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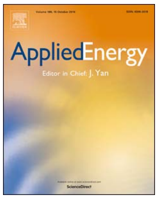

Recycled waste black polyurethane sponges for solar vapor generation and distillation

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HIGHLIGHTS

- 1st demonstration of recycled black sponge for solar evaporation and distillation.
- The black sponge was surface modified for performance enhancement.
- Solar evaporation efficiency was more than 3.5 times higher than natural process.
- Solar ethanol distillation up to 25 wt% concentration promotion was achieved.
- The mechanisms of the enhanced solar energy conversion were proposed.

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ABSTRACT

The abundant waste polyurethane sponge, commonly considered as one of the municipal wastes, can be recycled and converted into the valuable resources of environment. The increasing landfill cost and air-pollutions have made it a great urgent to develop the effective applications of waste polyurethane sponge. Recently, solar vapor generation has attracted extensive attentions, since energy shortage and water scarcity along with water pollution are becoming alarming global issues to be addressed. The solar vapor generation relies on the performance of the solar absorbers which convert the solar energy into heat for the vaporization process. A low cost, efficient and durable solar absorber is vital for the development of solar vapor generation. Here, we report that the recycled self-floating black polyurethane sponges are very promising solar absorber materials. which can efficiently generate water vapor after a simple one-step hydrophilic treatment with dopamine hydrochloride. The evaporating rate was more than 3.5 times higher compared to that of the existing natural evaporation process, exhibiting an evaporation efficiency of above 50%. Furthermore, this black polyurethane sponge can also drive solar ethanol distillation, yielding up to 25 wt% concentration promotion under each distillation cycle.

1. Introduction

Given the increasing global concerns of energy problems, renewable energy resources have been pursued in high demand, among which solar power is the most promising and naturally unlimited energy source in the foreseeable future. The solar energy that reaches the earth in an hour is able to cover the energy consumption of human for an entire year [1]. Practical technologies should be developed for better utilization of the solar energy for the energy consumption of human [2]. At present, solar thermal conversion technology comes to be the most effective one compared with other solar energy utilization approaches such as photocatalysis or photovoltaics [3–5]. Traditional vaporization is expensive and usually involves the consumption of depletable fossil fuels with heavy emissions of greenhouse gas, e.g. CO_2 [6,7]. Recently, the utilization of solar energy to enhance evaporation emerges to be an attractive strategy for sustainable and practical systems, which shows great potential applications in sterilizations [8], wastewater treatment [9,10], desalination [11–14] and ethanol distillation [15,16]. The solar evaporation relies on the development of a key component, *i.e.* solar absorber, which converts the solar energy into heat to vaporize water. The research on solar absorber materials is the main approach to realize the practical use of the solar evaporation

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technology.

In recent years, the plasmonic metallic nanoparticles have been most widely investigated as the solar absorbers due to their unique photothermal conversion property. Halas's group firstly introduced that the suspended gold nanoparticles can generate vapour bubbles for efficient evaporations of surrounding liquid because of their high solar absorption and scattering properties [15,17]. However, these methods usually require costly high optical concentrations (up to $10^3\ \mathrm{kW\ m^{-2}}$), and only a relatively low solar-thermal efficiency of about 24% has been obtained. As the heat is generated around the nanoparticles, large amount of the thermal energy will be transferred to heat up the surrounding liquid during the vapour bubbles rising to the evaporative surface. To overcome this problem, the plasmonic films were further demonstrated as high-performance and broadband absorbers to localize plasmonic heat at the air-water interface [18–22]. An efficiency of ~85% under the irradiation density of $10\ \mathrm{kW\ m^{-2}}$ was achieved by bio-inspired solar steam generation using floating Au nanoparticles membranes [23]. However, except that the focusing optics are usually required, the scarcity and high cost of metallic absorbers involving noble metals limit their practical applications. Moreover, after the long-time illumination, the plasmonic nanoparticles may fuse together and the plasmonic properties can be weakened, which results in lower solar thermal conversion efficiency [24].

Recently, more common non-metallic materials, such as carbon black [25,26], carbon nanotube [27], graphene and graphene oxide [28,29], polypyrrole (ppy) coated mesh [30], and bio-inspired materials like wood and mushrooms [31–33], have been extensively investigated for solar vapor generation with higher operation stability and lower cost compared with plasmonic metallic materials. Among these absorbers, bilayer structures are often proposed for the efficient solar evaporation with the top layer of photothermal materials for light absorption and heat conversion, and the bottom layer of thermal insulating materials with low thermal conductivity to prevent the heat loss [34–37]. Highly efficient solar vapor generation was achieved based on the carbon black coated paper supported by expanded polystyrene foam with a thermal efficiency of 88% under one sun irradiation [26]. These studies have been devoted to study the solar absorbers for high solar-thermal efficiency, which usually possess the unique features for the improvement of solar thermal conversion efficiency such as low material density so that it will float on the water surface, low thermal conductivity to reduce heat loss, hydrophilic and porous structure for fast fluid transport. However, these proposed absorbers usually have their own limitations, which are either not common, carbonation needed or too expensive for the practical application. Recycling and reutilizing is currently the trend for developing sustainable society. Using some common wastes as the absorbers for solar evaporation can be a new and popular research direction to reduce the overall cost and energy consumption for production, which ultimately achieves the goal of green energy and sustainable development.

Black polyurethane (BPU) sponge, one kind of three dimensional porous materials, has been widely used as anti-seismic packaging materials for transportation in our daily life today. The production of black PU sponges as packaging material comes to millions of tons every year [38–40]. However, most of them are abandoned after one-time utilization and cannot easily decompose naturally [41]. More and more attention is being paid on the recycling of PU sponge with the rise of regulatory and environmental issues. People are focusing on seeking alternative options to dispose these polyurethane materials for the conservation of petroleum resources and the reduction of environmental stress [42]. Recently, researchers have applied the PU sponges in areas such as reusable oil-absorbent [43,44] and templates for constructing porous structures [45,46].

In this work, for the first time we demonstrate that the recycled black PU sponge with porous structure, low thermal conductivity (~0.034 W/m K) [47], and low mass density to be self-floating, could behave as an ideal absorber for solar vapor generation except for its weak hydrophilicity. Therefore, surface chemical properties were modified by a facile dopamine solution stirring treatment to achieve the fast dynamic wettability of the BPU sponges for fluent water supply on the top surface of the absorber. The surface modified PU (SM-BPU) sponge showed that the evaporating rate increased more than 3.5 times compared to the existing natural evaporation process. The BPU sponge for solar ethanol distillation application was further examined and the results showed that this sponge can yield up to 25 wt% concentration promotion under each distillation cycle. Considering the BPU sponge as the major waste of packaging industry, the recycling of the waste BPU sponge for solar energy conversion can reduce the environmental pressure. While in conventional evaporation systems, it needs the consumption of fossil energy, which is a limited energy resource and generates greenhouse gas and pollutants during the combustion. From the views of environmental sustainability and energy cost, this work promises to be attractive and competitive for applications in practical solar-thermal technologies.

2. Material and methods

2.1. Material

The black polyurethane (BPU) sponge with a pore diameter of ~300 μm, density of $25\ \mathrm{kg/m^3}$ and thickness of 10 mm was purchased from Zhong Sheng Trade Co. (Wuyi, Zhejiang, China). Dopamine hydrochloride (98%) was obtained from J & K Scientific Ltd. (Beijing, China). Tris (hydroxymethyl) aminomethanehydrochloride (Tris-HCl) (pH 8.8, 1.5 M) was purchased from Solarbio (Beijing, China). All chemicals were used as received without further purification.

2.2. Preparation of hydrophilic PU sponge

The BPU sponges were tailored to circular with a diameter of 40 mm, and then ultrasonically washed with distilled water (DI) water and ethanol for three times, followed by drying in an oven at 50 °C. Dopamine solution ($2\ \mathrm{mg\ ml^{-1}}$, pH = 8.8) was obtained by dissolving dopamine hydrochloride in 10 mM Tris-HCl. The cleaned sponge was soaked into 20 ml freshly prepared dopamine solution followed by stirring overnight. Then, the as-prepared SM-BPU sponge was washed with DI water several times and dried in oven at 50 °C for 4 h.

2.3. Solar-vapor-generation experiment

The solar evaporation rates of different solar absorbers, e.g. white PU sponge, BPU sponge, and SM-BPU sponge were measured and compared with pure water, under the same solar illumination of $1\ \mathrm{kW/m^2}$ over 60 min. The sponges with a diameter of 40 mm and a thickness of 10 mm were floated on top of the water surface in the beaker and exposed exactly at the center of the light beam. All sponges were twisted and soaked in DI water to be wetted before floated on the water surface. A 300 W xenon lamp (PLS-SXE300; Beijing Perfect Light Technology Co., Ltd) served as the solar light source. The solar irradiation intensity of the sample surface was measured by a power meter (THORLABS, S314C). The real-time mass loss over the entire duration was recorded using a computer controlled electronic mass balance (Mettler Toledo, ME204) with accuracy of 0.1 mg. Further investigations of mass changes of water with SM-BPU sponge under various irradiation intensities from 1 to $5\ \mathrm{kW\ m^{-2}}$ were carried out. All experiments were conducted at room temperature of 20 ± 1 °C and humidity of about 60%.

2.4. Ethanol distillation

Ethanol solutions with volume fraction from 10% to 90% were prepared by diluting 99.8 v/v% ethanol with DI water, and charged into the beaker with diameter of 4 cm and depth of 6 cm for distillation,