Journal of Electronic Research and Application, 2024, Volume 8, Issue 2
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Advanced Technologies for Volatile Organic Compound (VOC) Emission Treatment: An Overview

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Abstract: This paper presents a comprehensive overview of various advanced technologies employed in the treatment of volatile organic compounds (VOCs), which are crucial pollutants in industrial emissions. The study explores different methods, including direct combustion, thermal combustion, catalytic combustion, low-temperature plasma purification, photocatalytic purification, membrane separation, and adsorption methods. Each technology is critically analyzed for its operational principles, efficiency, and applicability under different conditions. Special attention is given to adsorption concentration and catalytic combustion parallel method, highlighting its efficiency in treating low-concentration, high-volume VOC emissions. The paper also delves into the advantages and limitations of each method, providing insights into their effectiveness in various industrial scenarios. The study aims to offer a detailed guide for selecting appropriate VOC treatment technologies, contributing to enhanced environmental protection and sustainable industrial practices.

Keywords: Volatile organic compounds (VOCs); Emission treatment technologies; Catalytic combustion; Adsorption methods; Environmental protection

1. Introduction

There are several definitions for volatile organic compounds (VOCs), which can be divided into two categories. The first category provides a general definition of VOCs, explaining what VOCs are and under what conditions they are considered volatile. These compounds typically have a boiling point below 260°C and a vapor pressure of about 70 Pa or more at room temperature. The second category involves the context of environmental protection, referring to active or harmful VOCs. In terms of environmental protection, volatility and participation in atmospheric photochemical reactions are crucial factors. Compounds that do not volatilize or participate in atmospheric photochemical reactions are not considered harmful.

In China, the definition of VOCs in the "Emission Standard of Pollutants for Petroleum Refining Industry" (GB31570-2015) is based on organic compounds that participate in atmospheric photochemical reactions or those determined by prescribed measurement or calculation methods [1]. These compounds are the main pollutants emitted in the waste gas from the petroleum chemical industry, paint decoration, printing industry, electronic manufacturing, surface anti-corrosion, shoemaking, transportation, and various chemical production processes. With the development of industry and the improvement of living standards, the emission of VOCs has been increasing drastically. VOCs are characterized by a wide range, large emissions, various types, and strong toxicity, posing a serious threat to the ecological environment and human health. Under sunlight, they can react with nitrogen oxides (NO_x) to produce photochemical smog, contributing to this phenomenon. VOCs can cause cancer, teratogenesis in humans, and poisoning in animals and plants. Therefore, the rational treatment of VOCs is necessary.

2. Combustion method for treating VOCs

The combustion method is a process of purifying VOCs by burning them at a certain temperature in an incinerator, ultimately generating carbon dioxide (CO_2) and water (H_2O). Depending on the combustion temperature and method, it is generally divided into direct combustion, thermal combustion, and catalytic combustion.

2.1. Direct combustion method

The direct combustion method involves feeding VOCs directly into an incinerator for high-temperature combustion. This method is suitable when VOCs have a high concentration and good combustibility. For low concentrations, auxiliary fuel is required. The combustion process releases CO_2 and H_2O into the air, while the generated heat is recovered and utilized. This method has the advantages of low investment cost, simple equipment, and easy operation. However, maintaining high-temperature combustion (above 1100°C) incurs high operating costs. Additionally, the high temperatures can produce NO_x, a secondary pollutant, making this method less commonly used in the treatment of organic waste gas nowadays.

2.2. Thermal combustion method

In the thermal combustion method, VOC gases are first heated to a certain temperature through a heat exchanger before entering the thermal combustion chamber. This method can treat VOC concentrations ranging from 100 to 2,000 ppm, with an efficiency of 95% to 99% [2]. Compared to direct combustion, thermal combustion generally operates at temperatures between 700 and 900°C, resulting in energy consumption savings.

2.3. Catalytic combustion method

Catalytic combustion involves the reaction of VOCs in the presence of a catalyst to produce CO_2 and H_2O. Catalysts help lower the ignition temperature of organic compounds and shorten reaction time. Currently, catalysts used for VOC treatment include precious metals (such as platinum [Pt] and palladium [Pd]) and non-precious metals (such as vanadium [V], titanium [Ti], iron [Fe], and copper [Cu]). Pt/H-Beta and PdO/H-Beta catalysts exhibit strong selective catalytic decomposition for chlorinated hydrocarbons [3]. Studies have shown that Au/TiO_xN_y catalysts have high catalytic efficiency for organics like ethane, benzene, and propanol [4].

Compared to thermal combustion, catalytic combustion requires lower combustion temperatures (200 to 400°C), significantly reducing energy consumption. Moreover, combustion at lower temperatures avoids the generation of NO_x as a secondary pollutant. However, catalysts are susceptible to poisoning by substances containing sulfur (S), phosphorus (P), arsenic (As), etc., leading to a loss of their catalytic activity. Additionally, replacing the catalysts can be costly.

3. Low-temperature plasma purification method

Low-temperature plasma purification technology is a newly developed gas treatment technology in recent years. Low-temperature plasma can be obtained at room temperature and pressure through high-voltage pulse discharge. The high-energy electrons, ions, and free radicals in the plasma can react with various pollutants such as carbon monoxide (CO), hydrocarbons (HCs), NO_x, sulfur oxide (SO_x), hydrogen sulfide (H_2S), mercaptan (RSH), etc., transforming them into harmless or less harmful substances like CO_2, H_2O, nitrogen (N_2), S, sulfur dioxide (SO_2), thus purifying the exhaust gas.

Different chemical bonds require different amounts of energy to break. When the power is low and the energy of the active particles generated by the discharge is insufficient, some large molecules are only shattered, forming small molecular compounds without being completely oxidized. Especially in the purification of mixed gases, some molecules are easily destroyed and completely oxidized, while others are not easily destroyed or only degraded without complete oxidation.

Studies show that C-S and S-H bonds are relatively easy to break [5], so low-temperature plasma technology is effective for odor purification and has been applied in the deodorization of rubber exhaust and food processing exhaust. For the purification of aromatic compounds, studies have shown that it is effective when the energy of the plasma generation system is matched. For example, when the concentration of toluene is below 300 mg/m^3, the purification efficiency can reach 60% to 70%.

Low-temperature plasma has several advantages in exhaust gas purification: First, since the plasma reactor has almost no resistance, the system’s power consumption is very low. Second, the equipment is simple, with a modular structure, low cost, and easy relocation and installation. Third, as no preheating time is required, the device can be turned on and off instantly. Fourth, it occupies less space than existing technologies. Fifth, it has strong resistance to particulate interference and can operate without filtration for oil smoke, mist, etc., facilitating maintenance.

However, the mechanism of low-temperature plasma technology is not yet fully understood, and its efficiency in purifying organic compounds is generally below 70% [6].

4. Photocatalytic purification method

The photocatalytic oxidation method utilizes photocatalysts, such as titanium dioxide (TiO_2), to oxidize VOCs adsorbed on the catalyst surface [7]. The purification rate of photocatalysis depends on the performance of the catalyst and the light source used. The main catalyst used currently is the TiO_2 photocatalyst. Ultraviolet light sources, such as 185, 254, and 365 nm, have the best purification effect. For the purification of aromatic compounds, short-wave UV light (254 and 185 nm) shows better photocatalytic efficiency. In theory, photocatalytic oxidation can completely degrade pollutants into non-toxic substances like CO_2 and H_2O, but its slow reaction rate and low photon efficiency limit its practical application.

Under certain conditions, the photocatalytic oxidation of VOCs can produce intermediate products such as aldehydes, ketones, acids, and esters, causing secondary pollution. Issues such as catalyst deactivation and difficulty in catalyst immobilization also exist. To address these, coupling technologies such as electrochemistry, ozone (O_3), ultrasound, and microwaves have been attempted to enhance the photocatalytic oxidation process, effectively improving the rate of the photocatalytic process.

Photocatalytic oxidation technology is effective for low-concentration VOCs but has not yet been widely applied in industrial VOC purification.

5. Membrane separation method

Membrane separation is a process that utilizes natural or synthetically produced membrane materials to separate pollutants. It is a novel and efficient separation method suitable for treating high-concentration organic waste gases [8]. The organic waste gas is first compressed and condensed. The condensed organic substances are recovered, and the remaining gas enters the membrane separation unit, which is then divided into two streams. One stream is returned to the compressor for reprocessing, and the other is treated and discharged. Membrane separation was initially applied to gasoline recovery and is currently one of the main technologies for oil vapor recovery. In Japan, practical applications of this technology have been in place since 1988 and have shown good results.

6. Adsorption method

The adsorption method utilizes solid media with a microporous structure (adsorbents) to adsorb target substances (adsorbates) onto their surfaces, separating them from the main body [9]. Common adsorbents include activated carbon and zeolite molecular sieves. Activated carbon has a large specific surface area, high adsorption capacity, and non-selective adsorption, making it the most commonly used VOC adsorbent. Zeolite molecular sieves have a uniform microporous structure and exhibit strong selective adsorption.

Compared to other methods, the adsorption method has high removal efficiency, low energy consumption, mature technology, and is easy to promote and apply, offering excellent environmental and economic benefits. However, its drawbacks include large treatment equipment, complex processes, and susceptibility to deactivation by particulate substances or other impurities in the exhaust gas. This process is used to treat high-concentration, low-temperature, and high-pressure exhaust gases. It can achieve high efficiency with low energy consumption and almost completely purify organic waste gases. However, the equipment is bulky, and the process is complex; it involves substantial investment and may cause secondary pollution. Some small and medium-sized enterprises prefer this simple, low-cost activated carbon adsorption technology, especially in the spraying and packaging printing industries.

7. Adsorption concentration and catalytic combustion parallel method

For the emission of low-concentration, large-volume VOCs in the industry, direct catalytic combustion and high-temperature incineration consume a lot of energy, resulting in high operating costs. The adsorption concentration-catalytic combustion technology organically combines adsorption and catalytic combustion technologies, suitable for waste gas treatment in situations with large volumes and low or unstable concentrations [10].

In this process, honeycomb-shaped activated carbon is commonly used as the adsorbent, which has low resistance and good kinetic performance. There are also applications of thin-bed granular activated carbon and activated carbon fiber felt as adsorbents, frequently regenerating them through adsorption/desorption. The VOCs-laden bed is regenerated using a small volume of hot gas flow, and the regenerated high-temperature, high-concentration VOCs enter the catalytic combustor for catalytic oxidation. After concentration, the waste gas can maintain a self-sustaining combustion state in the catalytic combustor without external heating under stable operating conditions. The high-temperature flue gas generated after catalytic combustion can be used directly for the regeneration of the adsorption bed or used to heat fresh air for the regeneration of the adsorption bed.

This process characteristically transforms large-volume, low-concentration VOCs into small-volume, high-concentration VOCs, followed by catalytic combustion purification. After years of operational practice, this combined technology also exhibits some obvious defects: First, the safety of using activated carbon materials as adsorbents is relatively poor. The metal components in activated carbon can catalyze the oxidation of organics adsorbed on its surface. When the regeneration hot gas flow temperature reaches above 100°C, heat accumulation due to enhanced catalytic oxidation can cause the adsorption bed to ignite. Second, regenerating activated carbon with the hot gas flow has a low temperature, and some high-boiling-point compounds cannot be completely desorbed at the end of the desorption cycle, accumulating in the carbon bed and reducing its adsorption capacity. Due to safety issues, the usual regeneration temperature should not exceed 120°C. Therefore, organic compounds with boiling points higher than 120°C, such as trimethylbenzene, cannot be purified using this process. Third, activated carbon typically has a strong water absorption capacity; when the humidity of the waste gas is high (over 60%), the purification efficiency for organic substances is relatively low.

The characteristic of hydrophobic zeolite adsorbents is good safety; they can be desorbed and regenerated at high temperatures (up to 220°C, known as non-combustible adsorbents) and can treat most organic compounds. In recent years, hydrophobic zeolite has almost entirely replaced activated carbon in low-concentration VOC adsorption concentration processes in Japan, Taiwan, and Western countries. The adsorption capacity of molecular sieves is generally lower than that of activated carbon, and when using a fixed bed, its adsorption efficiency is lower than that of an activated carbon bed. In the 1990s, Japan developed a rotary adsorption concentration device that adsorbs and desorbs simultaneously, with higher adsorption efficiency than fixed-bed adsorption devices, becoming the mainstream technology for low-concentration VOC treatment internationally.

8. Conclusion

This paper has systematically reviewed and analyzed several advanced technologies for the treatment of VOCs, highlighting their critical role in addressing environmental pollution issues associated with industrial emissions. The detailed examination of methods such as direct combustion, thermal combustion, catalytic combustion, low-temperature plasma purification, photocatalytic purification, membrane separation, and adsorption methods reveals a diverse range of solutions, each with unique merits and limitations.

direct and thermal combustion methods, while effective, are energy-intensive and may produce secondary pollutants like NO_x. Catalytic combustion offers a more energy-efficient alternative, but its efficacy depends heavily on the nature of the catalysts used. Low-temperature plasma purification emerges as an innovative approach, especially effective in odor control, though its overall efficiency in VOC degradation requires further enhancement. The photocatalytic purification method, utilizing light energy to initiate the degradation process, shows promise for low-concentration VOCs but is limited by its reaction rate and potential for secondary pollution. Membrane separation stands out for its application in high-concentration VOC treatment, showcasing the importance of technological innovation in environmental management. The adsorption method, particularly using activated carbon and zeolites, is noted for its high efficiency and adaptability, although issues like adsorbent deactivation and complex regeneration processes must be addressed. The adsorption concentration and catalytic combustion parallel method represent a significant advancement, particularly for low-concentration, large-volume VOC emissions. This method’s ability to concentrate VOCs before catalytic treatment optimizes energy use and enhances overall efficiency, setting a benchmark for future developments in VOC emission treatment technologies.

In conclusion, while each technology offers distinct advantages, the choice of the most appropriate method depends on specific factors such as VOC concentration, emission volume, and the industrial context. Future research should focus on enhancing the efficiency and sustainability of these technologies, reducing operational costs, and minimizing secondary pollution. This study underscores the need for continuous innovation and adaptation in industrial emission treatment technologies, aligning with the broader goals of environmental protection and sustainable development.

Disclosure statement

The author declares no conflict of interest.

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