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Solar steam generation through bio-inspired interface heating of broadband-absorbing plasmonic membranes

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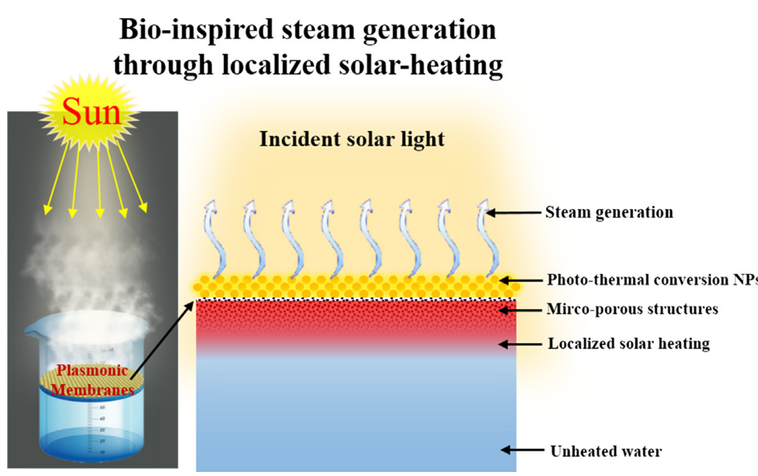
HIGHLIGHTS

- Bio-inspired solar steam generation using floating plasmonic membranes (PMs) proposed.
- High steam generation efficiency of 85% achieved at illumination power of 10 kW m^{-2}.
- PMs enhanced the productivity of a solar still for seawater desalination by ~80%.

GRAPHICAL ABSTRACT



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ABSTRACT

Efficient solar-enabled evaporation plays a critical role in solar power-based concentration systems, photochemical plants, seawater desalination technologies, etc. However, traditional processes for solar steam generation usually depend on high-temperature heating of the bulk liquid, which requires highly concentrated solar power and suffers from high energy and optical losses. Therefore, the enhancement of solar steam generation by bio-inspired interface solar heating is proposed in this work. In this study, easy-to-prepare, flexible, and reusable plasmonic membranes (PMs) were fabricated for realizing the bio-inspired interface solar heating and continuous steam transportation through the micropores of the membranes. A solar steam generation efficiency of ~85% was achieved at an illumination power of 10 kW m^{-2}. The effects of Au concentration in the membranes and optical power on the steam generation efficiency were systemically studied. The observed high evaporation rate and efficiency were attributed to three main factors: high (~90%) and broadband solar absorption, efficient photo-thermal conversion due to high plasmon dissipation losses, and fast capillary flow in the membrane micropores. Finally, the application of PMs in a single basin solar still system for seawater desalination was investigated and the PMs exhibited great performance on enhancing the productivity of clean water.

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1. Introduction

Solar energy is one of the most promising renewable energy sources because it is abundantly available and no pollutants are generated during its use [1–4]. Highly efficient steam generation is a key solar-energy application, e.g., for small-scale water purification [5], solar still [6], hygiene systems [7], large-scale solar-power concentrating systems [8], chemical plants [9], and desalination technologies [10]. Currently, solar steam generation systems are typically based on highly efficient solid surface absorbers that first collect solar energy and then transfer it to a bulk liquid or a thermal storage system [11–14]. Steam generation usually occurs because of the high temperature to which the bulk liquid gets heated [15]. However, complex artificial optical concentration systems are necessary to concentrate the solar light, and the use of these systems results in high energy and optical losses [16]. To enhance the evaporation process, multiple advanced technologies involving facility improvement, system optimization, thermal energy storage system, and development of highly efficient absorber materials have been studied.

Recently, nanofluids, i.e., fluid suspensions containing solid nanometre-sized particles (NPs), have been widely studied as potential direct-absorption solar energy collectors [17], owing to the strong coupling of NPs with light and their distinctive optical absorption properties, especially in the case of plasmonic metallic [18] and carbon-based [19] particles. The plasmonic NPs have the extraordinary capability to convert photo energy to thermal energy via localized plasmon resonance [20]. In real-time light-plasmon NP interactions, the photon–electron interaction is initially dominant, followed by the electron-lattice relaxation and, finally, heat dissipation to the environment [21]. Plasmonic NPs have a wide range of applications in sensing [22], photothermal therapy, and energy-harvesting [23]. Localized steam generation around plasmonic NPs can be achieved through irradiation of nanofluids with high-intensity light, typically using lasers [24]. Neumann et al. [25,26] demonstrated the use of Au-based nanofluids for direct steam generation and achieved device efficiencies of 24% at solar concentrations of 1000 suns (1 sun = 1 kW m^{-2}). Ni et al. [27] measured a steam generation efficiency of 69% at solar concentrations of 10 suns using graphitized carbon black, carbon black, and graphene suspended in water. Wang et al. [28] experimentally investigated the direct vapour generation performance of low-concentration carbon-nanotube nanofluids and realized an evaporation efficiency of 46.8%. In all of these applications using volumetric solar heating of nanofluids for steam generation, the bulk liquid temperature increased rapidly and reached a high temperature owing to the high light absorption of the dispersed NPs. Steam bubbles are usually generated around the NPs during steam generation using a nanofluid and these steam bubbles then move through the sub-cooled water to release. The movement of these steam bubbles in the sub-cooled water can result in heat losses via energy transfer to the bulk fluid, resulting in heating of the bulk liquid and reduction of the steam production. Notably, considerable heat dissipation losses from the hot solution to the surrounding environment are always observed, which is detrimental for steam generation.

Evaporation is also a vital function in many biological systems, such as the evaporation during sweating from human skin [29] and transpiration at leaf surfaces [30]. In human system, the maximum sweating rates for an adult can be up to 2–4 L/h. In the plant system, the transpiration in plants is a vital part in terrestrial hydrological cycle. There are two main factors affecting efficient water evaporation in biological systems: (1) localized heating and (2) capillary flow in porous structures, as shown in Fig. 1a. Inspired by these types of biological systems, a new strategy for enhancing the steam evaporation efficiency using floating porous materials capable of light-to-heat conversion at the air-water interface has been demonstrated [31]. In this bio-inspired solar steam generation method, the floating absorbers at the air-water interface collect sunlight and convert it to thermal energy, enabling surface heating at the interface and rapid evaporation while the bulk liquid temperature stays low. The heat and mass transfer processes in this system are illustrated in Fig. 1b for solar steam generation, where the only energy source is the solar irradiation and the effective utilization of energy is via evaporation. The heat losses include thermal radiation and convection losses from the absorbers to the surrounding environment, heat conduction losses to the sub-cooled water, and parasitic losses. Wang et al. [31] and Liu et al. [32] demonstrated fast and highly-efficient steam generation through localized plasmonic heating of gold NP (Au NP) films and air-laid paper-supported Au films, respectively. Bae et al. [33] fabricated black Au thin-film membranes that exhibited high plasmon dissipation losses, high flexibility, and ultra-broadband light absorption. They efficiently generated steam from water and achieved a solar thermal conversion efficiency of 57% at a light power of 20 kW m^{-2}. Zeng et al. [34] synthesized composite floating magnetic NPs (Fe_3O_4/C NPs with average diameter of 500 nm), and found that their application enhanced the evaporation rate by a factor of 2.3, compared with that of pure water. Ghasemi et al. [35] developed a porous volumetric receiver (double-layer structure consisting of an exfoliated graphite layer supported by hydrophilic carbon foam), and obtained a high solar thermal efficiency (~85%) at a solar illumination power of only 10 kW m^{-2}. Ni et al. [36] demonstrate a floating solar receiver capable of generating 100 °C steam under ambient air conditions without optical concentration using thermal concentration and heat localization. In 2017, Zhou et al. [37] prepared plasmonic absorbers with tunable broadband absorption and thermal stability through self-assembly. The spectrum selective plasmonic absorbers demonstrated excellent applicability for solar steam generation.

To date, only a few reports have been published regarding the enhancement of solar steam through bio-inspired interface heating, specifically using broadband-absorbing plasmonic membranes (PMs) [32,33,37]. In addition, most of these works focused on the material properties and complicated methods were required to fabricate the broadband absorber. The thermal and mass transfer mechanisms of bio-inspired solar steam generation should be further investigated. In this study, a facile and controllable method was developed for preparing porous, high-efficiency, and reusable plasmonic light-to-heat conversion membranes. The optical properties of PMs were optimised by varying the concentration of Au NPs on the PMs; the Au NPs are the main absorbers that interact with the solar light and realise the photo-thermal conversion. The experiments for determining the solar steam generation properties were implemented under simulated solar light irradiation. Firstly, the performance of different steam generation schemes including volumetric solar heating, bottom solar heating, and air-water interface solar heating were studied to demonstrate the advantages of the bio-inspired solar heating of PMs. Then, the effects of Au NP concentration, and optical power on the evaporation rate and efficiency were investigated systemically. As the basic design of the solar still used a water basin with black bottom to absorb the incoming solar flux, the radiative thermal losses from the hot water were high. Therefore, a solar still desalination experiment was conducted to demonstrate the potential of application of this method for such an application. This work advances the understanding of bio-inspired interface heating for solar steam generation based on PMs, which promises to be a low-cost technique with the potential application in a wide range of solar-energy-based technologies.