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Effective reduction of water molecules' interaction for efficient water evaporation in desalination

Hsiao-Chien Chen[a], Yi-Rui Chen[b], Kuang-Hsuan Yang[c], Chih-Ping Yang[a], Kuo-Lun Tung[b], Ming-Jer Lee[d], Jun-Han Shih[b], Yu-Chuan Liu[a,*]

[a] Department of Biochemistry and Molecular Cell Biology, School of Medicine, College of Medicine, Taipei Medical University, 250 Wuxing St., Taipei 11031, Taiwan
[b] Department of Chemical Engineering, National Taiwan University, 1 Roosevelt Rd., Sec. 4, Taipei 10617, Taiwan
[c] Department of Food and Beverage Management, Vanung University, 1 Van Nung Rd., Chungli City 320, Taiwan
[d] Department of Chemical Engineering, National Taiwan University of Science and Technology, 43 Keelung Rd., Sec. 4, Taipei 10607, Taiwan

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ABSTRACT

Water scarcity is one of the most serious global challenges of our time. One of the currently resolutions to this shortage is desalination. So far, most research on desalination has focused on preparing photothermal materials which possess the property of light-to-heat conversion. However, changing the intrinsic properties of water to improve the efficiency of solar evaporation has rarely been discussed. A new concept to increase the efficiency of desalination via destroying hydrogen bonds based on gold nanoparticles-adsorbed ceramic rods (AuNPs@CRs) is proposed here for the first time. Weakening the strength of interactions within water molecules by illumination with resonant light produces easily evaporable plasmon-activated water (PAW). This proposed system exhibits high efficiencies of steam generation in different experimental environments. Meanwhile, it was 140.0% and 107.5% more efficient than untreated water in an oven and an indoor environment, respectively. The source of resonant light from sunlight on a sunny or cloudy day can also achieve this performance. In addition, the results of water pump suction and direct contact membrane distillation (DCMD) further demonstrated that the illuminated AuNPs@CR system exhibits high potential for desalination.

1. Introduction

Due to global climate change, industrial growth, and environmental issues, many countries are currently facing long- or short-term water shortages [1,2]. In order to ensure stable water supplies, developing water resources and recycling water resources have become important trends worldwide. Various technologies have been investigated to meet increasing demands for clean water [3–6]. Harvesting water from humid air can be a viable solution to the water shortage crisis, because atmospheric water is present everywhere. However, the performance depends on humidity levels [7,8].

Seawater which covers approximately 71% of earth's surface is the most abundant water resource. Producing clean water from seawater via desalination is feasible and attractive. The most efficient desalination process is reverse osmosis which was first developed in the 1950s [9]. This conventional method still has the disadvantage of excessive energy requirements. In addition, high capital costs from poor durability and the formation of fouling are also concerns [10]. Membrane distillation (MD) is a thermally driven process that has been considered as a cost-effective process to desalination [11]. MD has several advantages including low energy requirement, low operating temperature [12]. The feed side of MD process can be powered by solar energy [13], geothermal energy and low-grade heat [14,15]. A hydrophobic porous membrane acts as a barrier to create an interface of liquid-vapor. Vapor pressure difference exists between feed and permeate sides of a hydrophobic porous membrane [16]. The purified water is collected at the permeate side. MD has attracted significant attention in concentration of aqueous solutions [17], wastewater treatment and desalination [18–20]. The feed and permeate side can be in direct contact with the membrane, which is called direct contact membrane distillation (DCMD). DCMD has the advantage of convenient operation and easy scaling up so that DCMD has attracted in industrial applications [21,22].

Nanomaterials with a surface plasmon resonance (SPR) effect have been widely investigated in the past decade because of their potential applications in cancer diagnosis and therapy. In addition, Halas and coworkers demonstrated that 80% of absorbed sunlight on gold nanoparticles (AuNPs) directly resulted in micrometer-scale bubbles at the

* Corresponding author.
E-mail address: liuyc@tmu.edu.tw (Y.-C. Liu).

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plasmonic nanoparticle surface [23–25]. Moreover, the remaining 20% of absorbed power can be used to heat the surrounding liquid, when the nanofluid containing AuNPs is irradiated by sunlight, due to a collective effect mediated by the scattering of multiple light particles from the dispersed NPs. The finding that local hot spots are produced by sunlight irradiation confirms localized heating from SPR, which would be beneficial for generating steam. Deng et al. indicated that a self-assembled thin film of AuNPs at the air-water interface performed with better efficiency than did the corresponding nanofluid, due to the instantaneous and localized plasmonic heating of the evaporative surface [26,27]. Close-packed AuNPs in nanoporous alumina exhibited pronounced absorption, a tunable bandwidth, and temperature stability [28]. A flexible gold membrane with multiscale funnel structures and energy gaps provided high absorption over a wide spectrum from ultraviolet to the infrared region [29]. The development of nanocomposites such as SiO_2/Ag@TiO_2, graphene oxide/AuNPs, and graphene/AgNPs showed that synergistic interactions activated the photothermal effect that significantly improved the efficiency of steam generation [30–32].

However, changing the intrinsic properties of water for desalination has been less discussed. Also, the efficiency of water evaporation associated with water's boiling point was not carefully considered in most designs. Recently, plasmon-activated water (PAW), which is created from treating deionized (DI) water with illuminated absorbed AuNPs on ceramic particles, was proposed [33–40]. Generated hot electrons from the decay of excited AuNPs are transferred to DI water which destroys hydrogen bonds (HBs) within water molecules [33,37]. The vapor of PAW is an environmentally friendly etching agent of glass [38]. Also, modification of artificial kidneys by AuNPs enhanced the efficiency of hemodialysis and inhibited protein adsorption [40]. Most importantly, compared to untreated DI water, this process results in a significant lowering of the boiling point of PAW to ca. 94.1 °C in normal conditions due to the weakened intramolecular interactions from HBs [37]. These interesting results encouraged us to develop an innovative strategy of solar steam generation based on PAW. In this study, AuNPs absorbed onto ceramic rods (AuNPs@CR) were prepared for efficient desalination under resonant illumination. Based on the proposed method, the efficiency of solar evaporation significantly increased regardless of whether the system was irradiated with sunlight or resonance light. Moreover, extraction of steam in a liquid state based on direct-contact membrane distillation (DCMD) also achieved a high efficiency. This novel technology has high potential for desalination which can help address the issue of water scarcity in the world.

2. Experimental

2.1. Chemicals and materials

Commercial chitosan (Ch) powder with a degree of deacetylation of 0.82 was purchased from First Chemical Works, Taiwan. Sodium chloride was purchased from Sigma-Aldrich Organics. All of the reagents were used as received without further purification. Ceramic rod (molar compositions: 92% SiO_2, 3.0% Na_2O and K_2O, 2.0% Fe_2O_3, 1.5% Al_2O_3, 0.5% CaO, 0.5% MgO, and other rare metal oxides) was purchased from Chyuan-Bang Enterprise Co., Ltd., Taiwan. All of the solutions were prepared using DI water (18.2 MΩ cm) provided from a Milli-Q system.

2.2. Preparation of gold nanoparticles (AuNPs)

The AuNPs aqueous solution was obtained through electrochemical and thermal reduction methods, in which the Au electrode was a working electrode in 0.1 N NaCl and 1 g L^{-1} Ch from −0.28 to 1.22 V vs. Ag/AgCl at 500 mV s^{-1} under slight stirring. Durations at the cathodic and anodic vertices were 10 and 5 s, respectively. Furthermore, the Au salt aqueous solution was heated to boiling at atmospheric pressure until the color changed from light yellow to dark pink. The solution was filtered to separate the Ch and AuNP solution.

2.3. Preparation of AuNPs-adsorbed ceramic rods (AuNPs@CR)

The ceramic rods were immersed into 50 ppm of an AuNP solution for 1 day. After being washed with DI water, the AuNPs coated CR was dried in an oven at 100 °C for 1 day. Further, the temperature was increased to 300 °C for the sintering process.

2.4. Preparation of plasmon-activated water (PAW)

DI water (pH 7.23 and a temperature of 23.5 °C) was passed through a glass tube filled with Au NP-adsorbed ceramic particles under illumination with green light-emitting diodes (LEDs) with the wavelength maxima centered at 530 nm. The time for the water to flow through the glass tube was ca. 25 min. Then the treated water (pH 7.25 and a temperature of 23.3 °C) was collected as soon as possible in glass sample bottles for subsequent tests.

2.5. In situ and real-time production of PAW

Three AuNPs@CR were placed in sample vials containing 20 mL of DI water. A green LED was fixed to the surrounding support. A constant distance of 9 cm was maintained between the sample vial and the LED. Under resonant illumination, the in situ and real-time production of PAW was achieved.

2.6. Saturated vapor pressure

A static vapor-liquid-liquid equilibrium (VLLE) apparatus was used to measure vapor-liquid equilibrium (VLE) and VLLE data. The heart of the apparatus is a visual equilibrium cell that is immersed in a visibility thermostatic bath (Model TV 4000, stability = ± 0.03 K, Neslab, USA). The phase behavior in the equilibrium cell was observed through the transparent windows. The bath temperature was measured with a precision thermometer (Model-1560, Hart Scientific, USA) with a platinum resistance temperature detector (RTD) probe to an accuracy of ± 0.02 K. A pressure transducer (Model PDCR-912, 0–1000 kPa, Druck, UK) with a digital indicator (Model DPI-261, Druck, UK) was used to measure the equilibrium pressure. The accuracy of the pressure measurement was about ± 0.1%. A proper amount of solution was loaded in the degassing unit at the beginning of the experiment. The degassed solution was then transferred to the equilibrium cell, in which levels of vapor-liquid-liquid interfaces could be properly adjusted such that the upper liquid phase was circulated. Both liquid and vapor mixtures were alternatively circulated by the circulation pumps to promote equilibration. When the system reached equilibrium, the pressure reading of the cell approached a constant.

2.7. Direct contact membrane distillation performance tests

A DCMD setup is shown in Fig. S1. The salt solution was heated (to 40 °C) in a feed tank and circulated with flow rates of 0.5 L/min by a circulating pump. The permeance side was connected to pure water which was cooled to 20 °C and circulated with flow rates of 0.6 L/min by a circulating pump. The water vapor passing through the glass fiber membrane was collected in a beaker. A hydrophobic glass fiber (GF) membrane with a nominal pore size of 0.4 μm and an average thickness of 560 μm was used as a membrane substrate (Advantec GB-140). The glass fiber membrane was fixed in a membrane module. The active membrane surface area that was exposed to the fluid streams was 10.74 cm^2. The permeate side was measure every 30 min. The AuNPs@CRs were placed in feed side under illumination of green light with the wavelength maximal centered at 530 nm.