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論 文 内 容 要 旨

With the continuous growth of the population, water consumption has increased sharply, which directly leads to the lack of clean water. In addition, many industrial activities not only consume large amounts of local water resources but also cause serious water pollution, which further aggravates the shortage of water resources. To solve this problem, the technology of seawater desalination has attracted a lot of attention. Traditional seawater desalination includes burning fossil fuels to produce high-temperature evaporation of seawater and capturing steam to produce treated fresh water. This method can treat seawater efficiently and quickly, but on the one hand, it causes a lot of fossil energy consumption. On the other hand, burning fossil fuels will produce a lot of pollutants, which will cause immeasurable harm to the local ecological environment. Energy crisis, shortage of freshwater resources, and increasingly serious water pollution are the challenges facing the world today. Therefore, it is urgent to develop a new, efficient, clean, and pollution-free seawater desalination technology to solve the current water crisis.

In recent years, the technology of solar-driven water interfacial evaporation has developed rapidly. The technology of using solar energy to heat seawater or wastewater to obtain steam can develop eco-friendly and cost-effectively freshwater production, and meet the energy and environmental needs at the same time. On the one hand, it can be attributed to the use of clean and renewable solar energy, no consumption of other energy sources, and environmental protection. On the other hand, it doesn't need a lot of materials or equipment, which makes the cost of this technology relatively low. In recent years, to improve the energy utilization efficiency of solar steam power generation technology, researchers have made a lot of exploration and made great progress. However, in practice, some heat will be consumed by a large amount of heating water and will be lost to the container and the environment through conduction, convection, and radiation. Researchers solve these problems by optical performance adjustment of the light absorber, structure of evaporation device, thermal management, and combining bionic design strategies. At the same time, the researchers also found that in the application of solar seawater desalination, the energy is mainly consumed in the evaporation process, and it is converted into latent heat through the vapor phase change. This kind of latent heat energy is usually wasted in collecting the solar steam generated. To further improve the efficiency of energy utilization, researchers can achieve the goal of pure water-power cogeneration. Generally speaking, solar evaporation has good application prospects in seawater desalination, sewage treatment, synergistic freshwater-power generation, and so on.

Recently, polymer materials have been widely studied in this field. Polymer materials are a promising candidate material for constructing solar evaporators. They can be designed from the molecular level to the macro level to achieve the chemical and physical characteristics required by high-efficiency solar evaporators (for example, high solar absorption rate, fast water pumping, excellent heat insulation, and low density). Poly(N-phenylglycine) (PNPG) is a kind of conjugated polymer, with easily available raw materials, a simple synthesis process, and good chemical and environmental stability. At the same time, it has remarkable optical properties and the potential for light-to-heat conversion. Based on the construction and application of the PNPG-based solar evaporation systems, this dissertation discusses the design of suitable solar evaporators to improve the evaporation rate and energy utilization efficiency. Specifically, considering the inevitable heat loss in practical applications, we improve the thermal management of the evaporation device through a biomimetic structural design strategy to increase the evaporation rate and efficiency. We also try to benefit from latent heat to further improve energy efficiency to achieve the goal of pure water-power cogeneration. The results show that PNPG-based solar evaporation systems have made some progress in the application mentioned above.

In chapter 1, the research background, development of solar desalination, the design principle of the solar evaporators, the polymer-based solar evaporators, and their application are introduced. Furthermore, the research significance and the construction of this dissertation are described. In addition, we clarified some problems with existing solar evaporators. The objectives of the research are to study the PNPG-based solar evaporation systems and their applications.

In chapter 2, the properties of experimental materials, as well as the experimental methods and the characterizations are presented. The preparation and application of polymer PNPG are presented throughout each chapter. Molybdenum disulfide, initiator ammonium persulfate, organic dyes, and natural seawater are also used. In addition, the experiment for solar desalination was also introduced. The micromorphology, UV-vis-NIR spectrum, FT-IR spectra, contact angles, zeta potential, IR mappings, temperature distributions, and cation concentrations were individually characterized in the studies.

In chapter 3, inspired by the Amazon water lily, an interfacial water-trapped structure solar evaporator was developed to achieve a continuous supply of water from the water-trapped layer and three-dimensional heat distribution management. The artificial photothermal membrane with PNPG can be easily prepared by vacuum filtration. Then, combined with the three-dimensional heat distribution management design and the water-trapped layer for a continuous supply of water, more optimized energy utilization and efficient interface heating were realized. Besides, because the novel nanoscale PNPG has excellent light capture performance and the absorbed solar energy can be concentrated in the water-trapped layer, which makes the solar evaporation more effective, showing higher energy efficiency (93.5%) and higher evaporation rate (1.72 kg m^{-2} h^{-1}) under 1 sun. This special structure aims to minimize energy loss and better regulate the relationship between water evaporation, solar energy conversion, and heat regulation. This bionic solar evaporator can provide new ideas for designing the structure of high-efficiency solar evaporators and new opportunities for practical applications.

In chapter 4, inspired by the transpiration of trees, a PNPG-wood solar evaporator was developed to further explore the possibility of reducing the cost of the solar evaporator. Compared with PVDF membrane, the price of wood blocks purchased in supermarkets is more competitive. PNPG coating greatly makes up for the weak light absorption of wood, and effectively improves the solar heat conversion efficiency. In addition, thanks to the low thermal conductivity and special microstructure of the wood, the relationship between water transportation, solar energy conversion, and heat regulation was better regulated. As a result, the PNPG-wood system can effectively and quickly generate steam, and the evaporation rate and efficiency can reach 1.64 kg m^{-2} h^{-1} and 90.4% under 1 sun, which is higher than that of most reported wood-based solar evaporators. Therefore, this kind of solar evaporation system with reasonable design, low cost, durability, and high efficiency has the potential to be applied to solve the practical problem of seawater desalination and water purification.

In chapter 5, to optimize the efficiency and form of solar heat utilization, a synergistic photothermal layer was created from PNPG/MoS_2 nanohybrid by the electrostatic induced assembly for broad-spectrum and efficient solar absorption. The PNPG/MoS_2 system provides effective synergistic photothermal conversion and good water transmission, which enables solar steam to escape quickly. It is worth noting that the synergistic coupling of solar evaporation-thermoelectric (TE) power generation has also been realized, which provides more effective solar energy development. The system demonstrated a solar evaporation rate up to 1.70 kg m^{-2} h^{-1} and achieved a maximum thermoelectric output power of 0.23 W m^{-2} under 1 sun. The high-performance PNPG/MoS_2 synergistic photothermal system developed in this research provides potential opportunities for coupling solar water purification and thermoelectric power generation to meet the demand of resource-scarce areas.

In chapter 6, the general conclusions of this dissertation are made. Solar desalination technology is a low-cost, green, and pollution-free water purification technology, but it has not been popularized for a long time due to the low photothermal conversion efficiency and the output of freshwater per unit area. The introduction of solar light absorbers and interface heating technology has greatly improved its photothermal conversion efficiency. This dissertation focuses on high-efficiency solar steam generation, studies the construction of polymer-based solar evaporators, and effectively explores potential applications. All in all, the polymer-based solar evaporator we designed has made progress in the structure design, improving the evaporation rate and efficiency, and has been well applied in seawater desalination, sewage treatment, and water purification synergistic power generation.

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論文審査結果要旨

本論文は、ポリマー系光熱変換材料を用いて、高性能で低コストの太陽光界面蒸発システムを設計・構築し、安全な水を安定的に供給することを目的とし、エネルギー変換効率と蒸発速度に焦点を当て、光熱変換材料とシステムの構造の両面から水の浄化と海水淡水化を検討しており、全 6 章で構成されている。

第 1 章では、水の浄化と海水淡水化に関する既存の研究から本研究の背景を述べ、本研究の目的を示している。第 2 章では、光熱変換ポリマーベースの材料の合成方法およびそれらの微細構造と物理的・化学的特性の評価方法について説明している。第 3 章では、アマゾン睡蓮の構造を模倣した太陽光界面蒸発システムを設計し、構造の面から継続的な水の供給と効果的な熱管理ができたことを明らかにした。ポリマー系光熱変換材料としてポリ-N-フェニルグリシン（PNPG）を利用し、1.72 kg m^{-2} h^{-1} の蒸発速度と 93.5%のエネルギー変換効率を達成し、有機物汚染水の浄化および海水淡水化を実現した。第 4 章では、太陽光界面蒸発システムのコストパフォーマンスをさらに向上させるために、植物の蒸散にヒントを得て木材ベースの太陽光界面蒸発システムを開発した。木材は熱伝導率が低く、特殊な微細構造をもつため、水輸送および熱調節ができる。PNPG コーティングは、木材の低い太陽光吸収を大幅に改善し、太陽光から熱への変換効率を効果的に向上させることを明らかにした。木材ベースの太陽光界面蒸発システムでは、1.64 kg m^{-2} h^{-1} の蒸発速度と 90.4％のエネルギー変換効率が得られ、これまでに報告されているほとんどの木材ベースの太陽光蒸発器よりも高い値を示した。第 5 章では、水問題とエネルギー不足問題の両方に対応できるシステムについて検討した。PNPG と MoS_2 の表面電荷を利用しセルフアセンブリで PNPG/MoS_2 材料を作製した。エネルギー吸収特性と温度上昇幅に対して最適な混合比率を明らかにした。PNPG/MoS_2 界面蒸発システムは、高い蒸発速度（1.70 kg m^{-2} h^{-1}）とエネルギー変換効率（92.9％）を維持しつつ、余熱の利用を目指し、微小電気創生システムを加えており、110mV の開回路電圧、0.23Wm^{-2} の出力を達成した。第 6 章は結論であり、本研究を総括している。

本論文は学術的価値だけでなく、水の浄化と海水淡水化という実用的な問題を解決するという観点から、工学的にも多大な貢献をしている。また、研究業績として、査読付き国際学術論文 3 編と国内会議 1 件を公表している。

よって、本論文は博士（工学）の学位論文として合格と認める。