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Technical Note

Influence factors of the evaporation rate of a solar steam generation system: A numerical study

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ABSTRACT

Many efforts have been dedicated to improve the solar steam generation by using a bi-layer structure. In this paper, a two-dimensional mathematical model describing the water evaporation in a bi-layer structure is firstly established and then the finite element method is used to simulate the effects of different influence factors on the evaporation rate. Results turn out that: besides the high solar energy absorptivity of the first-layer, an optimum porosity of the second-layer porous material should be applied and the optimum porosity is about 0.45 in this work. This optimum porosity is determined by the balance between the positive effect of the lowering effective thermal conductivity of the second layer and the negative effect of the reduced vapor diffusivity in the second layer when the porosity is decreased. The influence of the thermal conductivity of the second-layer porous material is negligible because the effective thermal conductivity of the second layer is determined by the porosity while a larger porosity means more water in the second layer. The ambient air velocity could greatly enhance the evaporation rate, and the evaporation rate will decrease linearly with the increase of the air relative humidity. This study is expected to supply some information for developing a more effective bi-layer solar steam generation system.

1. Introduction

Solar-enabled evaporation is a solar energy harvesting technology which has a potential application in modern power plants, chemical plants, and seawater desalination plants [1–9]. Recently, by applying a bi-layer structure for solar steam generation which was firstly proposed by Ghasemi et al. [10], many efforts have been dedicated to minimize the heat losses and thus to improve the evaporation efficiency of water. In a bi-layer structure, the first layer is the absorbent material used to absorb sunlight, and the second layer is a porous material for water absorption and heat insulation. A large number of interests have been focused on finding novel first-layer nanomaterials for high efficiency of light absorbing, such as, gold nanoparticle [11], graphene [12,13], carbon black nanoparticles [14,15], carbon foam [10], activated carbon[16] and carbon nanotubes [17]. The porous material is usually applied as the second layer material because of its high capillary effect and low thermal conductivity [18,19], such as wood [20,21], carbonized wood [22], carbonized mushrooms [23], and cellulose nanofibers [24]. Although a large number of studies have been carried out to look for cheaper and more efficient materials to increase the evaporation rate of the bi-layered structure for solar steam generation, to our knowledge, there is still no detailed study about the influence factors of the evaporation process in a bi-layer system, especially the ambient air velocity, the porosity of the second layer, etc.

In this paper, a two-dimensional mathematical model describing the water evaporation in a bi-layer system is firstly established, and then the finite element method is used to simulate the effects of different influence factors on the evaporation process, such as the ambient air velocity, the air relative humidity, the absorptivity of the first-layer material, the porosity and the thermal conductivity of the second-layer material. It shows that the thermal conductivity of the second layer is not as important as it assumed to be [25], and there is an optimum porosity for the second layer to enhance the evaporation rate. This study is expected to supply some information for developing a more effective bi-layer solar steam generation system.

2. Physical model and simulation methods

The water evaporation in a bi-layer system is schematically shown in Fig. 1(a). In such a system, the solar radiation causes a high temperature in the first layer, and this high temperature

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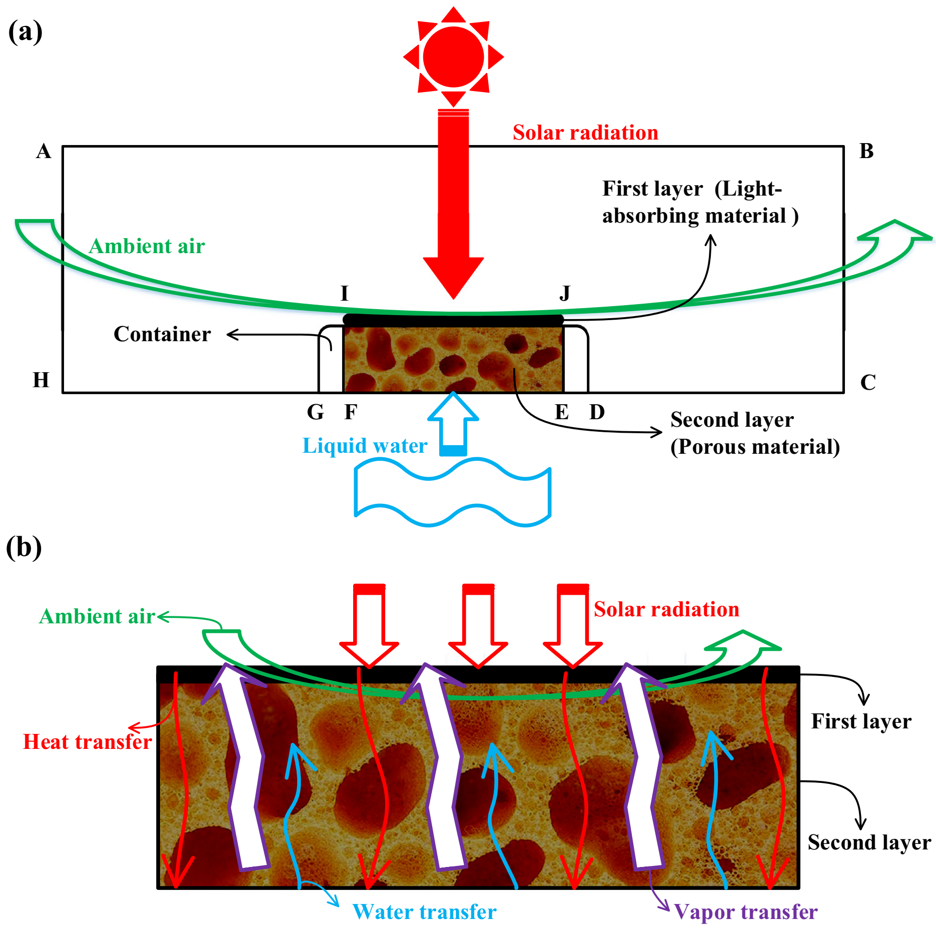

Fig. 1. Schematic bi-layer system for solar steam generation: (a) system under solar radiation; (b) the detail of the heat and mass transfer in the second layer.

further heats the second layer which is composed of a porous thermal insulation material for preventing the heat further transferring to the liquid water. The high temperature of the second layer could lead to vapor generation, and the capillary effect makes sure that the liquid water will flow into the second layer to replenish the water loss caused by the evaporation, as shown in Fig. 1(b). Accompanying this process, the ambient gas flows through the upside of the first layer, and the air could diffuse into the second layer and takes away the vapor. It is clear that there are three different physical processes in this system as shown in Fig. 1(b). To analyze such a system, we make the following assumptions:

(1) Ignoring the thickness of the first layer and regard it as an optic diffuse surface;
(2) The structure of the second layer is isotropic;
(3) Ignoring the radiation of the second layer to the environment;
(4) The viscosity dissipation like heat transfer and work caused by pressure changing is not considered to meet the assumption of local thermal equilibrium;
(5) The vapor is in equilibrium with the liquid or in other words, the time scale for evaporation is much smaller than the smallest time scale of the transport equations;
(6) The second layer absorbs water only from the bottom surface;
(7) The ambient-air flow is assumed to be laminar.

Under the above assumptions, the governing equations for each part of the system are solved by the Finite Element Method. The following size for the computational domain is applied: the lengths of AB, HA, IJ, JE, IF, and FG is respectively 90, 50, 30, 5, 5, and 1 mm. Governing equations, simulation technical details and the model verification can be found in Ref. [26,27].

3. Results and discussions

3.1. Influence of the ambient air velocity and relative humidity

It is difficult to keep the air static in a solar steam generation system, especially when the air is expected to take away the vapor. Thus, we need to consider the impact of the air velocity in the evaporation process. With the air velocity changing from 0.05 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$, the simulated evaporation rate is shown in Fig. 2(a)–(c). It can be found that the evaporation rate increases with the rise of the air velocity, after the air velocity reaching 0.5 $m \cdot s^{-1}$, the evaporation rate gradually tends to be a constant, as that shown in Fig. 2(a). This can be understood by that the air can take away more vapors from the second layer as the air velocity increases, and the evaporation rate tends to be a constant because the amount of vapor produced per unit time is limited by the combined effect of the porosity of the second layer and other influence factors which will be discussed in the following parts in this work. This is confirmed by that there is a lower vapor concentration in the second layer for the air velocity of 2 $m \cdot s^{-1}$ than that for the air velocity of 0.05 $m \cdot s^{-1}$, as that shown in Fig. 2(b) and (c).

The air relative humidity is also an important factor affecting the evaporation rate. The influence of the air relative humidity