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Review on the Preparation and Performance of Humidity-Adaptive Atmospheric Water Collection Materials

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ABSTRACT

With the rapid development of the global economy and the continuous growth of population, the shortage of water resources has become increasingly prominent, posing a significant challenge to sustainable development. Particularly in arid and semi-arid regions, freshwater resources are extremely scarce. Therefore, the development of efficient water collection technologies is particularly important. Atmospheric Water Harvesting (AWH) technology, as an innovative method to extract water from the air, has received widespread attention in recent years. AWH technology can be divided into fog collection technology in high-humidity environments and adsorption-based atmospheric water collection technology in low-humidity environments. This review summarizes the latest research progress in humidity-adaptive atmospheric water collection materials, focusing on the research findings of Deng Kaimin in his master's thesis titled "Preparation and Properties of Humidity-Adaptive Atmospheric Water Collection Materials," as well as other related research advancements.

KEYWORDS

Fog Collection; Sorption-based Atmospheric Water Harvesting (SAWH); Sorption; Desorption.

1. FOG COLLECTION TECHNOLOGY IN HIGH-HUMIDITY ENVIRONMENTS

In high-humidity environments (relative humidity, RH ≥ 90%)[1-3], fog collection technology achieves efficient water resource collection by mimicking natural biological water collection mechanisms. Deng Kaimin prepared a three-dimensional superhydrophobic Cu-CuO structure in his research and experimentally explored its fog collection performance.

1.1. Preparation and Principle of Superhydrophobic Surfaces

Superhydrophobic surfaces refer to surfaces with a water contact angle greater than 150°[4-7]. Such surfaces exhibit self-cleaning, corrosion resistance, and anti-icing properties, showing great potential in fog collection. Deng Kaimin successfully prepared a three-dimensional superhydrophobic Cu-CuO structure through an oxidation method and low surface energy modification process[8,9]. This structure, with its interconnected porous structure and superhydrophobicity, can effectively capture and transport water droplets from fog.

The preparation of superhydrophobic surfaces typically involves two main methods: top-down and bottom-up approaches[10]. Top-down methods include lithography, etching, and laser processing, which can precisely control the microstructure of the surface. Bottom-up methods, on the other hand, introduce hydrophobic functional groups onto the material surface through chemical modification techniques[11], such as coating, chemical vapor deposition, and sol-gel methods. Deng Kaimin's research adopted a chemical corrosion and low surface energy modification process, which is an effective strategy combining top-down and bottom-up methods[12].

1.2. Factors Affecting Fog Collection Performance

Fog collection performance is influenced by various factors, including wettability, pore structure[13], thickness, and wind speed. Deng Kaimin's research showed that the fog collection efficiency of the superhydrophobic Cu-CuO structure was significantly higher than that of raw copper foam and superhydrophilic Cu-CuO structures. Additionally, the thickness and pore size of the structure also significantly affected fog collection performance. Increasing the thickness appropriately and selecting moderate pore sizes can improve fog collection efficiency.

In addition to the material properties, environmental factors such as wind speed also have an important impact on fog collection performance. In windy environments, the transport speed of fog increases, but it may also lead to splashing losses of water droplets. Therefore, optimizing material structures to reduce water droplet splashing is an important challenge faced by fog collection technology.

1.3. Biomimetic Fog Collection Materials

Inspired by natural biological water collection mechanisms, researchers have developed a series of biomimetic fog collection materials. For example, mimicking the fog collection surface of the Namib desert beetle, the conical asymmetric structure of cacti, and the humidity-sensitive surface of spider silk. These biomimetic materials achieve efficient fog capture and transport through finely designed microstructures.

2. ADSORPTION-BASED ATMOSPHERIC WATER COLLECTION TECHNOLOGY IN LOW-HUMIDITY ENVIRONMENTS

In low-humidity environments (e.g., RH = 45%), adsorption-based atmospheric water collection technology realizes effective water resource collection by capturing and storing moisture in the air using adsorbent materials. Deng Kaimin prepared SA-TA/Fe3+@LiCl aerogel in his research and deeply explored its hygroscopic properties and water collection mechanism[13].

2.1. Principle of Adsorption-Based Atmospheric Water Collection Technology

Adsorption-based atmospheric water collection technology utilizes the hygroscopicity and thermal desorption principle of adsorbents to capture and extract moisture from the air. Common adsorbents include silica gel, zeolite, metal-organic frameworks (MOFs), and chemical absorbents (such as lithium chloride and calcium chloride). These adsorbents effectively adsorb water vapor from the air through their surface active sites and release the water under heating conditions.

The SA-TA/Fe3+@LiCl aerogel prepared by Deng Kaimin combines the advantages of sodium alginate (SA), tannic acid (TA), and lithium chloride (LiCl). Through Fe3+ ion-induced crosslinking and blackening methods[14], a porous aerogel with high solar absorption was successfully prepared.

This aerogel exhibits excellent hygroscopic properties and rapid adsorption/desorption kinetics in low-humidity environments.

2.2. Factors Affecting Hygroscopic Properties

Hygroscopic properties are influenced by various factors such as adsorbent type, pore structure, pore size, and humidity conditions. Deng Kaimin's research showed that the hygroscopic properties of SA-TA/Fe3+@LiCl aerogel improved with increasing pore size, as larger pore sizes provide more unobstructed access channels for water molecules. Additionally, the solar absorption rate of the aerogel also significantly impacts its hygroscopic properties[15]. A high solar absorption rate can accelerate the heating process of the aerogel, thereby increasing the evaporation rate of water.

In addition to material properties, environmental factors such as temperature and humidity also significantly affect hygroscopic properties. In low-humidity environments, the hygroscopic capacity of adsorbents is limited; therefore, optimizing material structures and improving solar absorption rates are necessary to enhance water collection efficiency.

2.3. Solar-Driven Photothermal Conversion Materials

Solar-driven photothermal conversion materials play a crucial role in adsorption-based atmospheric water collection technology. These materials absorb sunlight and convert it into thermal energy, accelerating the evaporation process of water in adsorbents. Common photothermal conversion materials include carbon-based materials, plasma materials, biological materials, semiconductor materials, and organic polymer materials[16].

Although Deng Kaimin's research did not directly involve the preparation and application of photothermal conversion materials, the SA-TA/Fe3+@LiCl aerogel he prepared exhibits high solar absorption, making it a potential photothermal conversion material. By further optimizing material structures and improving solar absorption rates, the water collection efficiency of the aerogel can be further enhanced.

3. CHALLENGES AND PROSPECTS FOR HUMIDITY-ADAPTIVE ATMOSPHERIC WATER COLLECTION MATERIALS

Despite significant progress in humidity-adaptive atmospheric water collection technology, numerous challenges remain. The following aspects require attention in future research[17]:

3.1. Optimization of Material Properties

Future research should focus on further optimizing material properties such as hygroscopic performance, photothermal conversion performance, and mechanical properties. By adjusting the microstructure and chemical composition of materials, their water collection efficiency and stability can be improved. For example, developing aerogel materials with larger specific surface areas and higher porosities, as well as photothermal conversion materials with higher solar absorption rates.

3.2. Consideration of Environmental Factors

In practical applications, environmental factors such as temperature, humidity, wind speed, and light intensity can all affect atmospheric water collection performance. Therefore, future research should fully consider the impact of these factors on material properties and develop humidity-adaptive atmospheric water collection materials suitable for different environmental conditions.

3.3. System Integration and Optimization

The practical application of atmospheric water collection technology requires comprehensive consideration of materials, equipment, and system integration. Future research should aim to develop efficient, stable, and easy-to-operate atmospheric water collection systems and improve overall water collection efficiency through system integration and optimization. For example, combining fog collection technology with adsorption-based atmospheric water collection technology to achieve round-the-clock water resource collection.

3.4. Cost Control and Commercial Application

Currently, the cost of atmospheric water collection technology is relatively high, limiting its commercial application. Future research should focus on cost control and large-scale production, reducing production costs through technological innovation and process optimization, and promoting the commercial application of atmospheric water collection technology.

4. CONCLUSION

As an innovative water resource collection method, humidity-adaptive atmospheric water collection technology holds great potential in addressing the issue of water resource shortage. By mimicking natural biological water collection mechanisms and optimizing material properties, researchers have developed a series of efficient atmospheric water collection materials. Future research should further focus on optimizing material properties, considering environmental factors, system integration and optimization, as well as cost control and commercial application, to drive the continuous development and improvement of atmospheric water collection technology. The research findings of Deng Kaimin in his master's thesis provide important references and inspirations for the study of humidity-adaptive atmospheric water collection technology.

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