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Application of Surface Super-wettability Materials in Oil/Water Separation

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Abstract: Oil-water separation has long been a critical issue in environmental protection. With industrial growth and the frequent occurrence of marine oil spills, oil-contaminated wastewater has caused severe pollution to aquatic environments, which not only results in irreversible damage to ecosystems but also leads to a significant waste of petroleum resources. Therefore, developing efficient oil-water separation materials has become a popular topic of research. This paper primarily analyzes the advantages and disadvantages of various oil-water separation materials that are based on hydrophilic and hydrophobic, focusing on their practical applications and limitations. Additionally, through the review, analysis, and synthesis of relevant academic literature and case studies, the paper compares the characteristics of filtration-based and adsorption-based separation materials. The conclusion drawn is that while current oil-water separation materials can perform well under specific conditions, they often fail to be fully effective in broader, real-world applications. Researchers need to continue exploring these materials, developing preparation methods that meet industrial production demands, and continuously evaluating and optimizing the materials for practical use.

Keywords: wettability, separation, filtration, adsorption, oil.

1. Introduction

With the advancement of industrialization and the occurrence of marine oil spills, oil-water separation has become a crucial factor in modern environmental protection. The pollution caused by oil-contaminated wastewater is increasingly severe, as this type of wastewater contains a large amount of toxic substances, such as hydrogen sulfide, toluene, and polycyclic aromatic hydrocarbons, which cause long-term damage to ecosystems, while the wastage of petroleum resources is also a significant concern [1]. While traditional treatment methods, including combustion, biodegradation, and electrocoagulation, are well-established, they often face challenges when dealing with complex oil-water mixtures, particularly in the separation of emulsified oils, which remains special difficulty [2]. Thus, the search for efficient, cost-effective, and recyclable oil-water separation materials has become a focal point of research. This paper centers on the study of super-wettability oil-water separation materials, specifically examining their performance under different separation mechanisms. By analyzing the characteristics of existing materials, conducting experimental validation, and summarizing application examples, the study highlights the differences in capability between filtration-based and adsorption-based materials. The research outcomes not only contribute to the

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optimization of separation material design but also provide theoretical and technical references for industrial oil-water separation. Moreover, this study holds significant social and environmental value, offering sustainable solutions for pollution control while guiding future researchers in the development of more innovative and practical oil-water separation materials.

2. Current Status and Trends in Oil-Water Separation Research

According to data from ISI Web of Science (Figure 1), the number of papers on oil-water separation has steadily increased from 1998 to 2016. The primary focus of these studies has been on surface super-wettability, such as super-hydrophobicity, super-hydrophilicity, and super-oleophobicity. These surface properties are crucial for enhancing the performance of oil-water separation materials, as they determine the selective adsorption of water and oil. In recent years, there has been a sharp rise in research and publications exploring efficient oil-water separation methods, underscoring the significance of this topic as a contemporary and cutting-edge area of study [3].

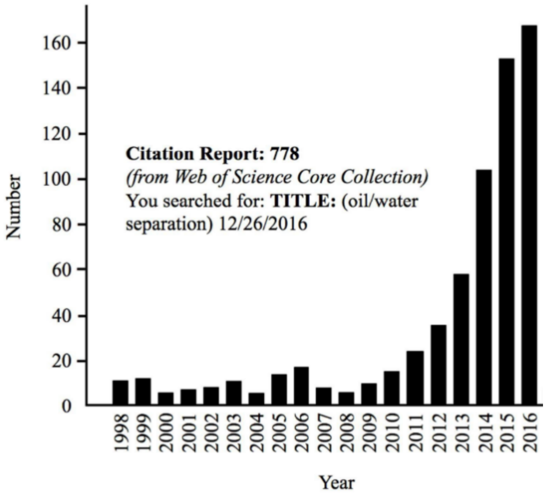

Figure 1: Numbers of oil-water separation related articles retrieved on ISI Web of Science with "oil/water separation" as title from 1998 to 2016.

3. Principles of Hydrophilicity and Hydrophobicity in Oil-Water Separation Materials

The key point of oil-water separation materials is the control of surface wettability, that is, through the different affinity of the material surface to water and oil to achieve separation [3]. The wettability of the surface of a material is mainly determined by its chemical composition and surface structure, and is usually described by the measure of water contact angle (WCA), as shown in Figure 2 [4]. To be specifically, when the contact angle of the droplets is greater than 10° and less than 90°, the surface of the material is considered hydrophilic; when the contact angle is greater than 90° and less than 150°, the surface is considered hydrophobic [5]. Further, super-hydrophilic or super-hydrophobic materials are more efficient for oil-water separation. They are the embodiment of more extreme hydrophilicity and hydrophobicity: super-hydrophilic surfaces have contact angles greater than 0° and less than 10°; and super-hydrophobic surfaces have contact angle greater than 150° and less than 180° [4]. What's more, in order to achieve efficient oil-water separation, researchers have developed super-hydrophilic - super-oleophobic materials that, after surface treatment, can almost completely repel oil and allow water to pass freely, thus achieving efficient oil-water separation [1].

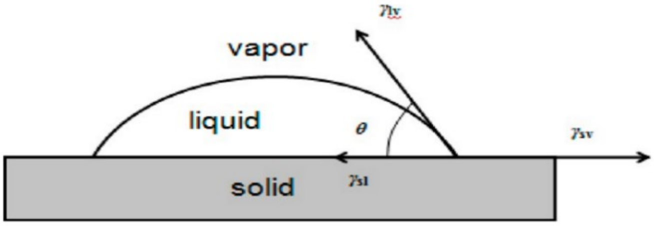

Figure 2: Contact angle θ between liquid and surface measured on a solid.

4. Filtration and Adsorption Oil-Water Separation Materials

Oil-water separation materials can be broadly classified into filtration and adsorption materials based on their wettability characteristics, each one has unique advantages and limitations [6]. Materials based on filtration - such as metal meshes, textiles, and polymer membranes - use the special wettability of their surfaces to allow only oil or water to pass through, enabling selective oil-water separation. Among these, metal meshes are considered ideal due to their excellent mechanical strength and high filtration flux; however, their high production cost and susceptibility to damage in corrosive environments hinder their widespread application [4]. In contrast, textiles and fabrics are also widely used by people because of their advantages such as lightness, low cost and renewable [7]. In particular, responsive-switchable wettability materials are able to adjust their wettability in response to changes in external conditions, allowing this material to still perform well in complex separation environments [4]. Additionally, polymer membranes have unique benefits in handling oil-water emulsions, particularly in separating tiny oil or water droplets. Nevertheless, the small pore size of these membranes makes them prone to fouling by oil, necessitating frequent cleaning or replacement [8].

On the other hand, Materials based on absorption - such as particle, powder adsorbents and three-dimensional porous structures - achieve separation through the selective adsorption of oil or water [6]. These materials have garnered significant attention for their high efficiency and ease of operation, especially in addressing oil spill incidents at sea. However, the limited adsorption capacity and high production cost of these materials present notable challenges in formal applications [9]. To address these issues, researchers have developed adsorbents with enhanced hydrophobicity and lipophilicity through surface modification, and they have explored the use of natural biomass or waste carbon materials to prepare low-cost three-dimensional porous adsorbents. It not only improves the mechanical strength of the materials, but also enhances their recyclability [10]. Thus, in practical applications, selecting suitable oil-water separation materials requires a comprehensive consideration of the materials' wettability characteristics, mechanical performance, cost-effectiveness, and adaptability to specific environments to obtain optimal separation outcomes [1].

5. Prospects and Applications of Oil-Water Separation Materials

The research on oil-water separation materials has shown great prospect and potential in the fields of industrial wastewater treatment, marine oil pollution cleaning and resource recovery, which has become one of the important tools of environmental protection [1]. First of all, in terms of wastewater treatment, these materials can effectively remove oils and hydrocarbons in wastewater through high-quality separation performance, significantly improving separation efficiency, and thereby reducing the negative impact on the environment of high-polluting industries such as mining, petrochemical, and metal processing [11]. Secondly, ocean oil cleanup is another key application area for oil-water separation materials. In the process of marine transportation and offshore oil extraction, oil spills pose a serious threat to marine ecosystems. The application of oil-water separation can effectively separate the leaking oil, not only prevent it from spreading and penetrating into the marine environment, but also reduce the harm to marine life [12]. Furthermore, these materials can not only cope with accidental oil spills, but also can be used in daily operations to separate oil and water, ensuring the long-term health of the marine environment [13]. In addition, oil-water separation technology also shows valid economic and environmental benefits in resource recovery and reuse. Through recycle by recovering valuable oil resources from wastewater, thereby reducing unnecessary waste [14].

6. The limitations and Challenges of Separating Materials

Despite significant progress in the research of oil-water separation materials, there are still many shortcomings and challenges when it comes to their practical applications. One of the most common barriers is that the preparation process for many of these materials are complex and costly, resulting in it being difficult to promote them a large-scale industrial use [3]. Additionally, the durability and practicality of oil-water separation materials are critical issues in current research. Many materials are easily damaged in actual applications, making it challenging for them to maintain stable performance over prolonged periods in complex working environments, which is particularly problematic when dealing with strong ocean waves and highly viscous oil spills, where the functionality of the materials may degrade rapidly [15]. Furthermore, the fabrication processes for super-hydrophilic and super-oleophobic materials require further optimization by researchers to ensure effective separation performance across various circumstances. Lastly, although the materials have demonstrated good selective oil-water separation performance under laboratory conditions, their effectiveness in real-world scenarios, such as handling multi-component mixtures or under mechanical disturbances, remains questionable [16].

7. Conclusion

This paper primarily explores the advantages, disadvantages, and applications of surface super-wettability materials used for oil-water separation. In short, the research on oil-water separation materials provides an innovative way to solve the problem of oil pollution. Despite many challenges, with the deepening of research and the development of new materials, oil-water separation materials have broad application prospects in industrial wastewater treatment, marine oil pollution cleanup and resource recovery. However, this paper does not provide an in-depth discussion and analysis of other oil–water separation materials, focusing solely on filtration and adsorptive materials. Moreover, this paper did not conduct actual experimental observations to obtain results but relied on theoretical analysis. Future research needs to not only continue to explore the basic mechanisms of these materials, but also to progress preparation methods that can meet the needs of industrial production, and to continuously evaluate and optimize the materials in practical application scenarios.

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