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Postprint: Photothermal Conversion Performance of PAM-PDA-PEG Modified Aerogels

Authors: Sun Zhiqiang, Zhou Jianhua, Miao Lei, Zhou Jianhua

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Abstract

Aerogels possess high porosity and low thermal conductivity, can absorb sunlight and convert it into thermal energy to heat liquid water, and are therefore widely applied in the field of solar-driven water evaporation, enabling efficient seawater desalination and wastewater treatment. To enhance the water evaporation rate of aerogels, polyacrylamide (PAM) with good water absorption properties was selected as the substrate, polydopamine (PDA) as the hydrophilic modification material, and polyethylene glycol (PEG) as the dispersant to prepare PAM-PDA-PEG (PG-PAM) modified aerogels via a freeze-drying method. The modified aerogels were characterized using scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), UV-vis-NIR spectrophotometry (UV-vis-NIR), water contact angle measurements, and Raman spectroscopy to analyze their microstructure, chemical composition, optical properties, hydrophilicity, and water state. Additionally, the photothermal conversion performance of PAM-PDA-PEG was evaluated using a simulated evaporation system. The results demonstrated that pure PAM exhibits weak photothermal conversion performance, whereas the modified PAM-PDA-PEG aerogels not only possess excellent light absorption and hydrophilicity but also contain abundant intermediate water, which can effectively reduce the energy required for evaporation. Testing revealed that PAM-PDA-PEG achieved an evaporation rate of 2.40 kg · m-2 · h-1 under a light intensity of 1 kW · m-2, which is five times that of pure PAM. Furthermore, desalination and dye removal experiments validated the practical application capability of PAM-PDA-PEG.

Full Text

Abstract

Photothermal aerogels with high porosity and low thermal conductivity can absorb sunlight and convert it into thermal energy for heating liquid water, making them widely applicable in solar-driven water evaporation for efficient desalination and wastewater treatment. To improve the water evaporation rate, we selected polyacrylamide (PAM) with excellent water absorption properties as the base material and prepared PAM-PDA-PEG (PG-PAM) modified aerogels via freeze-drying, using polydopamine (PDA) and polyethylene glycol (PEG) as hydrophilic modification agents. The microstructure, chemical composition, optical properties, hydrophilicity, and water state of the modified aerogels were characterized using scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), UV-vis-NIR spectrophotometry, water contact angle measurements, and Raman spectroscopy. The photothermal conversion performance was evaluated using a simulated evaporation system. Results demonstrate that PAM-PDA-PEG aerogels exhibit excellent light absorption and hydrophilicity while containing abundant intermediate water that effectively reduces the energy required for evaporation. Under illumination intensity of 2 kW m^{-2}, the evaporation rate reached 0.48 kg m^{-2} h^{-1}. Desalination and dye removal experiments confirmed the practical application potential of these modified aerogels.

Introduction

The rapid development of human society has led to accelerated consumption of Earth’s resources and increasingly severe environmental pollution, with water scarcity and contamination emerging as particularly critical issues affecting human survival and sustainable development. Conventional treatment methods, including physical adsorption, suffer from high equipment and operational costs as well as secondary pollution problems, which limit their large-scale deployment and fail to meet sustainability requirements. Solar steam technology, which utilizes solar energy to heat liquid water for rapid evaporation, enables seawater desalination and wastewater treatment through condensation to produce clean freshwater. Compared with traditional desalination and water treatment technologies, solar steam technology does not impose stringent material and equipment requirements and does not consume fossil fuels. Aerogels, possessing advantages of high porosity and low thermal conductivity, have become one of the most promising materials for efficient and stable solar-driven water evaporation. However, practical applications of aerogels are hindered by poor mechanical properties, complex synthesis processes, and stability issues. This study addresses these limitations by modifying polyacrylamide with polyethylene glycol and polydopamine to simultaneously enhance mechanical performance and hydrophilicity. The modified aerogels prepared via freeze-drying exhibit excellent channels for stable water transport to the evaporation interface, while the introduced hydrophilic groups provide strong hydration capacity and facilitate intermediate water formation, thereby effectively improving evaporation rates.

Experimental Methods

Materials and Preparation

The PAM-PDA-PEG modified aerogels were prepared through the following procedure: Tris(hydroxymethyl)aminomethane was dissolved in deionized water containing dopamine hydrochloride under stirring. Subsequently, PAM-PDA-PEG (PG-PAM) solution was added, followed by multi-walled carbon nanotube dispersion. N,N' -methylenebisacrylamide, ammonium persulfate, and sodium bisulfite were sequentially added to the mixture, which was then poured into molds and placed in a freeze-dryer to obtain the PAM-PDA-PEG modified aerogels.

Characterization

The surface morphology of the aerogels was examined by scanning electron microscopy (SEM). Chemical composition was analyzed using Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy. Optical properties were measured with a UV-Vis-NIR spectrophotometer. Hydrophilicity was assessed through water contact angle measurements. The ion concentration in evaporated water was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Photothermal Performance Testing

The experimental setup consisted of a water-filled container placed on an electronic balance and covered with polyethylene foam. A small hole in the foam center accommodated the aerogel sample, with its upper end exposed to light and lower end in contact with water. A xenon lamp served as the light source, while the balance was connected to a computer for real-time mass change recording. The experimental temperature was maintained at 25℃C$±1℃*andhumidityat*50±$2%.

Results and Discussion

Morphology and Microstructure

[FIGURE:N] The SEM characterization reveals that PAM-PDA-PEG aerogels possess a well-developed porous internal structure that ensures stable water transport. The addition of PEG facilitates uniform dispersion of acrylamide monomers in solution. During low-temperature freezing, ice crystals form and become encapsulated within the gradually polymerizing network. Subsequent vacuum drying leaves uniform pores throughout the polymer matrix, creating the characteristic aerogel structure.

Chemical Composition and Hydrophilicity

[FIGURE:N] FTIR spectra of both aerogel types confirm that polyacrylamide contains abundant amino and carbonyl groups. The peak at [wavenumber] cm^{-1} corresponds to the stretching vibration of [functional group], while the peak at [wavenumber] cm^{-1} arises from [functional group] stretching. PDA incorporation not only strengthens the amino peak but also introduces numerous hydrophilic groups. The peak at [wavenumber] cm^{-1} represents [group] stretching vibrations. The introduction of substantial hydrophilic groups enhances aerogel hydrophilicity, facilitates water transport, and promotes intermediate water formation.

[FIGURE:N] Water contact angle measurements provide direct visualization of hydrophilicity. The contact angle of [sample] is 36.33°, whereas PAM-PDA-PEG exhibits a contact angle of 12.59°, demonstrating significantly improved hydrophilicity and enhanced capillary action.

Optical Absorption Properties

[FIGURE:N] UV-vis-NIR absorption spectra demonstrate that [sample] shows relatively high transmittance and low actual absorbance. In contrast, PAM-PDA-PEG exhibits near-zero transmittance, and the incorporation of multi-walled carbon nanotubes effectively enhances light absorption throughout the spectrum.

Water State and Evaporation Enthalpy

[FIGURE:N] Raman spectroscopy was utilized to analyze water composition within the aerogels. The peaks at [wavenumber] cm^{-1} and [wavenumber] cm^{-1} correspond to free water with strong hydrogen bonding, while the peak at [wavenumber] cm^{-1} represents intermediate water with weak hydrogen bonds. By integrating and comparing the peak areas, the ratio of intermediate to free water in PAM-PDA-PEG was determined to be 1.37. The evaporation enthalpy was calculated using the formula $\Delta H =$ [formula], where [variables]. Due to the presence of abundant intermediate water that reduces evaporation energy requirements, PAM-PDA-PEG exhibits an evaporation enthalpy of [value] kJ kg^{-1}, which is lower than that of pure water.

Evaporation Performance

[FIGURE:N] The water evaporation performance was evaluated under various illumination intensities. The evaporation rate can be calculated from the slope of mass change curves. Under 2 kW m^{-2} illumination, PAM-PDA-PEG achieved an evaporation rate of 0.48 kg m^{-2} h^{-1}. The evaporation rate increases with light intensity, demonstrating the material' s responsive performance. Even at elevated intensities, the aerogel maintains stable evaporation rates due to its hydrophilic nature and intermediate water content.

Desalination Performance

[FIGURE:N] Desalination performance was tested using saline solutions of varying concentrations. The evaporation rate remains stable across different salinities, achieving [value] kg m^{-2} h^{-1} at 3.5 wt% NaCl concentration. The aerogel' s efficient water transport channels maintain stable supply to the evaporation surface even under high-salinity conditions. All ions were effectively removed during evaporation, with post-condensation water quality exceeding WHO safe drinking water standards. Calcium ion concentrations were reduced below detection limits, demonstrating excellent desalination capability.

Pollutant Removal Applications

[FIGURE:N] The purification capability was demonstrated using simulated organic pollutants. Methyl orange and rhodamine solutions with initial concentrations of [value] mg/L showed prominent absorption peaks before treatment. After evaporation, the condensed water exhibited near-zero absorbance, confirming effective pollutant removal. Additional outdoor experiments validated practical performance under natural conditions.

Outdoor Performance Validation

[FIGURE:N] Outdoor experiments were conducted to evaluate real-world applicability. The evaporation rate varied with natural light intensity fluctuations throughout the day, reaching a maximum of [value] kg m^{-2} h^{-1}. The average daily evaporation rate was [value] kg m^{-2} h^{-1}, confirming good practical performance. However, outdoor rates were somewhat lower than laboratory values, indicating that environmental stability requires further optimization.

Conclusion

This study successfully prepared PAM-PDA-PEG modified aerogels using a polyacrylamide substrate via freeze-drying. The aerogels exhibit regular porous structures ensuring stable water transport, excellent hydrophilicity with a contact angle of 12.59°, and abundant intermediate water that reduces evaporation enthalpy to [value] kJ kg^{-1}. Evaporation performance tests demonstrate stable rates of 0.48 kg m^{-2} h^{-1} under 2 kW m^{-2} illumination, with consistent performance across varying light intensities and salt concentrations. Post-evaporation water analysis confirmed effective ion removal and pollutant purification. While outdoor experiments validated practical applicability, the discrepancy between field and laboratory performance indicates that long-term environmental stability requires further investigation.

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