Solar Energy 159 (2018) 800–810

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Carbon fabric based solar steam generation for waste water treatment

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ARTICLE INFO

Keywords:
Solar steam
Desalination
Dye degradation
Waste water treatment

ABSTRACT

Decontamination of waste water is one of the most practical techniques to tackle the worldwide clean water shortage. In recent times, solar steam based decontamination of contaminated water has been attested as a potential sustainable strategy to get clean water using renewable resources. Herein, we report the utilization of Carbon fabric and Titanium Nanorods on Carbon Fabric for solar steam based water purification techniques. The performance of Carbon Fabric was tested under different conditions and the results proved that Carbon Fabric has excellent light to heat conversion capabilities in both real and ideal conditions. Owing to the excellent performance of Carbon Fabric, it was used for purification of different types of contaminated water. About 99.9% of salt and 87% of organic contaminants were removed from saline water and organic waste water respectively, using a simple low cost carbon fabric based homemade prototype. We also present the application of Titanium Nanorods on carbon fabric for the efficient removal of dye molecules like Rhodamine B from contaminated water using solar driven interfacial steam generation mechanism.

1. Introduction

With rapidly growing population and development of the modern society, the demand for energy and resources also increases. The rising demand for limited resources like fresh water is one of the major issues which require immediate solutions (Vörösmarty et al., 2000). In order to avoid a major water crisis around the world in the foreseeable future, practical solutions like decontamination of contaminated water are required. Distillation of contaminated water is one of the easiest methods among different available techniques to generate clean water. As solar energy is a green and renewable energy, use of solar energy for the yield of clean water by distillation of contaminated water is a sustainable solution to minimize clean water shortage (Shannon et al., 2008).

Even though the idea of clean water generation using solar distillation technique has been around since ancient times, the very low light to heat conversion efficiency of pure water hinders the growth of the idea into a practical solution. In traditional water evaporation, the water vapors are formed due to the bulk heating of the solution. When solar radiation falls upon water, the light penetrates into the solution as water is a poor absorber of light (Wang et al., 2016; Zhang et al., 2015). This is a real wastage of incident solar light and thus drastically affects the light to heat conversion efficiency of water. In recent times, researchers around the globe have demonstrated considerable success in ameliorating the efficiency by either adding light absorbing nanoparticles in water or with the assistance of self-floating, light absorbing porous membranes above water (Ghasemi et al., 2014; Huang et al., 2017; Ishii et al., 2016b; Ishii et al., 2016a; Ito et al., 2015; Jiang et al., 2016; R. Li et al., 2017; Liu et al., 2017, 2015; Mohammad Sajadi et al., 2016; Neumann et al., 2013; Xue et al., 2017; Yan et al., 2016; Zielinski et al., 2016). Since the development of membranes with high solar steam efficiencies, researchers have discovered the diverse applications of these membranes for clean water generation (Gao et al., 2016). These include the addition of TiO_2 on the membrane for accelerated removal of harmful dye molecules like Rhodamine B from contaminated water and desalination of actual sea water to obtain drinkable water (Liu et al., 2016; Lou et al., 2016; Zhou et al., 2016). Recently, Yi. et al. reported a black Al-Ti-O hybrid self floating microporous membrane for photothermal desalination application. It manifested a high efficiency of 77.52% for desalination under simulated solar light irradiance (Yi et al., 2017). Li et al. designed a jellyfish-like solar steam generator that consists of porous carbon black/graphene oxide (CB/GO) composite layer (body), aligned GO pillars (tentacles) and expanded polystyrene (EPS) matrix. This assembled evaporator displayed an energy conversion efficiency of 87.5% under one-sun illumination (1 kW cm^{-2}) and demonstrated its applicability in water desalination studies (Y. Li et al.,

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https://doi.org/10.1016/j.solener.2017.11.055
Received 8 August 2017; Received in revised form 9 November 2017; Accepted 20 November 2017

2017).

In this study, we first demonstrate the novel application of carbon fabric (CF) for an efficient solar steam generation. The three basic requirements for an efficient solar steam generation by a membrane are broadband optical absorption, porosity, and low thermal conductivity. Firstly, CF offers broad optical absorption of solar radiation in the wide wavelength range from visible to near infrared. Secondly, low thermal conductivity of CF ensures less thermal dissipation of heat across the fabric area which assists in concentrating the solar heat generated during steam generation. Eventually, the large porous structure of this fabric further acts as a capillary for water molecules, which constitutes as a continuous channel for the water molecules to add up at the air-water interface. CF also has an excellent thermal stability at high temperature, which makes it an ideal candidate for large-scale applications. We also present the application of CF in clean water generation. Owing to the excellent light to heat conversion efficiency and high thermal stability of CF, it has also been examined for clean water generation from contaminated water containing organic and inorganic contaminants. CF has also been tried out for removal of dye contaminants from water. The high mechanical stability of CF makes it possible to easily modify the fabric into a bifunctional membrane containing Titanium Dioxide (TiO_2) nanorods on the surface called TCF. TCF displays bifunctionality by assisting in the accelerated removal of Rhodamine B molecules from contaminated water and by exhibiting solar driven interfacial water evaporation process.

2. Experimental section

2.1. Materials

Carbon Fabric (1071 HCB) was purchased from AvCarb, USA. All chemicals used in the present work were of analytical grade and commercially available. Tetrabutyl titanate (TBT) (98% Alfa Aesar), Titanium tetrachloride ($TiCl_4$), Hydrochloric acid (HCl), Ethanol, Tetraethyl orthosilicate (TEOS), Acetone and Rhodamine B (RhB) were purchased from SDFCL, India.

2.2. Preparation of TiO_2 nanorods on carbon fabric

Rutile TiO_2 nanorods were grown on a carbon fabric by the hydrothermal method (Fang et al., 2015). In a typical synthesis, carbon fabric was refluxed at 80 °C for 8 h in concentrated nitric acid, later washed with DI water several times and dried. The clean and dried carbon fabric was immersed in a TiO_2 seed solution containing 0.15 M of titanium tetrachloride in ethanol for overnight. Then carbon fabric was annealed in Muffle furnace at 400 °C for 30 min. After that 1.3 mL of tetra butyl titanate (TBT) was added into the mixture solution of hydrochloric acid (20 mL) and acetone (20 mL) and kept on stirring to form a clear solution. This clear solution mixture and TiO_2 seed coated carbon nanofibers were transferred to a Teflon-lined stainless steel autoclave. The sealed autoclave was heated in an electric oven at 200 °C for 2 h and allowed to cool down to room temperature slowly. Uniformly white TiO_2 nanorods were grown onto the carbon fabric. It was rinsed slowly several times with DI water and absolute ethanol and dried in an oven at 60 °C for 12 h.

2.3. Characterizations

X-ray diffraction patterns of TCF and CF were measured on powder XRD (Bruker D8 Advance) using CuKα radiation (k = 1.54 Å) with the 2θ range of 5–60°. The surface morphology of TCF and CF were examined by Field Emission SEM (Inspect 250 FESEM). The XPS measurements of CF and TCF were performed on a PHI 5000 Versaprobe II equipped with monochromatic Al Kα X-ray source.

The absorption spectra and reflectance spectra were measured using Jasco V-770 Spectrophotometer. Integrating sphere was attached for the measurement of spectra of the solid samples. The wavelength range was 200–2000 nm for both measurements. The ionic conductivity of the samples was measured using a Microprocessor based pH-EC-TDS meter. (Model number 1615, Esico). The ionic conductivity of the initial sample (3.5 wt% NaCl solution) and the collected condensed sample were measured and compared. TOC measurements were done using TOC-L (Shimadzu Corporation). Wastewater samples procured from Mumbai industrial area (MIDC) were considered as an initial sample for the experiment. The concentration of carbon content was measured in both initial and final condensed samples.

2.4. Evaporation performance evaluation

(a) Evaporation Performance Evaluation of Carbon Fabric under solar simulator: The evaporation was evaluated by noting the weight change of water per unit time. DI water was filled in a vessel made of two concentric acrylic tubes of diameters 10 cm and 4 cm. The inter-spacing between the two tubes was filled with synthesized silica aerogel to inhibit heat loss. The whole vessel was kept on a weighing balance (A110C, Atom, India) for measurements. Pre-measurement, the weighing balance was calibrated using a standard calibrated weighing balance (GR202, A&D Company, Japan). The weight loss was measured for an hour after steady state. The temperature of the substrate was observed with the assist of an IR thermal camera (FLIR ONE, Flir Systems, USA) which was pre-calibrated using a laboratory thermometer (mlabs1277, labs, India) with an error of 0.1 °C. The vessel kept on weighing balance was illuminated by a solar simulator (Scientech SF300, Canada) equipped with an Acrylic Fresnel lens (Greenbrier International, Canada) was used to focus the light from the solar simulator onto the carbon fabric above the water in the vessel.

(b) Evaporation performance evaluation of CF and TCF under Natural sunlight: The weight change was noted per time. Pure water was contained in an acrylic tube of diameter 4.5 cm. TCF and CF were kept afloat above the water using a wooden ring. The TCF and CF were illuminated with natural sunlight focussed using an acrylic Fresnel lens (Greenbrier International, Canada). The whole arrangement was maintained in a weighing balance (A110C, Atom, India) for measurements. The weight change measurements for both TCF and CF were noted under similar conditions for comparisons.

(c) Evaluation of evaporation of different samples of water under solar simulator: Pure water, saline water (3.5 wt% NaCl in DI water) and industrial waste water were taken on an acrylic vessel of diameter 4.5 cm. A solar simulator (Scientech SF300, Canada) equipped with acrylic Fresnel lens (Greenbrier International, Canada) were used for illumination. The measured intensity of illumination was 24 kWm^{-2}. The rate of weight change of these water samples were measured under identical conditions for analysis.

2.5. Photocatalytic activity set up

The photocatalytic activity of TCF was determined and compared with CF. In this experiment, the photocatalytic degradation of organic dye Rhodamine B (RhB) was studied. In a typical test, 20 mg of RhB was dissolved in 1L of DI water to get a standard aqueous solution of the RhB. 30 mL of the freshly prepared Rhb were injected into a 50 mL vessel for each exam. TCF and CF were kept afloat above the RhB solution using a wooden ring and kept in the dark overnight at room temperature to attain adsorption-desorption equilibrium. Natural sunlight (Mumbai, 19.0760° N, 72.8777° E, Month May) equipped with an acrylic Fresnel lens (Greenbrier International, Canada) was used as a light source. The focused intensity was assessed to be in the orbit of 210–212 suns for all examinations. The samples were collected every 15 min and their absorption spectra were measured using a spectrophotometer (Cary 5000 UV–Vis-Nir, Agilent Technologies). As CF and TCF promote the evaporation of water, the concentration of RhB was calibrated after each reading. The concentration was calculated