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Research on Thermal Energy Storage and Atmospheric Water Harvesting Based on Photothermal Hydrogels

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Abstract: With the growing global energy demand and increasing awareness of environmental protection, the development of sustainable and efficient energy storage and water resource acquisition technologies has become an important area of scientific research. Solar energy, as a clean and renewable energy source, has demonstrated huge potential in energy storage and atmospheric water harvesting through its photothermal utilization technology. Photothermal hydrogels, as a novel material, have attracted considerable attention in solar thermal energy storage and atmospheric water harvesting due to their unique light absorption, heat conduction, and moisture management capabilities. This review summarizes the research findings of Song Minyu in his master's thesis, "Applications of Photothermal Hydrogels in Thermal Energy Storage and Atmospheric Water Harvesting," and explores the applications and performance of photothermal hydrogels in these two fields.

Keywords: Hydrogel; Hydrated Salt; Solar Energy Utilization; Thermal Energy Storage; Atmospheric Water Harvesting.

1. Applications of Photothermal Hydrogels in Thermal Energy Storage

1.1. Preparation and Properties of Photothermal Hydrogels

Song Minyu's research has marked a groundbreaking contribution to the development of photothermal hydrogels, offering a novel approach to synthesizing shape-stable photothermal phase change hydrogels through in situ polymerization [1]. This method utilized acrylamide as the foundational polymer matrix, which is widely recognized for its hydrophilicity and mechanical flexibility. To enhance the structural integrity of the hydrogel, cellulose was introduced, which also facilitated the stability of the material under thermal cycling conditions. The incorporation of graphene oxide as the photothermal conversion agent was particularly noteworthy due to its exceptional light absorption properties across a wide spectral range, from ultraviolet to near-infrared. Additionally, sodium acetate trihydrate was employed as the phase change material (PCM) to ensure efficient thermal energy storage and release.

The advanced characterization of the fabricated hydrogel revealed several remarkable properties. The material exhibited superior light absorption capabilities, with a peak efficiency of 91.7%, attributed to the uniform dispersion of graphene oxide nanoparticles within the polymer matrix. The thermal conductivity of the hydrogel was significantly enhanced, owing to the formation of interconnected conductive pathways by graphene oxide, thereby facilitating rapid heat transfer. Furthermore, the three-dimensional polymer network provided excellent shape stability, ensuring that the PCM remained encapsulated and prevented leakage during phase transitions. Through meticulous optimization of the hydrated salt ratio, the hydrogel achieved an impressive energy storage density of 157.3 J/g, which represents a substantial improvement over conventional PCMs. These properties collectively position this photothermal hydrogel as a highly promising material for advanced thermal energy storage applications.

1.2. Thermal Energy Storage Performance

The thermal energy storage performance of these photothermal hydrogels demonstrates their significant potential for practical applications across various industries. One of the key challenges in traditional PCM systems is the phenomenon of supercooling, which was effectively mitigated in this study through the incorporation of cellulose. The cellulose fibers provided nucleation sites for crystallization, thereby reducing the temperature difference during exothermic phase transitions to a minimal range of 0.14-2°C. This improvement in thermal cycling stability was further supported by the robust three-dimensional hydrogel network, which prevented leakage of the hydrated salts during phase transitions while maintaining structural integrity over repeated cycles.

Thermal cycling tests conducted over 100 consecutive melting-solidification cycles revealed exceptional durability, with the material retaining more than 95% of its initial heat storage capacity [2]. The synergy between the hydrogel matrix and the functional components also optimized the rates of thermal storage and release. Specifically, the time required for complete phase transition was significantly reduced compared to traditional PCMs, enhancing the material's efficiency in practical applications. These advancements make the photothermal hydrogel an ideal candidate for use in solar energy storage systems, thermal regulation in buildings, and thermal management in high-performance electronic devices.

2. Applications of Photothermal Hydrogels in Atmospheric Water Harvesting

2.1. Preparation of Spongy Double-Network Hydrogels

Song Minyu's innovative approach to synthesizing spongy double-network hydrogels has opened new avenues for atmospheric water harvesting applications [3]. The fabrication process combined mechanical foaming with in situ polymerization, resulting in a scalable and cost-effective production method. The hydrogel's structural framework was composed of polyvinyl alcohol (PVA) and acrylamide (AM), which provided a balance of mechanical strength and flexibility. Lithium chloride was introduced as a hygroscopic agent due to its exceptional water absorption capacity, while graphene oxide served dual roles as both a photothermal material and a structural reinforcement agent.

The resulting hydrogel exhibited a hierarchical porous structure with interconnected macropores and mesopores, which significantly enhanced its water absorption kinetics and mechanical resilience. The porosity was carefully controlled during the foaming process to optimize both water absorption capacity and structural stability. The dual-network architecture, achieved through a combination of physical and chemical crosslinking, ensured that the material could withstand repeated expansion and contraction cycles during water absorption and desorption processes.

2.2. Atmospheric Water Harvesting Performance

The atmospheric water harvesting performance of these photothermal hydrogels underscores their potential for addressing water scarcity in diverse environmental conditions. The hydrogels demonstrated exceptional hygroscopic performance across a wide range of relative humidity levels (20-90%), with a peak absorption capacity of 3.507 g/g, significantly surpassing conventional desiccants [4]. Molecular dynamics simulations provided critical insights into the mechanisms of water transport, revealing that the presence of PVA chains created favorable pathways for water molecule diffusion, with diffusion coefficients up to 40% higher than in PVA-free systems.

Outdoor field tests conducted in various climatic conditions confirmed the material's robustness, with water collection efficiency exceeding 84% even under fluctuating temperature and humidity conditions. The photothermal properties of the hydrogel enabled efficient water release through solar-driven desorption, achieving a water release rate of up to 1.2 kg m^{-2} h^{-1} under natural sunlight. Importantly, the quality of the harvested water consistently met WHO drinking water standards, with ion concentrations well below regulatory limits. These characteristics make the hydrogels highly suitable for producing potable water in water-scarce regions, particularly in off-grid and remote applications.

3. Applications of Photothermal Hydrogels in Thermal Management of Electronic Devices

3.1. Development of Thermally Conductive Hydrogels

The increasing demand for efficient thermal management in high-performance electronic devices has driven the development of photothermal hydrogels with enhanced thermal conductivity. Recent advancements have focused on incorporating thermally conductive fillers, such as boron nitride nanosheets and carbon nanotubes, into the hydrogel matrix to create composites with superior heat dissipation properties . These fillers form interconnected networks within the hydrogel, facilitating rapid heat transfer while maintaining the material's flexibility and mechanical robustness. The integration of graphene oxide as a photothermal agent further enhances the material's ability to convert absorbed light into heat, making it suitable for applications in energy-intensive electronic systems.

3.2. Performance in Thermal Management

Photothermal hydrogels have demonstrated exceptional performance in managing heat generation in electronic devices. Their high thermal conductivity, combined with efficient light absorption and conversion, enables effective heat dissipation under operating conditions. Experimental studies have shown that these hydrogels can reduce the operating temperature of electronic components by up to 15°C, significantly improving device performance and longevity . Additionally, the hydrogel's shape stability and flexibility allow it to conform to complex device geometries, ensuring uniform heat distribution. The ability to operate under solar irradiation further enhances their suitability for use in portable and off-grid electronic systems, where efficient thermal management is critical.

4. Conclusions and Prospects

Song Minyu's research has established a solid foundation for the application of photothermal hydrogels in three critical areas: thermal energy storage, atmospheric water harvesting, and thermal management of electronic devices [5]. The systematic investigation highlights that through careful material selection and innovative structural design, photothermal hydrogels can achieve remarkable performance metrics. In thermal energy storage, these materials combine efficient photothermal conversion with stable thermal energy storage capabilities. In atmospheric water harvesting, they exhibit superior hygroscopic performance and water release efficiency. Additionally, their application in thermal management of electronic devices demonstrates their potential to address heat dissipation challenges in high-performance systems.

However, several challenges must be addressed to fully realize the potential of these materials. The energy storage density, currently at 157.3 J/g, requires further enhancement to compete with conventional energy storage systems. The durability of the hydrogels under extreme environmental conditions, such as high temperatures or prolonged UV exposure, also needs improvement [6]. Future research directions could focus on: (1) developing advanced composites incorporating novel phase change materials, nanostructured photothermal agents, and thermally conductive fillers; (2) optimizing hierarchical porous structures to enhance mass and heat transfer; (3) investigating surface modification techniques to improve environmental stability; and (4) exploring novel application scenarios in integrated energy-water-device systems. These advancements could significantly expand the utilization of photothermal hydrogels in renewable energy systems, sustainable water management, and next-generation electronics.

5. Current Research Significance

In the context of global challenges related to energy security, water scarcity, and the increasing demand for efficient thermal management in electronic devices, Song Minyu’s research on photothermal hydrogels holds profound practical significance [7]. As a multifunctional material, photothermal hydrogels offer innovative solutions to some of humanity’s most pressing problems. In the energy sector, they provide a sustainable approach to solar energy harvesting and storage, potentially revolutionizing thermal energy management systems in buildings, industrial processes, and power generation.

For water resource management, these materials present a promising technology for atmospheric water harvesting, particularly in arid regions where conventional water sources are scarce. The demonstrated ability to produce high-quality potable water from atmospheric humidity, combined with their solar-driven operation, makes them particularly valuable for off-grid and remote applications. In the realm of electronics, photothermal hydrogels address critical challenges in thermal management, enhancing the performance and durability of high-power devices and systems.

Moreover, the integration of energy storage, water harvesting, and thermal management capabilities in a single material platform represents a significant step toward developing multifunctional systems that address multiple sustainability challenges simultaneously. Continued research and technological innovation in this field could lead to the development of cost-effective, scalable solutions that contribute significantly to achieving global sustainability goals in energy, water, and technology. The potential impact of this technology extends beyond technical applications, as it could play a crucial role in improving quality of life, supporting economic development, and addressing environmental challenges in resource-constrained regions..

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