, HC, PM, Fumes and dust
	Bulk cargo terminal	Transport, storage, loading and unloading of coal and ore in the port area Dust from the road	TSP, PM
	Container Terminal	Large-scale container lifting equipment Container transport equipment	Fuel is diesel and emits NO _x , etc.
	Petrochemical Terminal	Liquid bulk transfer and storage	VOCS-based organic vapors

Based on the main air pollutant components of the port summarized in the table, this paper will mainly discuss the detection methods and monitoring means for these air pollutants.

2.1. Air Pollutant Sample Collection

In air pollutant monitoring, air sampling is an important part of the monitoring process, and the collection methods of air pollutant samples can be summarized into two categories: direct sampling method and enrichment (concentration) sampling method [22]. When the concentration of the measured component in the air is high or the analytical method is sensitive, the direct sampling method is used. The direct sampling method is a gas sampling method in which gas samples are collected directly in gas sampling bags or vacuum bottles and other containers and then are brought back to the laboratory for analysis and testing; the common sampling containers are syringes, plastic bags, and some fixed containers, etc. They are used to measure instantaneous concentration of pollutants in the air or the average concentration over a short period.

When the concentration of the measured component in the air is low, the enrichment sampling method is used. The enrichment sampling method, also known as the concentration sampling method, is the collection of air samples to be measured in the concentration of components enriched in the absorption medium and then analyzed and tested methods, including the solution absorption method, filling small column sampling method, low-temperature condensation method, and filter sampling method. The sampling time of this method is generally longer, and the average concentration of pollutants in the atmosphere during the sampling time is measured, which can better reflect the real pollution situation of the atmosphere in a period of time [23–25]. According to the different power used to collect air pollutants, the enrichment sampling method can be divided into active sampling method and passive sampling method. The active sampling method is a method in which the sampling pump makes the air sample pass through the sampling tube or absorption bottle containing the absorption medium so that the pollutant gas to be measured in the air is concentrated in the absorption medium. According to the different absorption media, it can be divided into solid active sampling method and liquid active sampling method. Additionally, the passive sampling method is a concentrated sampling method based on the principle of molecular permeation or diffusion to enrich the air with polluting gases. The passive sampler using this method can be divided into two types: infiltration type and diffusion type according to the different gas enrichment principles [26–28].

In general, the method of air sampling needs to be chosen according to the purpose of sampling and the site conditions to ensure that the quality of the collected samples meets the monitoring needs. For port air pollution monitoring, for example, because the direct

sampling method for the sample container sealing and chemical inertness requirements are high and are often used in the case of high concentrations of air pollutants, taking into account the environmental conditions in the port and on board the ship, the direct sampling method is generally not applicable. The more applicable enrichment sampling method is divided into active sampling method and passive sampling method; active sampling method is characterized by the need for external power to sample the air through the absorbent medium. The method is more applicable in the port such as the ability to provide electricity and a higher tolerance for noise environment. The diffusion-type passive sampler has the characteristics of small size, no interference from atmospheric particles and aerosols, etc., and can measure a variety of atmospheric pollutants at the same time, which is suitable for the environment with various types of atmospheric pollutants in ports and is also suitable for the situation where space is scarce on ships.

2.2. Detection Methods for Gaseous Pollutants

After investigation, the current common analysis methods for various types of air pollutants are shown in Table 4. The methods can be divided into manual analysis methods and automatic analysis methods according to the detection method, detection conditions, and the continuity of their detection data. According to the summary of the emission list in Table 3, the gaseous air pollutants in the port mainly include SO₂, NO_x, CO, HC, and VOCs. According to the relevant ambient air quality standards (GB 3095—2012), this subsection will focus on the detection methods of SO₂, NO_x, and CO, three air pollutants that have a greater impact on the ambient air.

Table 4. Analytical methods for each type of pollutant.

Pollutants	Manual Analysis Methods	Automatic Analysis Methods
SO ₂	Spectrophotometry, iodometry	Ultraviolet fluorescence method, DOAS, Constant potential electrolysis
NO _x	Ethylene diamine dihydrochloride spectrophotometric method	Chemiluminescence, DOAS
CO	NDIR spectrometry method	Gas filter correlation IR absorption, Non-dispersive IR absorption method
TSP	Gravimetric methods	—
PM _{2.5}	Gravimetric methods	Micro-oscillation balance method, Light scattering method, The beta-ray method
PM ₁₀	Gravimetric methods	Micro-oscillation balance method, Light scattering method, The beta-ray method

2.2.1. SO₂ Detection Methods

SO₂ is one of the major air pollutants as a Class 3 carcinogen and is a necessary item for environmental monitoring. For this purpose, Qinghua Du [29] and Liebing Xu [30] described the detection method of SO₂ concerning the technical standards and norms of environmental monitoring. The detection methods of SO₂ gas can be roughly divided into manual analysis methods and automatic analysis methods according to their detection methods. The commonly used methods of manual analysis methods include spectrophotometry and iodometry. These methods generally take the pollutant samples collected through the sampler to the laboratory to determine the concentration of pollutants by chemical and other methods. The automatic analysis methods do not require specific laboratory conditions, and the monitoring equipment using this method can automatically obtain the concentration of the detected pollutants without manual comparison and calculation of the experimental detection results. The commonly used methods of automatic analysis include the ultraviolet fluorescence method, DOAS (Differential Optical Absorption Spectroscopy),

and constant potential electrolysis. These methods are often used in various detection equipment and sensors to achieve automatic continuous monitoring. Now automatic online monitoring is also the mainstream of development.

2.2.2. NO_x Detection Methods

NO and NO₂ are the most common nitrogen oxides in atmospheric environmental monitoring; they are mainly derived from the combustion of fossil fuels such as coal [31] and are one of the main parameters for monitoring ambient air. Similarly, NO and NO₂ analysis methods can be divided into manual analysis methods and automatic analysis methods. The main manual analytical method commonly used for the detection of NO and NO₂ is the ethylene diamine dihydrochloride spectrophotometric method [32], while chemiluminescence [33] and DOAS [34] are commonly used in automated analytical methods.

2.2.3. CO Detection Methods

CO is a major pollutant in the air and is mainly produced by the incomplete combustion of carbonaceous substances in the air. When the human body inhales high concentrations of CO, it can induce symptoms such as memory loss, myocardial infarction, coronary heart disease, and hypoxic asphyxia [35], so the monitoring of CO concentration is also important. The manual analysis methods commonly used today to detect CO concentrations are NDIR (Non-dispersive Infrared) spectrometry method [36], and the automated analysis methods are the gas filter correlation IR absorption and the non-dispersive IR absorption method [37].

2.3. PM Detection Methods

According to the emission inventory in Table 3, TSP (Total Suspended Particulate) and PM (Particulate Matter) are the particulate pollutants that have a great impact on the ambient air in the port, so this section will mainly discuss the detection methods of TSP, PM_{2.5}, and PM₁₀.

2.3.1. TSP Detection Methods

TSP in the form of free distribution in all corners of the air environment is very easy to be inhaled into the body. Some of the particles of small size enter into the blood and with the blood circulation flow gradually into the body to various tissues and systems, then threatening the health of the human body [38]. Because the components of TSP in the atmosphere are very complex (including PM_{2.5} and PM₁₀) and vary greatly, the only method often used to detect and analyze TSP is the gravimetric method, which is a manual analysis method, and the sampler used for this method needs to have certain cutting characteristics. Through this sampler, a quantitative volume of air is extracted at a constant speed, and TSP with a particle size of less than 100 µm is trapped on a constant weight filter membrane. The mass concentration of TSP is calculated based on the difference between the weight of the membrane before and after sampling and the volume of air collected [39].

2.3.2. PM_{2.5} and PM₁₀ Detection Methods

PM emissions are the most important air pollutant in shipping, and it causes health damage costs [40], so it is important to monitor airborne PM today. The properties of PM₁₀ and PM_{2.5} are the same, and the difference lies in the different aerodynamic diameters, so the detection method applicable to PM_{2.5} is also applicable to PM₁₀. The manual analysis method for PM₁₀ and PM_{2.5} detection and the method for TSP detection are both gravimetric methods, while the commonly used automatic analysis methods include the micro-oscillation balance method, the light scattering method, and the beta-ray method [41].

These are the main methods of detecting air pollutants in the port, which can be divided into manual monitoring and automatic monitoring according to the method of detecting the concentration of air pollutants. The main difference between these two types of monitoring lies mainly in the experimental conditions required for their monitoring and

the continuity and time interval of their monitoring. Because the detection methods for various pollutants in the laboratory are relatively mature and because the detection data accuracy is high, the development direction of manual monitoring is mainly the research and improvement of samplers.

Due to technical reasons, the current detection methods used by traditional detection instruments are all automatic analysis methods. To ensure the accuracy of the data, these instruments usually include many auxiliary tools, so the prices of such traditional instruments are relatively expensive, as shown in Table 5.

Table 5. Some traditional testing instruments (Adapted from [42]).

Pollutants	Example Products	Detection Methods	Price (USD)
SO ₂	Teledyne Model 6400T/6400E Sulfur Dioxide Analyzer	UV Fluorescence	About \$30,000
	Aeroqual Series 500 with SO ₂ Sensor Head	Electrochemical Sensor	About \$2000
	Hanwei MQ-136 SO ₂ Sensor	Solid-State Sensor	About \$50
NO ₂	Teledyne Model T500U Nitrogen Dioxide Analyzer	Cavity Attenuated Phase Shift Spectroscopy	About \$30,000
	Aeroqual Series 500 with NO ₂ Sensor Head	Electrochemical Sensor	About \$2000
	SGXSensorTech MiCS-2714 NO ₂ Sensor	Solid-State Sensor	About \$10
CO	Teledyne Model T300U Gas Filter Correlation Carbon Monoxide Analyzer	IR Absorption with Gas Filter Correlation Wheel	About \$30,000
	Aeroqual Series 500 with CO Sensor Head	Electrochemical Sensor	About \$2000
	Hanwei MQ-7 CO Sensor	Solid-State Sensor	About \$10
PM _{2.5}	Met One Instrument BAM-1020 Beta Attenuation Monitor	Beta Attenuation	About \$25,000
	Met One Instrument Aerocet 831 Aerosol Mass Monitor	Light Scattering	About \$2000
PM ₁₀	Teledyne Model 602 BetaPLUS Particle Measurement System	Beta Attenuation	About \$30,000
	Met One Instrument Aerocet 831 Aerosol Mass Monitor	Light Scattering	About \$2000

For current ports, automatic monitoring is a trend. Since the air pollution situation in the port area is highly correlated with human activities (e.g., ships entering and leaving the port), the concentration of air pollutants in the port may change significantly in a short period of time. Therefore, for air pollutant monitoring in ports, the monitoring equipment should have the characteristics of continuity and high temporal resolution. Continuous automatic monitoring equipment will be more suitable for the port environment. The automatic monitoring is achieved by various types of pollutant detection equipment and sensors based on the principle of automatic analysis methods, and the development direction is to improve the accuracy of detection equipment, anti-interference, and monitoring types.

The high cost of traditional testing instruments puts a high burden on their coverage in the port area. Relatively speaking, various sensors will be much cheaper, and the sensor-

based monitoring system will have greater advantages in covering the port area. Although the accuracy and anti-interference of many sensors are not as good as manual monitoring and traditional detection instruments, with the development of technology, automatic monitoring based on sensors will become mainstream in the future.

3. Air Pollutant Monitoring Systems for Ports

For most of the air pollution in ports, the pollutants mainly come from two sources. One is the various terminals in the port, and the other is all kinds of ships. The dust and exhaust emissions caused by the work of loading and unloading equipment at the port terminals and the combustion exhaust from internal combustion engines when ships enter and leave the port constitute the main part of air pollution at the port. Therefore, at present, monitoring the air pollution in the port mainly is to monitor the port terminal and the ships entering and leaving the port. The commonly used monitoring methods and their advantages and disadvantages are shown in Table 6.

Table 6. Commonly used monitoring methods for ports and ships.

Monitoring Object	Monitoring Method	Monitoring Equipment	Advantages	Disadvantages
Ports and Terminals	Manual monitoring	Sampler combined with laboratory	Wide sampling range, Accurate detection data	Has a certain hysteresis, low time resolution, and poor efficiency
		Manual portable detector	Easy detection and high spatial resolution	It cannot be detected for a long time, and the data accuracy is low
	Automatic monitoring	Traditional monitoring station	Able to monitor data for a long time with high accuracy	Expensive and space-constrained with poor spatial resolution
		Sensor based monitoring system	High spatio-temporal resolution with inexpensive sensors	Shorter lifetime and immunity to interference
Ships	Manual monitoring	Oil sample collection combined with laboratory	The collected data are more accurate	Has a certain blindness and hysteresis, and the efficiency is not good
		Manual portable detector	Higher efficiency	On-site judgment is required, and the time resolution is low
	Automatic monitoring	Inspection equipment loaded in a fixed position	Capable of long-term continuous monitoring with high data accuracy	Expensive, low spatial resolution, a large number of laying requires a lot of money
		Sensor based monitoring system	High spatio-temporal resolution and low cost	The life of the sensor is not high due to the long-term smoke environment
		UAVs with sniffers	Higher spatio-temporal resolution and more flexibility at lower cost	Sea wind speed and air superiority have a certain influence on the path planning of UAVs

3.1. Port Air Pollutant Monitoring

3.1.1. Continuous Monitoring

For the port, most of the ports are relatively large, and a port contains many terminals. The need to monitor a wide range of air pollutants and the concept of the intelligent port are now prevalent, and automatic online monitoring will be the future development trend. If automatic monitoring is used, the monitoring equipment needs to have the function of monitoring multiple air pollutants simultaneously. Many companies in the market have launched continuous automatic monitoring systems with qualified tests, such as TE's 6002 system, Beijing (China) SDL's AQMS-900 and Wuhan (China) Tianhong's TH-2000, and other automatic ambient air quality monitoring systems. These instruments can

simultaneously carry out continuous online monitoring of SO_2 , NO_x , CO, PM, and other pollutants through different automatic analysis methods and have real-time data acquisition and transmission functions, thus achieving real-time online monitoring of port air pollution. In the face of the need to monitor multiple terminals, the TH-2000, for example, as shown in Figure 1, can also be assigned many sub-stations; the data collected by the sub-stations are gathered through the communication network to the central station; the data processing at the central station can also directly generate statistical reports, making environmental monitoring more convenient. Although there is a certain error between the data measured by these devices and the manual analysis method in the complex environment of the port, with the development of technology, this error has been reduced to a certain range to a usable standard. However, although the accuracy and precision of the monitoring of these devices are higher and more convenient to use, their size is huge; in terms of price they are generally more expensive; and the full coverage of the port area requires a certain cost.



Figure 1. TH-2000.

In addition to the monitoring systems developed by individual companies, many researchers have investigated methods for the simultaneous monitoring of pollutants such as SO_2 , NO_x , CO, and PM. Jieshu Zou et al. [43] innovated from the monitoring principle, improved and innovated the traditional DOAS, and developed a new measurement method, called GP-DOAS (Gas & Particle Differential Optical Absorption Spectroscopy) for simultaneous measurement of gas and particle pollutant concentrations, which can be used for simultaneous measurement of SO_2 , NO_2 , and PM concentrations. The principle of conventional DOAS is that a light beam transmitted in a medium interacts with the medium. When the medium is some kind of gas and the beam is transmitted in the optical path, the variation in its radiation intensity can be expressed by the Lambert–Beer law. Additionally, according to the Lambert–Beer law, the concentration of the gas can be measured, and the basic principle is shown in Figure 2.

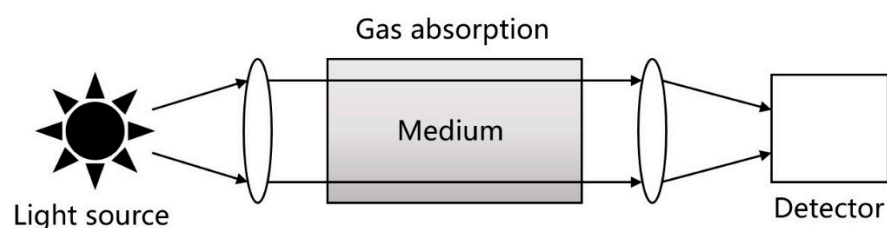


Figure 2. Lambert–Beer law for measuring gas concentration.

After the gas concentration is obtained from the traditional DOAS method, the gas absorption spectrum and air Rayleigh scattering spectrum are then deducted from the absorption spectrum to analyze the attenuation spectrum of the particles, and the attenuation spectrum of the particles is compared with the light source spectrum to analyze the attenuation coefficient of the particles, and finally, the particle concentration is obtained from the attenuation coefficient. The advantages of using this method for monitoring are that the same principle of equipment can be used to monitor several major air pollutants in the port online at the same time, which can save costs and reduce the size of the equipment to a certain extent, but in the case of complex working conditions there will be a certain degree of measurement error, and at present, the technology needs further improvement, but it can be used as an auxiliary tool to make a general judgment on the environmental quality of the port.

Unlike devices with improvements to the monitoring principle, there are many different gas detection technologies available today, each with its advantages and disadvantages. To date, five types of low-cost portable gas sensors are most suitable and widely available, namely electrochemical sensors, catalytic sensors, solid-state (semiconductor) sensors, NDIR, and PID (photo-ionization detector) sensors. However, no single sensor is capable of measuring all hazardous gases [42]. In the face of various air pollutants in the port, to meet the monitoring of the main air pollutants, a combination system of multiple sensors can be used. Zhijian Mei [44] applies emerging technologies and designs a ZigBee-based air pollution monitoring system, which uses ZigBee-based wireless sensor network technology for data transmission, and the data come from the corresponding air pollutant sensors. Most of the sensors used in these monitoring systems are electrochemical sensors and absorption gas sensors, which have been developed to have the appropriate accuracy and immunity to interference. In this mode, the monitoring system can distribute a large number of sensors to obtain a large amount of monitoring data, and the management center can remote control the monitoring system. Thanks to ZigBee technology and today's air pollutant sensor technology, the system not only monitors the accuracy of the data obtained and effectively reduces the cost of the system, but also with only a large number of wireless sensor monitoring nodes needed in each place to monitor the terminal, you can achieve real-time online monitoring of port air pollutants. Similarly, the LoRa-based port air pollutant monitoring system designed by Ruixuan Sun et al. [45] has the same monitoring mode as the ZigBee-based monitoring system, which uses sensors as data collection terminals and transmits data through the network. The difference is that LoRa spread spectrum technology has solved the contradiction between low power consumption and long-distance transmission of ZigBee technology and has the advantages of low power consumption, low cost, long-distance transmission, and strong anti-interference, which has better transmission effect in ports with large area and relatively complex environment.

Although sensors have great advantages in monitoring the coverage of ports, due to the influence of the port environment and the limitations of sensors themselves, the life of sensor-based monitoring systems is not ideal. Various gas sensors commonly used in pollutant monitoring, and their service life are shown in Table 7.

Table 7. Five commonly used gas sensors and their average life expectancy (Adapted from [42]).

Sensor Types	Detectable Gases	Life Expectancy
Electrochemical	Gases which are electrochemically active, about 20 gases	1–2 years
Catalytic	Combustible gases	Up to 3 years
Solid-state	About 150 different gases	10 years or more
Non-dispersive Infrared	Hydrocarbon gases and carbon dioxide	3–5 years
Photo-ionization	Volatile organic compounds (VOCs)	Depend on the Ultraviolet lamp, normally 6000 h

Owing to the low lifetime of sensors, the more developed sensor-based monitoring systems require regular inspection and replacement of sensors. The best reference for determining whether the components of a monitoring system are functioning properly is the data from manual monitoring.

3.1.2. Discontinuous Monitoring

On the other hand, the online monitoring equipment designed for port air pollutants is not consistent with the manual analysis method combined with the laboratory in terms of analysis principles, working conditions, and sampling methods. However, the criteria for determining the accurate and stable operation of the online monitoring equipment are comparing monitoring with the manual analysis method in the laboratory [46], so it is also very important to conduct regular manual monitoring of port air pollutants. While the prerequisite for manual analysis in the laboratory is the sampling of air pollutants, the development trend of air samplers is currently intelligent, integrated, and multi-functional. To reduce the complexity of the work of the port staff, the use of the combined sampler of air and particulate matter designed by Linghan Zhang [47] can provide a certain convenience for the collection of air samples. The sampler samples SO_2 , NO_x , PM, and other air pollutants through four independent channels, and its temperature control PID algorithm and rotameter error analysis in use allow the system to significantly improve the control accuracy and achieve the expected sampling results. In this way, only one style of the sampler is needed to complete the work in the face of the diverse air pollutants in the port, greatly saving the work's tediousness.

Xue Liu et al. [48] then designed a wireless sensor multipoint network group air sampler based on a learning wireless remote sensor, which can achieve flexible and variable sampling of air pollution monitoring and provide effective samples for air pollutant monitoring. The sampler, through the learning function of the learning wireless remote control sensor, achieved a multi-sampler synchronous sampling and delayed sampling flexible control, while using PWM (Pulse Width Modulation) to adjust the sampling speed of the sampler, sampling speed 0.1–0.8 L/min adjustable, to achieve reliable automatic sampling of the air. When the sampler is used, the workload of port staff can be reduced, making the construction of smart ports a step further.

3.2. Ship Exhaust Monitoring

Air pollution from ships also has a large impact on the port environment, so it is especially important to monitor the emissions from ships entering and leaving the port. For ships, given the conditions and the navigation cycle, generally do not use the combination of sampler and laboratory discontinuous monitoring equipment, more commonly used is the continuous online monitoring equipment for ship flue gas. In terms of monitoring equipment, the guidelines issued by the IMO (International Maritime Organization) recommend the use of monitoring equipment that works on the principle of NDIR. At the same time, it is also clear that the competent authorities of various countries can recognize other forms of monitoring equipment based on full experiment and evaluation. There

are many manufacturers on the market whose products have been approved by different classification societies, such as SICK, VIMEX, SIMENS, ABB, EMSYS, etc. Among them, the technology of EMSYS is a new quantum cascade laser infrared spectrometry, which can detect eight kinds of air pollutants at the same time, providing great convenience for the monitoring of ship exhaust gas.

In addition to monitoring equipment from various manufacturers, there are many other promising designs for monitoring systems. Yanfei Deng et al. [49] designed a ship exhaust gas online monitoring system, which combines embedded technology to design the data acquisition terminal of the monitoring system and uses the currently well-developed sensor module for data acquisition, which has some practical application value for improving the current ship exhaust gas monitoring technology. Turkin et al. [50], on the other hand, developed a four-wavelength laser system that allowed measuring the laser radiation attenuation signal using differential extinction at three wavelengths and the Mie scattering signal on aerosol particles at a fourth wavelength, and calculated the average volumetric-surface diameter of the aerosol particles based on the measured attenuation signal. The wavelength of laser detection is also selected according to the particle size range, and by applying the differential laser attenuation method to soot particles of different wavelengths in ship exhaust, the concentration and size distribution can be evaluated simultaneously.

At the same time, monitoring systems for ship exhaust are not only installed on ships but also on the shipping lanes and nearby terminals where ships sail. Seyler et al. [51] monitored SO_2 and NO_2 concentrations in ship exhaust gases using Multi-axis DOAS (MAX-DOAS). In the spring and summer seasons, when a northerly wind prevails and when the wind blows from the ocean to the land, it is possible to effectively monitor the emission of ship exhaust from the port terminal by placing the telescope horizontally and collecting the signal of the light directly passing through the ship exhaust and using the measured spectrum in the direction of the sun's zenith angle as the reference spectrum, as shown in Figure 3.

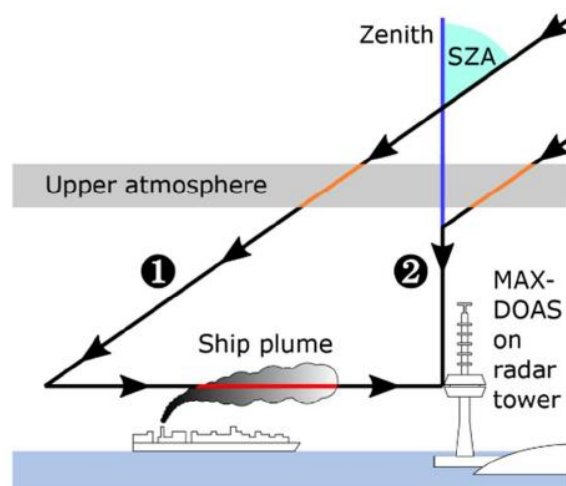


Figure 3. MAX-DOAS monitoring of ship emissions (Reproduced from [51] under the terms and conditions of a CC-BY copyright license agreement).

Additionally, in recent years, in the face of ship exhaust monitoring on the waterway, in addition to this fixed-point monitoring equipment, UAVs (Unmanned Aerial Vehicles) have been gradually applied to ship exhaust monitoring because of their high flexibility and maneuverability. These UAV monitoring systems mainly consist of rotary-wing drones, sniffing sensor modules, flight controllers, and rapid screening systems for ship emissions [52]. They monitor the content of air pollutants in ship exhaust gas through the exhaust gas plume entering the ship and can transmit data through 4G or 5G networks and monitor real-time data through cloud platforms. Lixin Shen et al. [53] developed a new multi-UAV collaborative path planning model for ship air pollution detection in dynamic

environments. Aiming at the uncertainty brought by the ship's dynamic position, this model uses different UAVs to detect different numbers of ships and proposes a multi-UAV cooperative detection strategy with lower detection cost and higher detection efficiency. Through this method, it is possible to remotely monitor in real-time whether the ships entering the port comply with the emission standards, and it is possible to cooperate with the monitoring equipment at the terminal to achieve comprehensive online monitoring of the port.

4. Summary and Prospect

At present, whether it is a fixed monitoring station or movable monitoring equipment, according to its monitoring results, air pollution monitoring technology can be divided into continuous monitoring equipment and non-continuous monitoring equipment. Non-continuous monitoring equipment is generally a combination of samplers and laboratories for the analysis of monitoring equipment. The advantage is the low cost, and monitoring results are generally more accurate. Continuous monitoring equipment, on the other hand, is online monitoring equipment that uses various automatic analysis methods as a principle, as well as various types of air pollutant sensors. Although different principles are applied to design and combine different pollutants, continuous monitoring equipment is relatively expensive and bulky. However, with the development of the times, the monitoring of port air pollution will gradually tend to be intelligent, and various types of continuous monitoring equipment will have a wider application and development, while non-continuous monitoring equipment will be able to play a supporting role to ensure the accuracy of online continuous monitoring of port air pollutants. There are currently three areas that are more conducive to the development of port air monitoring.

(1) In terms of monitoring methods, to reduce the high price and large size caused by the application of different principles to design online monitoring equipment, it will be a future trend to study the use of the same principle, such as DOAS, to simultaneously monitor a variety of air pollutants, such as SO₂, NO_x, and PM, which will greatly reduce the economic costs of air monitoring when covering the whole port.

Although many related types of research are still not mature enough and the accuracy of such equipment is not very high, with the development of technology, the accuracy, precision, and anti-interference of such monitoring equipment will be greatly improved and then used in the actual port air pollutant monitoring project.

(2) The second is the development of more mature types of gas sensors, with their low price, strong integration, rapid response, and continuous monitoring capabilities having the advantage of a wide range of applications at present, and along with the latest iterations of technology they should also have higher monitoring accuracy, range, and anti-interference ability. The sensor-based online monitoring system has greater advantages in monitoring port air pollution. At the same time with the combination of UAV and sensors, it can also be combined with the monitoring system with the sea and port land to achieve comprehensive monitoring of air pollution in the port area.

(3) In the monitoring mode, the combination of continuous monitoring and regular non-continuous monitoring will be a healthier mode of monitoring air pollutants in the port. The results of non-continuous monitoring can be used as a reference to check whether the continuous monitoring system is operating normally and to determine whether the components of the monitoring equipment have been damaged due to the changing environment in the port area so that the equipment can be repaired and replaced in time to provide an additional layer of protection for air pollution monitoring in the port.

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