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Review

Solar water evaporation by black photothermal sheets

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ABSTRACT

Solar energy-to-heat conversion for steam generation is an essential metrology for power generation, water purification and desalination. Harvesting light energy and converting it to heat as terminal energy by black photothermal sheets is a novel strategy to attain this goal. This technology rely on use of black nanomaterials as light absorber to increase the absorption and conversion efficiency of solar energy. Fundamental understanding of their structure-property has to be fully exploited for further developing efficient solar-to-heat systems. This report summarizes physical understanding and experimental advances in development of black photothermal sheets for solar water evaporation. We examine the popular photothermal systems with remarkable vapor generation performance to identify the state-of-the-art of the device design. Three groups of the photothermal sheet are discussed in terms of different light-harvesting materials, such as carbon-based sheets, plasmonic sheets as well as semiconducting sheets. The physical difference of these novel devices with their steam releasing property are also highlighted.

1. Introduction

Harvesting solar energy for steam generation is one of the most important strategies of green energy innovation because the technology underpin a broad range of applications, such as power generation, absorption chillers, desalination systems, water purification and sterilization systems [1–4]. Current technology of producing steam using solar energy rely on a surface to absorb solar irradiation, and transferring the accumulated heat to the bulk water directly or via an intermediate heat transfer fluid [5,6]. This requires high optical concentration and suffers from high optical loss and surface heat loss, or needs vacuum to reduce convective heat loss under moderate optical concentration, which add complexity and cost to the photothermal system. Therefore, there is a significant need to develop cost-effective and high efficient solar energy harvesting systems for vapor/steam generation.

Low-cost, micro/nanostructured photothermal systems with broadband light harvesting has recently been emerging as a promising approach. Fluids seeded with nanoparticles (NPs) as volumetric absorbers minimize the surface energy loss by uniform temperature in the fluid and enhance thermal conductivity, such as the dispersed Au NPs in water solution achieve a solar-thermal-conversion efficiency of 24% [7–9]. Nevertheless, a significant of the absorbing NPs in this situation is wasted due to absorption and scattering of the incident light by the NPs above [10]. To overcome the issue, floating sheets such as carbon-based foam, paper, porous anodic alumina and cellulose membrane have been suggested to localize the absorbing material on air-water interfaces for more efficient and cost-effective steam generation [11–16].

In these platforms, steam generation by heat localization is performed through a sequential cooperation of light absorbing, thermally insulating and capillary action (Fig. 1) [13,17–20]. Absorbers using various black materials, such as porous carbon materials, metallic plasmonic structures and semiconducting NPs are demonstrated for efficient solar absorption. The substrate for heat localization functioned as thermal insulator that reduce the heat transfer between vaporization region and bulk liquid. Due to the channel-capillary effect of the supports for water transport at negative pressures and steam escape (Fig. 2), localized evaporation is achieved with improved thermal efficiencies ~ 64% [20–24]. In addition, the use of solar concentrator further enhance the thermal efficiencies up to 85–90% [14,15,25]. However, how to build efficient solar-to-steam systems by use of absorbing nanomaterials and/or porous supports still remains a challenging goal.

In this work, we summarize physical understanding and experimental advances on development of black photothermal sheets for solar water evaporation. We firstly describe the physics of black material for light-to-heat conversion to illustrate conceptual development. The

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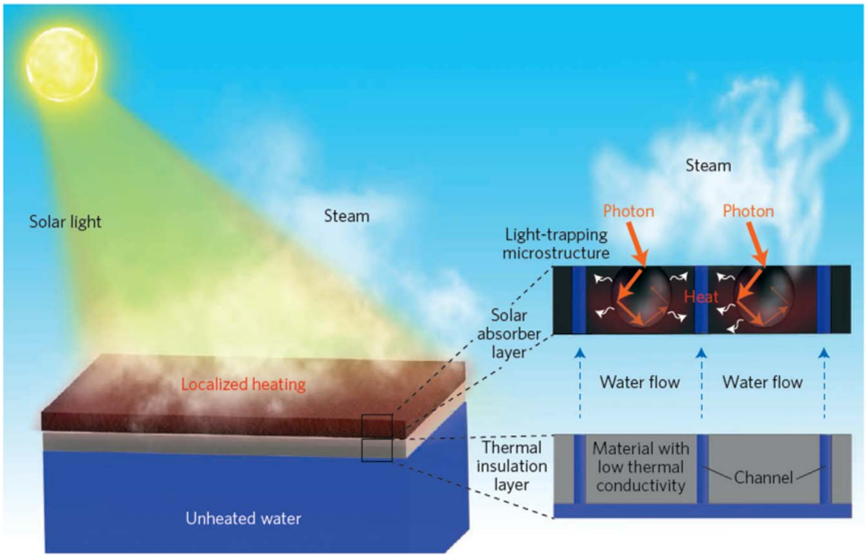

Fig. 1. The interfacial-photothermal sheet floating at air-water interface. Solar light harvesting by the absorber layer and then converted into thermal energy heats up the water at interface. The thermal insulation layer consists of material with low thermal conductivity and helps confine the heat at the interface. The channels within the thermal insulation layer and the absorber layer wick the beneath water to the hot interface for vapor generation. The insets show the conversion of photon energy to heat in the absorber layer and the transportation of water in both the absorber and the thermal insulation layer. Reproduced with permission [17]. Copyright 2017 Nature Publishing Group.

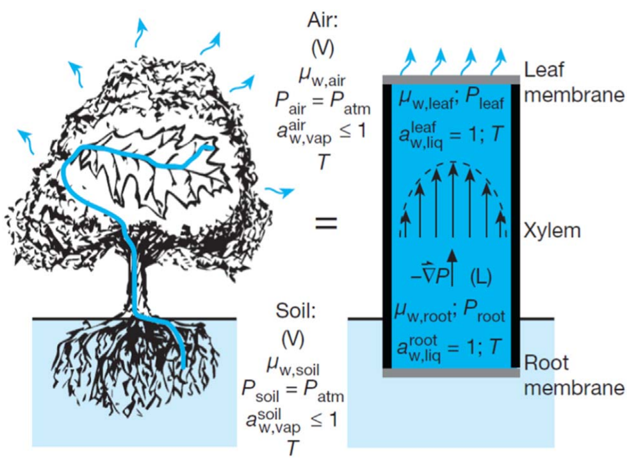

Fig. 2. Negative transpiration of liquid water. Water transport from the soil to the air in a tree and of a minimal model of the components. Water loss by evaporation reduces the liquid pressure within the leaf relative to atmospheric pressure, which wicks water out of the soil and up the xylem to preserve hydration. Reproduced with permission [22]. Copyright 2008 Nature Publishing Group.

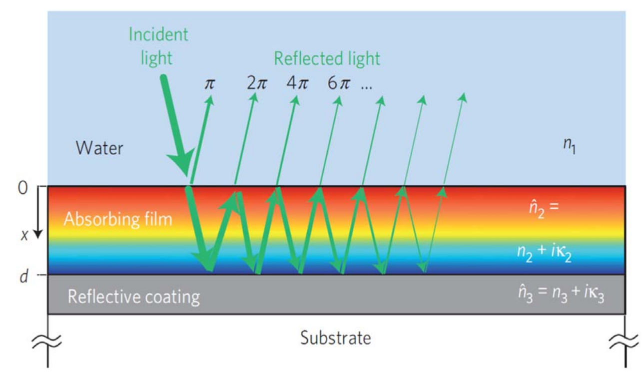

Fig. 3. Resonant light trapping in quarter-wave films. Reproduced with permission [27]. Copyright 2012 Nature Publishing Group.

solar-to-steam platforms are thus classified in terms of the light-harvesting materials, such as carbon-based sheets, plasmonic sheets as well as semiconducting sheets. We then discuss the photothermal sheets in particular form to identify state-of-the-art of the device design. The key factors yielding remarkable photothermal performance are also highlighted to distinguish the physical difference of devices. Finally, the report concludes with a summary on the current achievements and a few prospect on remaining challenges.

2. Physics of black material for light-to-heat conversion

Conversion of solar radiation into heat is normally achieved either by direct absorption in a heat transfer fluid, or indirectly by some kind of black absorbing surfaces from which the heat is collected and conducted to heat transfer fluid (Fig. 3) [26,27]. The heat generation process involves absorption of incident photons, and heat transfer from black materials to surrounding media. The heat releasing mechanism is that light-induced electric field drives mobile carriers inside crystals of the material, and the energy gained by carriers turns into heat. Then the heat diffuses away from materials leading to an increased temperature of surrounding medium [28]. Two parameters are normally used to assess the evaporation performance. The water evaporation rate is described by equation $\dot{m} = \frac{dm}{A \times dt}$, where m is the mass of evaporated water, t is time and A is the surface area of photothermal sheet. The solar thermal efficiency is calculated by the formula $\eta_{th} = \frac{Q_e}{Q_s} = \frac{\dot{m} h_{LV}}{C_{opt} q_i}$, where Q_s is the power of solar illumination and Q_e is the power for water evaporation, h_{LV} is the total enthalpy of liquid vapor phase change, C_{opt} is the optical concentration, and q_i is the normal direct solar irradiation. Particularly, the calculation of the total enthalpy of liquid-vapor phase change should consider both the sensible heat and the temperature-dependent enthalpy of vaporization.

There are many candidates for the absorber layers and mainly three types of photothermal agents are employed, e.g. carbon-based material, plasmonic metals and semiconducting materials. Amorphous carbon composed of a mixture of sp^2 and sp^3 bonding, is a carbonaceous solid that has no long-range crystalline order, and usually contains hydrogen and nitrogen. It has good ability in broad-band light absorption due to closely spaced energy levels of the loosely-held π electrons. Moreover, stability engendered by the aromatic bonds makes the material nearly inert at atmospheric temperatures and insoluble in water and many other solvents [29]. Conventional carbon black or graphite absorb visible light due to the π-band's optical transitions as well, while they are limited by a moderate reflection of 5–10% at air-dielectric interface [30]. An interesting approach to overcome the limit is to use nanostructures, especially vertically aligned carbon nanotubes or porous graphene [31–35]. By this way, large amount of optical microcavities are formed by reflecting faces on two sides of spacer layer, which confine light to small volumes by resonant recirculation that enhance interaction of light with the materials significantly [36].