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Research Progress of Low-Temperature Plasma Technology in the Treatment of Malodorous Gases

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Abstract

With the rapid pace of urbanization, malodorous gases stemming from industrial and domestic activities present a severe threat to both the environment and human health. Conventional treatment techniques, including biological, chemical, and physical methods, suffer from drawbacks such as low efficiency, high costs, and potential secondary pollution. In contrast, modern technologies like UV photolysis purification and plasma - based approaches exhibit distinct advantages in terms of efficiency, cost - effectiveness, and environmental friendliness. Low - temperature plasma technology, as an emerging environmental deodorization method, can efficiently decompose a wide range of malodorous gases, such as NH_3, H_2S, and VOCs, by generating high - energy active particles through gas ionization. Under specific conditions, its removal efficiency can exceed 95%, with a minimal risk of secondary pollution. This paper systematically reviews the principles, application status, optimization directions, and future challenges of this technology, offering novel perspectives for environmental governance.

Keywords: low-temperature plasma, malodorous gases, removal technology, environmental protection, public health

1. Introduction

1.1 Problem Introduction

The emission of malodorous gases not only deteriorates air quality but also has the potential to induce respiratory ailments and exacerbate psychological stress, thus posing a significant threat to human health. Traditional removal methods, such as biological, chemical, and physical processes, have numerous limitations. Consequently, there is an urgent demand for a novel, efficient, cost - effective, and environmentally friendly technology. Low - temperature plasma technology has gradually emerged as a research hotspot due to its high energy density and broad applicability. This paper aims to review the application status of low - temperature plasma technology in malodorous gas removal, analyze its advantages and challenges, and propose future research directions.

1.2 Significance of the Problem

The issue of malodorous gas pollution holds great significance. With the continuous development of industry and the expansion of urban areas, the emission of malodorous gases is on the rise, seriously affecting the living environment and the quality of life of residents. Resolving this problem can enhance air quality, safeguard the ecological balance, and protect public health. Low - temperature plasma technology has unique advantages in malodorous gas treatment but also faces certain challenges. Therefore, further research on this technology is crucial for promoting its widespread application and effectively addressing the problem of malodorous gas pollution.

1.3 Review of Relevant Scholarship

Previous studies have explored various methods for treating malodorous gases. Traditional methods, although widely used, have limitations. In recent years, low - temperature plasma technology has attracted increasing attention. Some studies have concentrated on its reaction mechanisms, while others have probed into its applications in different scenarios. However, there are still many aspects that require further investigation, such as improving the energy efficiency and stability of the technology and exploring new composite treatment methods.

1.4 Hypotheses and Research Design

This paper hypothesizes that by optimizing the design of the plasma generator and integrating it with other technologies, the treatment efficiency of low - temperature plasma technology for malodorous gases can be significantly enhanced, and its energy consumption can be reduced. The research design encompasses reviewing relevant literature, analyzing experimental data, and discussing the application status and challenges of the technology. Through these efforts, theoretical support and practical suggestions can be provided for the development and improvement of low - temperature plasma technology in malodorous gas treatment.

2. Current Situation of Malodorous Gas Treatment

2.1 Sources and Hazards of Malodorous Gases

Malodorous gases have diverse sources, mainly including industrial production, domestic sewage and waste treatment, and agricultural activities. In industrial production, sectors such as chemical engineering, pharmaceuticals, papermaking, printing and dyeing, and food processing are major emitters of malodorous gases. For instance, in chemical manufacturing, chemical reactions release malodorous substances like hydrogen sulfide, ammonia, and thiols. During pharmaceutical production, the decomposition and synthesis of raw materials also release pungent odors. The problems associated with domestic sewage and waste treatment cannot be overlooked. The decomposition of organic matter in sewage emits unpleasant odors, and waste releases a large quantity of malodorous gases during landfilling and incineration.

Malodorous gases have substantial harmful impacts on both the environment and human health. Environmentally, they not only severely degrade air quality and reduce people's living comfort but also participate in atmospheric chemical reactions, forming secondary pollutants such as acid rain and smog, and severely disrupting the ecological balance.

Table 1. An analysis of the types and characteristics of common malodorous gases

Malodorous Gas Type	Main Components	Sources	Odor Threshold (ppb)	Health Effects
Hydrogen Sulfide	H_2S	Sewage treatment, chemical plants	0.5	Irritates the respiratory tract, causes headaches and nausea
Ammonia	NH_3	Agriculture, fertilizer production	5	Irritates the eyes, throat, and lungs
Volatile Organic Compounds	Multiple organic compounds	Paints, cleaners, solvents	10 - 100	Causes headaches, dizziness, and damage to the nervous system
Chlorine	Cl_2	Disinfectants, chemical products	0.5	Irritates the respiratory tract, causes pulmonary edema
Nitrogen Oxides	NO_x	Transportation, industrial emissions	0.5	Causes respiratory diseases and cardiovascular problems

2.2 Traditional Malodorous Gas Treatment Methods

There are several traditional malodorous gas treatment methods, such as adsorption, absorption, combustion, and biological methods. The adsorption method utilizes the adsorption capacity of adsorbents to transfer malodorous substances from the gas phase to the solid phase. The absorption method is divided into water absorption and liquid absorption. The former takes advantage of the property that some substances in malodorous gases are readily soluble in water, allowing the malodorous gas components to directly contact and dissolve in water to achieve deodorization. The latter uses the property that some substances in malodorous gases react chemically with the liquid reagent to remove certain malodorous gas components. The combustion method involves fully mixing malodorous substances with fuel gas at high temperatures and burning them. Biological methods include biofilters and biotrickling filters. After pretreatment, malodorous gases are decomposed by the metabolic activities of microorganisms attached to the filter media. Rybarczyk et al. comprehensively reviewed the treatment of malodorous air in biotrickling filters and emphasized the importance of these systems in purifying air contaminated with sulfur and nitrogen compounds, as evidenced by recent studies. Although traditional methods have applications in the field of malodorous gas treatment, they generally have certain limitations.

3. Plasma Technology Basics

3.1 Basic Principles

Low - temperature plasma technology generates plasma from gases at low temperatures. Its essence lies in ionizing gas molecules through an electric field or other excitation means, generating a variety of reactants, including charged particles, free radicals, and neutral particles. These active substances possess high reactivity and can effectively react with harmful components in malodorous gases to achieve removal.

In low - temperature plasma, when gas molecules are excited, some molecules lose electrons to form positive ions, while others gain electrons to form negative ions. This process can be represented by the following reaction formula:

$$M + e^- \rightarrow M^* + e^-$$

Here, M represents gas molecules, e^- is an electron, and M^* is an excited - state molecule. Excited - state molecules will further break down during mutual collisions to generate free radicals and other reactants, which can effectively react with organic components in malodorous gases and convert them into harmless substances.

3.1.1 Reaction Principles between Low - Temperature Plasma and Malodorous Gases

Free radical reaction: The generated hydroxyl radical (·OH) is a highly reactive oxygen species that exists widely in the atmosphere, water bodies, and living organisms. It exhibits strong oxidizing properties and can react oxidatively with most organic substances non - selectively, decomposing them into harmless carbon dioxide (CO_2), water (H_2O), and other inorganic substances. This property endows hydroxyl radicals with broad application prospects in environmental governance. For example, for the common malodorous gas hydrogen sulfide (H_2S), hydroxyl radicals can rapidly react with it to oxidize it into sulfur dioxide (SO_2), water, and other substances.

Electron collision reaction: High - energy electrons have sufficient energy. When they collide with malodorous gas molecules, they can cause the gas molecules to be excited, dissociated, or ionized. For example, for malodorous gases in volatile organic compounds (VOCs), when they encounter collisions with high - energy electrons, their molecular structures are damaged and decomposed into smaller fragment ions and free radicals. These fragment ions and free radicals further react and are ultimately converted into harmless or less harmful substances such as carbon dioxide and water.

Oxidation reaction: Active oxygen species in plasma (such as ozone O_3) have strong oxidizing properties and can react oxidatively with malodorous gases. Taking methanethiol (CH_3SH) as an example, ozone can gradually oxidize it and finally decompose it into harmless small - molecule substances.

3.2 Principles of Plasma Air Purification

3.2.1 Generation of Low - Temperature Plasma

Low - temperature plasma refers to plasma generated at low temperatures. It is mainly formed by ionizing gas molecules to form a mixture of charged particles and free radicals. Common generation methods include dielectric barrier discharge and microwave excitation. These methods can generate high - energy plasma at room temperature, effectively promoting the efficient decomposition of malodorous gases.

3.2.2 Action Mechanism of Plasma on Malodorous Gases

High - energy electrons, free radicals, and other active particles within the plasma have extremely high reactivity and can effectively collide with malodorous gas molecules, promoting the degradation of gas molecules. For example, high - energy electrons can excite gas molecules, causing them to decompose into free radicals, and these free radicals further react with malodorous gas molecules to generate harmless products.

3.3 Structure and Working Principle of Plasma Air Purifiers

Plasma air purifiers mainly consist of electrodes, a discharge area, and a gas flow system. The plasma purifier generates high - energy plasma by ionizing gas molecules and uses high - energy electrons, free radicals, and other active particles to act on pollutants, causing pollutant molecules to decompose in a very short time, thereby achieving efficient degradation of malodorous gases.

The working process of a plasma air purifier typically involves the following steps:

a. Gas introduction: The malodorous gas to be treated enters the purifier through the air inlet.

b. Ionization process: A high voltage is applied between the electrodes to ionize gas molecules and generate plasma.

c. Degradation reaction: High - energy particles in the plasma collide with malodorous gas molecules, triggering chemical reactions and decomposing them into harmless substances such as carbon dioxide and water.

d. Product discharge: The degraded gas is discharged through the air outlet to complete the purification process.

3.4 Factors Affecting Plasma Purification Efficiency

The purification efficiency of plasma is influenced by numerous factors, which can be summarized into aspects such as gas composition, plasma parameters, reaction conditions, and system design.

Gas composition: Different malodorous gases have distinct chemical properties and reaction activities. Gases such as hydrogen sulfide (H_2S) and ammonia (NH_3) exhibit high reaction activities in low - temperature plasma, while some volatile organic substances (VOCs) may react more slowly.

Plasma parameters: These include power, frequency, and gas flow rate. Increasing the power can increase the energy density of the plasma, generate more active species, and improve the removal efficiency. However, overly high power will waste energy and damage the equipment, so it is necessary to balance efficiency and economy.

Reaction conditions: Factors such as temperature and pressure also affect the removal efficiency. Appropriate control of temperature and pressure can significantly increase the reaction rate and enhance the removal effect.

System design: The structure of the reactor, the gas flow pattern, and the distribution of the plasma all impact the uniformity and efficiency of the reaction. Through rational design, the contact area between the gas and the plasma can be increased, effectively improving the reaction rate.

Plasma air purifiers can efficiently degrade malodorous gases by generating high - energy active particles, featuring fast speed, high efficiency, and no secondary pollution. However, their performance is affected by many factors, and it is necessary to optimize the operating conditions.

4. Application Examples

4.1 Industrial Waste Gas Treatment

4.1.1 Chemical Waste Gas Treatment

Plasma air purifiers perform commendably in the treatment of chemical waste gases. For example, in an industrial park, a research team employed low - temperature plasma technology to remove volatile organic compounds (VOCs) and ammonia. This technology generates high - energy electrons through a high - voltage electric field, breaking the molecular bonds of pollutants and achieving the elimination of gaseous pollutants. Experimental results show that after treatment with low - temperature plasma, the removal rate of ammonia reached over 90%, and the removal rate of VOCs also exceeded 85%. Due to its high removal efficiency and low operating cost, low - temperature plasma technology is widely applied in VOCs removal processes.

4.1.2 Treatment of Sulfur - Containing Malodorous Gases

Plasma air purifiers also demonstrate effective treatment outcomes for sulfur-containing malodorous gases, such as hydrogen sulfide. In the application at a sewage treatment plant, the removal rate of hydrogen sulfide reached as high as 96.67%, significantly alleviating the odor issue during sewage treatment.

4.2 Urban Sewage Treatment Plants

Plasma air purifiers are extensively used in the malodorous gas treatment of urban sewage treatment plants. For example, in a sewage treatment plant, after using low - temperature plasma technology, the removal rates of ammonia and volatile organic compounds reached 90% and 85% respectively. This data is consistent with the application effect of low - temperature plasma technology in the treatment of volatile organic compounds (VOCs) and ammonia in the field of environmental protection governance.

4.3 Other Applications

In landfills and transfer stations, plasma air purifiers are utilized to remove malodorous gases such as methanethiol. According to research on the purification of organic malodorous gases by plasma, the removal rate of methanethiol reached 95%, significantly reducing the odor around landfills.

The application of plasma air purifiers in indoor environments (such as homes and offices) has also yielded favorable results. Research indicates that this technology can effectively remove volatile organic compounds such as formaldehyde and benzene, improving indoor air quality.

The application prospects of plasma air purifiers in medical settings (such as hospital operating rooms) and public transportation (such as subway carriages and buses) are extremely broad. For example, in a hospital operating room, a plasma air purifier can effectively remove bacteria and viruses in the air, reducing the risk of infection.

Plasma air purifiers exhibit good malodorous gas degradation capabilities in various scenarios. However, their practical applications still face challenges such as equipment costs, energy consumption, and secondary pollution, and it is necessary to further optimize the technical solutions.

5. Discussion

5.1 Advantages and Limitations of Plasma Air Purifiers

Compared with traditional air purification technologies (such as biological, chemical, and physical methods), plasma air purifiers offer the following advantages: high efficiency, capable of efficiently degrading a diverse range of malodorous gases in a short time; environmental friendliness, without generating secondary pollution during the treatment process; wide applicability, suitable for various types of malodorous gases. However, plasma air purifiers also have some limitations: high equipment costs, high energy consumption, and complex technical operations. The high initial investment cost restricts the application of plasma air purifiers in some small enterprises or locations. Plasma air purifiers consume a large amount of electricity during operation, and their operation and maintenance require professional technical personnel.

5.2 Future Research Directions

Future research can focus on the following aspects:

Improving energy efficiency and stability: By optimizing the design of the plasma generator, employing advanced materials and structures, it is anticipated to significantly enhance its energy conversion efficiency. This measure can not only reduce energy consumption but also strengthen the stability of the technology in practical applications. For example, numerical simulation methods can be used to accurately analyze parameters such as the internal electric field and air flow of the generator, and targeted design improvements can be made based on this to achieve a dual improvement in energy efficiency and stability.

Exploring new composite technologies: Combining other mature technologies such as biological and chemical methods to construct composite treatment schemes is an effective approach to improve pollutant removal efficiency. The synergistic effect of different technologies can fully exploit their respective advantages and compensate for the deficiencies of single technologies. For example, integrating low - temperature plasma technology with biological degradation technology, using plasma to pretreat pollutants to enhance their biodegradability, and then further decomposing them through microorganisms, is expected to greatly improve the removal effect of complex pollutants.

Strengthening ecotoxicological research: There is an urgent need to strengthen the ecotoxicological research on the degradation products of low - temperature plasma technology. Thoroughly evaluating the potential impacts of degradation products on various components of the ecosystem and establishing a comprehensive risk assessment system are crucial for ensuring the safety of this technology in the treatment of indoor pollutants. Simulated ecological environment experiments can be carried out to monitor the migration and transformation laws of degradation products in different media and their toxic effects on organisms, providing a scientific basis for the safe application of the technology.

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