Powder Technology 321 (2017) 276–285

Contents lists available at ScienceDirect

Powder Technology

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

Enhanced direct steam generation via a bio-inspired solar heating method using carbon nanotube films

Xinzhi Wang [a], Yurong He [a,*], Xing Liu [b], Jiaqi Zhu [b]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] Centre for Composite Materials and Structures, School of Astronautics, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 31 July 2017
Accepted 6 August 2017
Available online 08 August 2017

Keywords:
Carbon nanotubes
Direct steam generation
Nanofluids
Micro-porous channels
Solar harvesting

ABSTRACT

In this paper, a novel direct solar steam generation method is proposed that realizes highly efficient vapour generation. The strategy was inspired by the evaporation of sweat from the human skin and the transpiration of plants in biological systems. A micro-porous structured broadband absorption paper-based carbon nanotube (CNT) film was prepared by a facile vacuum filtration process, and was utilized as both the solar harvesting surface and steam generation skin. The excellent optical absorptivity and water conductivity of CNTs make great contributions to the solar steam generation. The heat and mass transfer properties on the direct solar steam generation performance of CNT films was investigated. The evaporation rate and temperature distribution of the steam generation system were experimentally studied to evaluate the evaporation performance. The results demonstrate that the bio-inspired solar heating of CNT films has significant advantages for enhancing direct solar steam generation compared to those of direct volumetric solar heating. Through this research, it was found that the localized photo-heating of floating CNT films at the water-air interface and the fast capillary flow through the porous structures of the films enhanced the solar steam generation process. This bio-inspired direct solar steam generation method using carbon nanotube films has great potential in a variety of industrial applications, including electrical power generation, freshwater distillation, and solar hygiene systems.

1. Introduction

The process of generating steam is widely used in a wide range of industrial applications, such as electrical power generation, freshwater distillation, and solar hygiene systems [1–3]. Renewable solar energy is recognized as one of the most promising alternative energy sources for achieving highly efficient steam generation. In concentrated solar power systems, solar energy is collected and converted into thermal energy by way of a solar concentrator and collection system [4,5], and is then converted to electrical energy via a steam turbine [6–8]. A solar desalination system typically uses the energy of the sun to generate steam, and then to condense the vapour into pure water [9–11]. In these applications, the generation of steam and vapour is usually desired, which greatly influences the performance. Current solar steam generation methods typically rely on the heating of black surface absorbers to harvest and convert the solar energy into thermal energy, which is then used to heat the bulk working fluid to its boiling point through heat convection and heat conduction [12–15]. These methods usually require a highly concentrated optical system, and the process involves high thermal and optical losses.

Nanomaterials, especially nanoparticles, were widely utilized to enhance the photo-thermal conversion process. Nanofluid, a fluid containing nanoparticles, has attracted attention in the enhancement of direct solar energy collectors due to their distinct photo-thermal conversion properties [16–20] and excellent thermophysical performance [21–27]. In addition to heating bulk nanofluids using solar energy, these systems are also attractive because they realize direct solar steam generation through the interaction between the solar energy and the nanofluids [28]. Jin et al. [29] performed steam generation experiments using a solar light intensity of 220 suns (1 sun = 1 kW m^{-2}), and found that the steam was produced by the highly non-uniform energy distribution in the system. Fu et al. [30] investigated the enhancement of GO-Au nanocomposite nanofluids on solar steam generation and found that the trace amounts of Au nanoparticles significantly improved the steam generation efficiency. In Ni et al.'s [31] work, a solar steam generation efficiency of 69% was experimentally obtained using graphitized carbon black nanofluids illuminated with a solar light intensity of 10 suns. Wang et al. [32] experimentally investigated the direct solar vapour generation performance of low concentrated carbon-nanotube nanofluids and realized a high evaporation efficiency. In this study, they demonstrated that the high evaporation rate was due to the localized heating of the water-air interface rather than the heating of the bulk fluid. Kabeel et al. [33] designed a modified single basin solar still and demonstrated that the nanofluids improved the solar still water

* Corresponding author.
E-mail address: rong@hit.edu.cn (Y. He).

http://dx.doi.org/10.1016/j.powtec.2017.08.027

Nomenclature

A	absorption efficiency (%), $A = 1 - T - R$.
$A_{abs}(\lambda)$	absorption efficiency at wavelength of λ (%)
C_p	specific heat of water (J kg^{-1} K^{-1})
h_{fg}	phase–change enthalpy of water (J kg^{-1})
I	power density of solar light (W m^{-2})
$I(\lambda)$	intensity of solar light at wavelength of λ (W m^{-2} nm^{-1})
$\dot{m}$	evaporation rate (kg m^{-2} h^{-1})
Δm	mass change (kg)
m_{CNT}	mass of CNTs in the CNT films (g)
m_{rest}	resting mass of water after the evaporation process (kg)
Q_{abs}	solar spectral absorbance
R	reflectance efficiency (%)
S	surface area of the film (m^2)
SVP	specific vapour productivity (m^3 g^{-1} h^{-1})
t	illumination time (h)
T	transmittance efficiency (%)
ΔT	temperature increase of bulk fluid (K)
$\dot{V}$	volume of vapour flux (m^3 h^{-1})

Greek symbols

$\eta_{evaporation}$	evaporation efficiency (%)
$\eta_{heating}$	heating efficiency (%)
η_{total}	total photo-thermal conversion efficiency (%)
ρ_{vapor}	the density of water vapour (kg m^{-3})
λ	wavelength (nm)

productivity by about 116%. Wang et al. [34] investigated the water bubble generation process in a nanofluid with pulsed laser heating of its flow boiling, and found that high laser intensities usually are required for the water bubble generation. Chen et al. [35] experimentally investigated the thermophysical and optical properties of SiC nanofluids and confirmed the feasibility of nanofluid applications in solar distillation systems.

In the volumetric solar heating of nanofluids in direct steam generation systems, the nanoparticles could rapidly reach equilibrium with the surrounding fluid, and the vapour was primarily generated from the temperature increase of the bulk fluid. This causes inevitable thermal losses to the bulk fluid. To reduce the thermal losses, a novel strategy that was inspired by evaporation processes in nature, such as the sweating of human skin and the transpiration of plants, was first demonstrated by Wang et al. [36], as shown in Fig. 1a. In their study, the localized plasmonic heating of floating gold nanoparticle films at the water-air interface with a low temperature bulk fluid was used to efficiently generate steam. In the transpiration process, the solar radiation was absorbed by the plant leaves, the water inside the leaves was heated and converted into vapour, and the vapour was then released from the stomatal pores of the leaves [37]. The stomatal pores act much like the pores of the skin in the human body. In both the sweating and transpiration processes, the localized heating and capillary flow of liquid within the evaporation surface are critical for efficient evaporation. Furthermore, Liu et al. [38] fabricated an air-laid paper supported gold film through self-assembly and achieved reusable and high-performance solar steam generation. Bae et al. [39] designed an adiabatic plasmonic nanofocusing membrane, which had ultrabroadband light absorption and achieved efficient water vapour generation with an energy conversion efficiency of 57% under a solar light intensity of 20 kW m^{-2}. Ghasemi et al. [40] fabricated a double-layered porous structure, which consisted of a hydrophilic carbon foam as the bottom layer and an exfoliated graphite layer as the top layer, and used it as solar energy receiver to achieve highly efficient solar steam generation by heat localization.

In most previous works, broadband light absorbers which consisted of nanomaterials were prepared through complex chemical processes. In addition, there has been little investigation into the heat and mass transfer processes in bio-inspired solar steam generation systems. Carbon nanotubes (CNTs) have excellent optical absorptivity over a wide range of 200 nm–200 μm due to their π-band optical transitions, which is favourable for solar energy harvesting. Moreover, the frictionless surface of CNT walls could lead to fast water transportation through the CNT films. Both the optical and water transportation properties of CNTs mean that porous CNT films are promising alternatives for high efficient solar steam generation. However, only a few reports have been published on the subject. In this work, a facile vacuum filtration process was used to prepare porous structured CNT films, and their solar steam generation performance was evaluated. The experiments were carried out with a system for recording the evaporation rates and temperature distributions. A comparison of the evaporation rates between the bio-inspired solar heating of CNT films and the direct solar heating of CNT nanofluids was conducted. The effects of the CNT mass concentrations and solar power intensities on the evaporation performance and efficiencies of the CNT films were discussed in detail.

2. Experimental section

2.1. Preparation of CNT films

Single-wall CNTs were obtained (Solutions Inc., Riverside, CA, USA) and used without any further processing. First, 100 mg of CNTs were homogeneously dispersed into 1000 ml deionized water through 2 h of ultrasonication without surfactant. Subsequently, the prepared CNT dispersion was filtrated onto the surface of porous filter paper (pore size: 2.0 μm, Shanghai Xinya Co., Ltd., Shanghai, China.) and the mass concentration of the CNTs on the filter paper was adjusted by changing

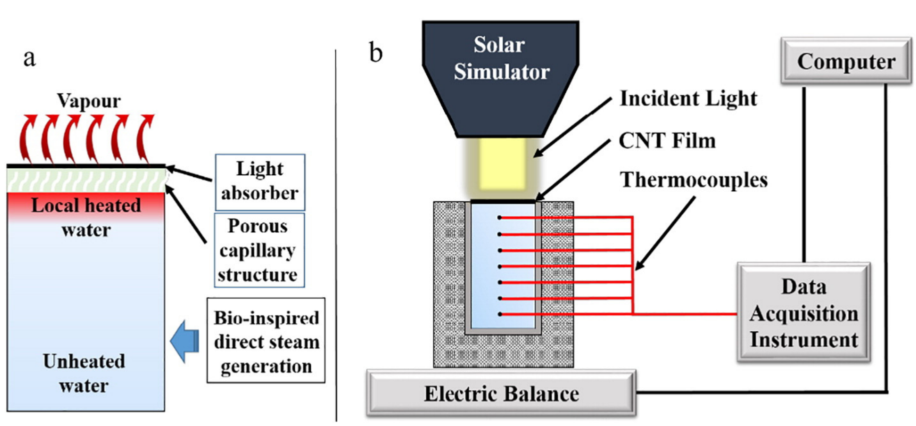

Fig. 1. Schematic diagram of (a) bio-inspired solar steam generation, and (b) the experimental setup for solar steam generation.