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Study of Graphene Oxide/Polymer Composite Membranes in Air Filtration of PM2.5

Yang Zhang

Faculty of Civil Engineering, Central South University, Changsha, Hunan, 410083, China

8406210214@csu.edu.cn

Abstract

pollution, particularly the issue of fine particulate matter (PM2.5), which has emerged as a significant environmental and public health concern globally. It is particularly important to develop efficient, economical and sustainable air filtration materials to reduce the concentration of PM2.5. In this study, we investigated the potential application of some polymers such as polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN) and polyaniline (PANI) composites with graphene oxide (GO) for efficient PM2.5 filtration. These composites were found to have excellent filtration performance, thermal stability. PVDF/ GO/PI nanofiber membranes maintained stable performance under repetitive filtration cycles and high temperature conditions. PAN/GO/PI nanofiber membranes exhibited good mechanical properties and stable cycling performance.PANI/GO composites took advantage of the unique properties of the conductive polymers, and in TGA experiments, they showed minimal mass loss. Their durability and efficiency remain high even after multiple wash cycles, highlighting their potential for practical applications.

Keywords

Graphene; Air Filtration; Composite Membranes; Polymers.

1. Introduction

Particulate matter (PM) air pollution is a significant global issue that endangers human health[1, 2]. PM2.5 submicron particles are especially dangerous as they can infiltrate the lungs and migrate to other organs, leading to increased risks of heart and respiratory diseases[3]. For example, asthma. and heart failure and lung cancer etc. [4-6]. The adverse effects of particulate matter on human health are making environmental problems increasingly severe. There is a pressing need for effective methods to remove PM. Notably, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) have demonstrated that GO membranes successfully capture PM2.5. The fabrication process of GO membranes is straightforward and environmentally friendly, offering a novel approach to combat air pollution[7].

Graphene, a novel material, consists of a two-dimensional crystal structure composed solely of carbon atoms, each layer just one atom thick, which is characterized by a large theoretical specific surface area, good thermal/chemical stability, and high mechanical strength. These excellent mechanical properties make graphene able to withstand higher pressure differences and harsher working environments in the field of air filtration. Graphene oxide, a derivative of graphene, is characterized by the same excellent mechanical properties as graphene, and also due to its screening properties, graphene oxide can effectively separate precipitates, suspensions, and other small particles, and secondly, graphene (including graphene oxide) has an extremely large specific surface area, which enables it to provide numerous adsorption sites, which enhances the adsorption of airborne pollutants. Graphene oxide contains hydroxyl and carboxyl groups on its surface, which further enhance its adsorption performance. In addition, the graphene oxide exhibits a two-dimensional surface chemical structure and sharp physical edge structure, which enable it to destroy the cell membrane structure of bacteria, thus killing them. This antimicrobial property is particularly important in the field of air filtration, especially in places where high cleanliness air is required.[8]

Focusing on the application of air filtration, some exploratory research work has been carried out both at home and abroad, i.e., filtration of adsorption through the fabrication of nanofiber membranes is a simple, direct and efficient way. And among the various fabrication techniques, electrostatic spinning is a simple technique capable of producing nanofibers continuously, which involves a low-cost equipment .[9] Electrostatic spinning can produce nanofiber membranes with precise porosity and morphology, a high specific surface area, and robust mechanical properties.[10-12] Electrospun nanofibers not only exhibit strong adsorption effects on PM but also maintain a robust interaction with the substrate. As a result, the nanofiber layer remains intact when dust is removed from the filter material's surface[13-15]. A variety of different polymers have been used to fabricate nanofiber membranes as air filters using electrostatically spun fibers, consisting of polyurethane[16] , polyacrylonitrile [17, 18]， polyaniline and polyvinylidene fluoride [19, 20] .

Therefore, this paper focuses on these composite membranes formed by the combination of different polymers and graphene oxide fabricated by electrostatic spinning technology, analyzes the characteristics and shortcomings of these nanofibrous membranes by reviewing the latest research results, and explores the value of their practical application in air pollution prevention and control. It is expected that this study will illustrate new ideas and methods for solving air pollution problems, promote the progress of air filtration technology, and ultimately realize the goals of improving air quality and protecting human health and the environment.

2. Discussion

2.1. Polyvinylidene Fluoride/GO Composite PM2.5 Filtration

Polyvinylidene fluoride (PVDF) is readily incorporated into composite filters due to its hydrophobic nature, affordability, and exceptional chemical stability. This integration enhances the hydrophobicity of the composite filters and prolongs their lifespan.[21, 22] Among these, PVDF stands out for its affordability and outstanding chemical stability[23]. Moreover, the polarity of PVDF enhances the interaction between PM and nanofibers, thereby boosting PM capture efficiency[24]. Yet, PVDF-based membranes encounter challenges like low mechanical strength and inadequate thermal stability, restricting their application[25].

Therefore, Chen et al. prepared air filtration membranes by doping polyimide and graphene oxide into PVDF nanofibers. These PVDF/GO/PI composite nanofiber membranes are lightweight with good permeability. Moreover, the PVDF/GO/PI nanofiber membranes exhibit high filtration efficiency (99.6%), low pressure drop (123 Pa), excellent mechanical properties (7 MPa), and exceptional thermal stability (450°C), as confirmed by thermogravimetric spectroscopy experiments. Additionally, the PVDF/GO/PI nanofiber membrane maintained an outstanding removal efficiency of 99.1% after heat treatment at 450°C for 1 hour. The composite membrane also demonstrated excellent mechanical and cycling durability, maintaining a filtration efficiency of 99.1% in repeated filtration experiments. In summary, the incorporation of GO and PI into PVDF not only enhances its mechanical strength but also improves the interaction between PM2.5 and nanofibers due to PVDF's polarity. The resulting PVDF/GO/PI nanofiber membrane exhibits excellent comprehensive performance and presents a promising new material for various applications.[26].

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2.2. Polyacrylonitrile/GO Composite PM2.5 Filtration

Polyacrylonitrile, with the chemical formula$(C_3H_3N)_n$, is a polymer compound consisting of the monomer Acrylonitrile It is obtained by free radical polymerization reaction. The acrylonitrile units in the macromolecular chain are connected in a joint-tail fashion[27].

In the field of air filtration, Zhang et al. incorporated reduced graphene oxide (rGO) nanosheets into electrospun PAN nanofiber membranes (NFMs) to improve the surface activity and permeability of composite NFMs. They demonstrated that rGO NSs dispersed in PAN NFMs significantly increased the capture sites on uncrosslinked PM2.5 nanofibers through hydrogen bonding and dipole-dipole interactions.[28]

Therefore, Dai et al. prepared NFMs by adding polyimide and graphene oxide to a solution containing PAN. Compared to filtration materials based on commercial filters and pure PAN nanofibers, the PAN/GO/PI nanofiber membranes showed an increase in filtration efficiency by 11% and 3.7%, respectively, and a reduction in pressure drop by 79.8% and 37.4%. This demonstrates both high filtration efficiency and low pressure drop. Additionally, after heat treatment at 300°C, the PAN/GO/PI nanofiber membrane maintained an excellent removal efficiency of 99.2%. The mechanical properties remained stable even under high stress conditions[29] .To summarize, PAN/GO/PI nanofiber membranes are highly effective for capturing PM2.5, demonstrating exceptional overall performance.

2.3. Polyaniline/GO Composite PM2.5 Filtration

As a conductive polymer, polyaniline (PANI) demonstrates great potential for application in air filtration due to its excellent physicochemical properties and environmental friendliness. Polyaniline has unique redox properties, good chemical stability and high mechanical strength, which make it excellent in capturing and decomposing harmful particles in the air. In addition, polyaniline can be synthesized simply and inexpensively, which makes it suitable for large-scale production.[30, 31] And the pore size can be controlled by acid treatment to get rid of penetration of small particles.[32]

Charlotte et al. incorporated graphene oxide into a hybrid GO/PANi composite filter with polyaniline to assess its durability. They found the filter achieved a filtration efficiency of 99.7% ± 0.08% and maintained high efficiency after 10 wash cycles. Thermal stability was evaluated via TGA experiments on filters with virgin PANi and GO/PANi compositions, revealing the hybrid GO/PANi filter exhibited minimal mass loss, indicating suitability for high-temperature environments. The study on pressure drop versus filtration efficiency highlighted that while electrostatic precipitation led to higher pressure drops compared to physical filtration, hybrid GO/PANI filters, being electrically conductive, show promise for electrostatic applications with voltage application potential[20] .

Ultimately, hybrid composite GO/PANi filters demonstrate significant potential and practical value for manufacturing and deployment across diverse locations. i.e., high efficiencies can be realized without increasing maintenance costs and power.

3. Conclusion

This paper systematically evaluates the potential of polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), and polyaniline (PANI) composites with graphene oxide (GO) for high-efficiency PM2.5 filtration. The following conclusions are drawn from a comparative analysis of the comprehensive performance of different composite nanofiber membranes:

(1) PVDF/GO/PI Nanofiber Membrane: Demonstrated excellent filtration efficiency (99.6%), low pressure drop (123 Pa) and excellent thermal stability (450°C). Not only did this membrane show high efficiency in capturing PM2.5 particles under laboratory conditions, it also

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maintained stable performance after repeated filtration experiments and high-temperature treatments.

(2) PAN/GO/PI Nanofiber Membrane: Compared with traditional PAN nanofiber membrane, it shows 11% higher filtration efficiency and significantly lower pressure drop (79.8%). It maintains high PM2.5 removal efficiency (99.2%) at high temperatures, showing good mechanical properties and stable recycling characteristics.

(3) PANI/GO composites: As a kind of conductive polymer, the hybrid composite of PANI and GO not only exhibits efficient PM2.5 filtration capability under the influence of electrostatic precipitation, but also possesses excellent thermal stability and long-term stable filtration efficiency (99.7%±0.08%), which suggests that it possesses significant application potential and economic benefits in practical applications.

In summary, these composites not only showed excellent performance under laboratory conditions, but also possessed a wide range of application prospects to effectively enhance air quality and safeguard public health. Future research should further optimize the preparation process and properties of these materials to promote their practical applications in industry and environmental protection.

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