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# Graphite powder/semipermeable collodion membrane composite for water evaporation

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ABSTRACT

Water evaporation, a promising and environmentally friendly technology driven by local hot spots on the water-air interface, is an efficient way to utilize solar energy. Herein, we present a novel laminar solar absorber consisting of graphite powder (GP) and a semipermeable collodion membrane (SCM) as an integrated structural system for highly efficient water evaporation. The GP/SCM composite can efficiently convert the absorbed solar energy to heat energy, e.g., the 8 mg-GP/SCM (i.e., the GP/SCM with 8 mg GP added) enables water evaporation with high efficiency of 56.8% under 1.5 kW/m$^2$ irradiation and 65.8% under 3 kW/m$^2$ irradiation, respectively. Cycling tests verify that the GP/SCM could retain stable water evaporation performance over 20 cycles under the same conditions. Contrast experiments show that the other carbon-containing solar-absorbers, such as acetylene black (AB) and graphene nanoplates (GNPs) in SCM, display relatively low evaporation efficiency of 41.4% and 36.7%, respectively, under the simulated solar irradiation with a light density of 1.5 kW/m$^2$. The laminar GP/SCM composite obtained in our work is low-cost, easy-to-prepare, recyclable, and highly efficient in its photothermal performance, so that it distinctly contributes to water evaporation.

## 1. Introduction

Solar energy, an inexhaustible and renewable energy, can be utilized for a variety of processes, e.g. in the photovoltaic, photocatalysis, and solar photothermal conversion fields. Among them, solar photothermal conversion is regarded as the most efficient method of solar-energy-harvesting [1,2]. Thus, water evaporation, as the most promising and important approach among a range of practical applications of solar photothermal conversion, has been widely used in wastewater treatment [3,4], the separation of liquid-liquid phases [5], power generation [6], seawater desalination [7], etc. In traditional methods of solar-driven water evaporation, solar energy is generally received by a solar absorber and then converted to thermal energy, which is used for heating up a bulk of water to generate vapor [8–13]. Obviously, there are several drawbacks to traditional methods. For instance, the absorber, as a light harvester, is inevitably heated itself to a high temperature on its surface, resulting in heat losses by convection or/and radiation processes. Additionally, hot bulk water is sensitive to heat loss mechanisms. Specifically, there is unnecessary heating of the water beneath the surface, which does not take part in the water evaporation but consumes the absorbed light energy. Thus, it is still a challenge to reduce the energy requirements for water distillation.

Recently, as a new technical route, interfacial water evaporation has emerged, which can reduce the loss of absorbed energy and enhance the photothermal conversion efficiency [14–18]. In detail, a membrane-like solar absorber floats on the water surface, which can not only absorb solar energy to generate vapor, but also prevents the energy from heating up the bulk liquid simultaneously. Importantly, compared to the conventional methods, the photothermal conversion process occurs at the water-air interface, and the converted thermal energy can be isolated from the bulk water. Therefore, only a small amount of water on the surface in contact with the absorber could be heated up to the vapor state, resulting in a remarkable reduction of heat loss. In this new technique, the absorber is the most important component. Up to now, several kinds of solar absorbers have been designed for converting thermal power to generate vapor. Consequently, the structure of the absorber has extreme effects on the light harvesting. Thus, much attention has been focused on extensively exploring new light absorbers with different structures. Among them, the typical bi-layered structural absorber composed of a top layer (photothermal layer) and a bottom layer (supporting layer) has high photothermal conversion efficiency and is regarded as one of the most popular and promising types of light absorber for water evaporation [19–28].

On the one hand, in the bi-layered light absorber, the top layer

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composed of light-to-heat conversion materials plays a key role in guaranteeing sufficient water evaporation for practical application. When properly irradiated by sunlight, the light-to-heat conversion materials cause striking heat localization resulting in a local temperature increase, up to or even in excess of the boiling point temperature of liquid water. Evaporation of the host water will lead to a non-equilibrium state at the interface between the hot photothermal materials and the colder liquid water, attaining the purpose of water evaporation [29–32]. Typical photothermal materials include plasmonic noble metal nanoparticles (e.g. Au [11,33–38], Ag [13,26], Al [39]), semiconductor materials with localized surface plasmon resonances (e.g. $Cu_{2-x}S$ [40–43], $Cu_{2-x}Se$ [44–46], and $Cu_{2-x}Te$ [47]), carbon-based materials (e.g. graphene [48], graphene oxide [49–54], reduced graphene oxide [55–57], and carbon foam [58]). Lately, a new definition of "thermoplasmonics" i.e., using metallic nanostructures as heat nanosources, was proposed by scientists [59,60]. The noble metals nanoparticles, for example, Au nanoparticles, are prone to fuse together, however after long periods of solar irradiation, leading to the degradation of efficiency in capturing solar light. Recently, some nonmetallic photothermal nanoparticles, including heat-treated mushrooms [61], titanium nitride nanoparticles (TiN) [62], titanium sesquioxides ($Ti_2O_3$) [28], carbon black based gauze [22], carbon-coated paper/expanded polystyrene foam (CP/EPS) [63], carbon nanotube nanofluids [9], and carbonized wood (C-wood) [19] have been explored for water evaporation. Among those nonmetallic photothermal materials, carbon-based materials, as the most promising photothermal materials for water evaporation, have attracted considerable attention due to their light-stability and low cost.

On the other hand, the bottom layer, serving as a support in the bi-layer structured light absorbers, also remains extremely important in water evaporation. The supporting layer should possess the following features: high porosity, high hydrophilicity, low thermal conductivity, low weight (low density), and low cost [20]. The porosity and hydrophilic nature of the supporting layer make it easy for water to be transported from the bulk water to the hot surface of the solar absorber. Again, its low thermal conductivity ensures minimum heat loss during the water evaporation process. Its low weight feature allows it to float on the surface of water, whereas the low cost dictates its suitability for practical application. Most of the ongoing work has featured materials with the above-mentioned characteristics being employed as supporting materials for the light absorber, including gauze [22], paper [33], wood [19–21], foam [64], poly (vinylidene fluoride) (PVDF) membranes [26], cellulose ester (MCE) membranes [55], etc. Although the bi-layer structure discussed above has many advantages, one major demerit is that the light-conversion materials in the top layer tend to fall off from the supporting layer with time due to low adhesion. In view of this, there is an urgent need to discover a new solar absorber with a new structure that is capable of long-life service in solar water evaporation.

In this work, we developed a novel compact solar absorber consisting of a photothermal material uniformly embedded in the supporting structure. It was fabricated by physical mixing of graphite powder (GP) and a collodion solution to form a semipermeable composite membrane (GP/SCM), in which the GP work as the photothermal material and the SCM is employed as the corresponding supporting material. The supporting material for the solar absorbers in this work possesses the following remarkable features: i) Low-density, ensuring that the semipermeable membrane (SCM) and the GP/SCM can freely float on the water surface. ii) Hydrophilicity, with the initial surface contact angle of the pure SCM reaching 64 ± 1°, so that it displays a good wettability towards water. iii) Low-thermal conductivity, which can reduce the heat loss and enhance the photothermal conversion efficiency. The water evaporation efficiency of the pure SCM can be up to 1.1 times that of pure water. iv) Physical compatibility (the most crucial advantage), so that the photo-thermal materials are easily mixed into the collodion solution (precursor solution of SCM), forming a solar absorber with an integrated structure. Thereby, the photothermal materials are firmly fixed in the interior and on the surface of the supporting material, so that they are difficult to peel off. v) The cost of the pure SCM is also quite low. The GP/SCM solar absorber easily floats at the air-water interface, and not only concentrates heat at the surface of the SCM, but also offers an efficient water transport route to the surface of the SCM through the micropores of the SCM. The GP/SCM demonstrated a high water evaporation efficiency, for example, the 8 mg-GP/SCM showed a high evaporation efficiency of 56.8% under a light-density of 1.5 kW/$m^2$ and 65.8% under a light-density of 3 kW/$m^2$, respectively. Based on the same supporting material (SCM), here, the performances of acetylene black (AB)/SCM and graphene nanoplates (GNPs)/SCM have also been comparatively investigated. Excitingly, the innovative integrated structure shows great potential for a sequence of practical applications in water evaporation, sterilization of waste, large-scale light absorption, heat localization, etc.

## 2. Experimental section

### 2.1. Materials

Graphite powder was obtained from Shanghai Xili Carbon Co., Ltd. Acetylene black was supplied by Tianjin Baochi Chemical Co., Ltd. Graphene nanoplates were provided by Nanjing XFNANO Materials Tech Co., Ltd (5–10 μm in size, 3–10 nm in thickness). Absorbent cotton was obtained from the Shandong Caoxian Hualu Textile Co., Ltd. Ethanol and ether were of analytical grade and purchased from Shanghai Aladdin Biological Technology Co. Ltd. All reagents were of analytical grade and used as received without further purification.

### 2.2. Preparation of collodion solution

Collodion solution was prepared as follows: first nitric acid and sulfuric acid in proportions of 5–10 mL, respectively, were mixed in a 100 mL capacity beaker. 1 g of cotton wool was then soaked in the mixed-acid solution prepared earlier for 1 h, after which the absorbent cotton wool was rinsed in deionized water. The nitrocellulose was then dried in an oven for 24 h at a constant temperature of 30 °C. 1 g of dried nitrocellulose was soaked in 25 mL ether solution and then added into an Erlenmeyer flask with 25 mL of ethanol solution. This was then shaken vigorously to form a collodion solution.

### 2.3. Fabrication of pure SCM, GP/SCM, AB/SCM, and GNPs/SCM

6 mL of collodion solution was mixed together with various amounts of graphite powder (GP) added (i.e., 3.375, 6.75, 13.5, 27, 54, and 108 mg) in a 20 mL beaker. This mixture was then magnetically stirred at room temperature for a period of 30 min. 2 mL was pipetted from the stirred mixture and transferred into a 500 mL capacity beaker with a 74 mL bottom diameter. This mixture was then spread uniformly on the bottom of the beaker and left to dry naturally to form the GP/SCM. The dried GP/SCM was trimmed into disks using a 35 mm diameter circular disk template. Therefore, the SCMs with various amounts of graphite powder added (i.e., 0.25, 0.5, 1, 2, 4, and 8 mg per disk) were fabricated respectively. This technique was also used to fabricate the control specimens, e.g., 8 mg-AB/SCM (i.e., the AB/SCM with 8 mg AB added), 8 mg-GNPs/SCM (i.e., the GNPs/SCM with 8 mg GNPs added), and Pure SCM (i.e., without any photothermal materials added).

### 2.4. Characterization

Phase characterization was performed on a PANalytical X'Pert Pro diffractometer operated with Cu Kα radiation (λ = 1.5418 Å) at 40 kV voltage and 40 mA current. The field-emission scanning electron microscopy (SEM) images were collected on a JSM-6700F scanning electron microscope. The optical transmittance spectra were measured by a Lambda 35 ultraviolet-visible-near-infrared (UV–vis–NIR) scanning