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Research Paper

Surrounding effects on the evaporation efficiency of a bi-layered structure for solar steam generation

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HIGHLIGHTS

- A calculation model is developed for a bi-layer solar steam generation system.
- Efficiency linearly depends on temperature of ambient air or/and liquid water.
- An equation is given to describe effects of temperatures of surroundings.
- Thermal insulation at bottom of water is not needed when depth of water is large.
- Thermal conductivity can be not considered when selecting second-layer materials.

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ABSTRACT

The bi-layered structure has drawn a wide interest due to its good performance in solar steam generation. In this work, we firstly developed a calculation model which could capture experiment data well. Then, this model was applied to numerically study the effects of the depth of the bulk water, the temperature of the ambient air, the temperature of the bulk water, the porosity and the thermal conductivity of the second-layer porous material on the evaporation efficiency. Results show that when the depth of the bulk water is large enough, the thermal insulation at the bottom of the bulk water is unnecessary. There is a linear dependence of the evaporation efficiency on the temperature of the ambient air or/and the temperature of the bulk water, and an equation has been given to describe this phenomenon in the text. Compared to the temperature of the ambient air, the temperature of the bulk water has a much larger effect on the evaporation efficiency. The effective thermal conductivity of the second layer, which could impose important effect on the evaporation efficiency, mainly depends on the porosity rather than the thermal conductivity of the second-layer porous material. Thus, when selecting second-layer materials, the thermal conductivity is not an important factor for consideration. This study is expected to provide some information for designing a high-evaporation-performance bi-layered system.

1. Introduction

Contrasting to the traditional evaporation process which requires consumption of fossil energy [1–4], solar-enabled evaporation is green [5–10] and has a potential application in wastewater treatment [11], desalination [12,13], medical sterilization [14] and even for electricity generation [15]. Many efforts have been dedicated to minimize the heat losses and thus to improve the efficiency of water evaporation by using a bi-layered structure, which was firstly reported by Ghasemi et al. [16]. Based on the scheme of the bi-layered structure, some applicable systems have already been successfully developed recently [12,17,18]. For example, a hierarchically nanostructured gel (HNG) based on polyvinyl alcohol and polypyrrole has been developed to serves as an independent solar vapor generator to evaporate water [12]. This floating HNG sample could evaporate water with a rate of $3.2\,\mathrm{kg\,m^{-2}\,h^{-1}}$ via 94% solar energy from 1 sun irradiation, and 18–23 l of water per square metre of HNG can be delivered daily when purifying brine water. Although there are some successful systems, the method to further enhance the evaporation efficiency is still desirable when the evaporation efficiency is usually less than 85%.

In a bi-layered structure, the absorbent material is usually applied as the first layer to absorb sunlight, when a porous material is commonly used as the second layer for water absorption and heat insulation [19–21]. Lots of efforts have been dedicated to find novel first-layer

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Nomenclature

a_w	water activity
c	concentration, mol·m^{-3}
c_{sat}	saturation vapor concentration, mol·m^{-3}
c_{v0}	initial water vapor concentration, mol·m^{-3}
C_p	heat capacity, J·kg^{-1}·K^{-1}
D_{cap}	capillary diffusivity, m^{2}·s^{-1}
D_{eff}	effective vapor diffusivity, m^{2}·s^{-1}
D_{va}	air-vapor diffusivity, m^{2}·s^{-1}
e_b	blackbody hemispherical total emissive power, W·m^{-2}
G	irradiation, W·m^{-2}
H_{vap}	latent heat of evaporation, J·kg^{-1}
$\boldsymbol{I}$	identity matrix
k	thermal conductivity, W·m^{-1}·K^{-1}
k_e	effective thermal conductivity, W·m^{-1}·K^{-1}
K	evaporation coefficient, l·s^{-1}
L_{in}	entrance length, m
M	molecular weight, kg·mol^{-1}
$\boldsymbol{m}$	mass flux, kg·m^{-2}·s^{-1}
$\boldsymbol{n}$	normal vector
P	pressure, Pa
P_{in}	entrance pressure, Pa
P_{out}	exit pressure, Pa
P_{sat}	saturation pressure in second layer, Pa
$\boldsymbol{q}$	heat flux vector, W·m^{-2}
$\boldsymbol{q}_e$	radiation heat flux, W·m^{-2}
q_{eff}	efficient thermal, W·m^{-2}
q_l	thermal loss, W·m^{-2}
q_{tot}	total thermal input, W·m^{-2}
Q_{vap}	the heat of evaporation, W·m^{-3}
R	ideal gas constant, J·mol^{-1}·K^{-1}
r_{pc}	phase change rate, mol·m^{-3}·s^{-1}
S	saturation
S_{iw}	initial water saturation of second layer
T	temperature, K
$\boldsymbol{u}$	velocity, m·s^{-1}
$\boldsymbol{u}_{mean}$	fluid velocity in second layer, m·s^{-1}

Greek letters

φ_p	porosity
μ	viscosity, kg·m^{-1}·s^{-1}
η	evaporation efficiency, %
ε_a	surface absorptivity
ε_r	surface reflectivity
ε_t	surface transmissivity
$\varkappa$	permeability of the porous matrix, m^{2}
$\varkappa_r$	relative permeability, m^{2}
$(\rho C_p)_e$	effective volumetric heat capacity, J·m^{-3}·K^{-1}
ρ	density, kg·m^{-3}

Subscripts

0	ambient air
a	dry air
bottom	lower surface of bi-layered structure
g	gas in second layer
p	porous second layer
fside	front side of bi-layered structure
rside	rear side of bi-layered structure
tot	fluid of second layer
top	top surface of bi-layered structure
v	air in ambient air domain
w	water in second layer
wg	vapor in second layer

materials for high efficiency of light absorbing, such as nanoparticle [18,22,23], activated carbon [24], carbon nanotubes [25,26], polypyrrole [12,27], and graphene [17,28]. The second-layer material also has drawn a wide interest, and the organic porous material is usually applied as the second-layer material because of high capillary-effect performance and low thermal conductivity, such as wood [29,30], polyvinyl alcohol [12], carbonized mushrooms [31], and cellulose nanofibers [32]. Although a large number of studies have been carried out to probe cheap and efficient first or/and second layer materials to increase the evaporation efficiency of the bi-layered structure, to our knowledge, there are few systematic studies to probe proper structures of materials to enhance the evaporation efficiency. The influence of the ambient environment on the evaporation efficiency is also scarcely considered in previous works, when the depth and the temperature of the bulk water could impose important effects on the evaporation efficiency.

In this work, we firstly developed a calculation model for simulating the evaporation process in a bi-layered structure, then this model was verified by experiments. Finally, the model was used to probe the effects of the temperature of the ambient air, the depth and temperature of the bulk water on the evaporation efficiency. This study is expected to provide some information for designing a high-evaporation-performance bi-layered system.

2. Mathematical model

In this section, the physics phenomena associated with the water evaporation in a bi-layered system is introduced firstly. And then, some assumptions are made to simplify the description of the evaporation process in the bi-layered system. Thirdly, governing equations for each phenomenon are given. Finally, the boundary conditions for these governing equations are summarized.

2.1. Physical model

The water evaporation in a bi-layered system is schematically shown in Fig. 1. In such a system, the solar radiation causes a high temperature at the first layer, and this high temperature further heats the second layer which is composed of a porous material and the water holding in it. The high temperature of the second layer could generate vapor, and the capillary effect of the second layer makes sure that the

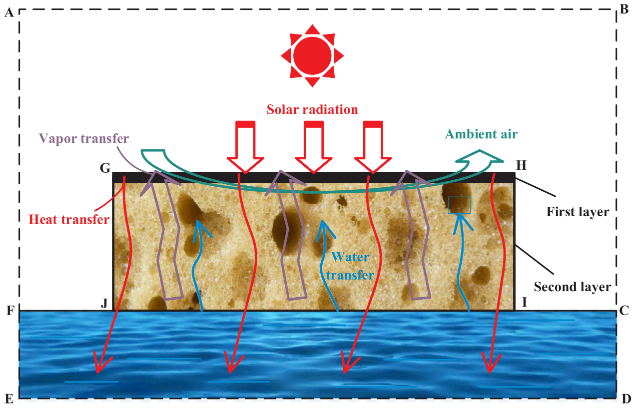

Fig. 1. Schematic bi-layered system for solar steam generation, where the system is composed of the bi-layered structure and its surroundings including the bulk water and the ambient air.