Supporting Information

Three-Dimensional Porous Solar-Driven Interfacial Evaporator for High-Efficiency Steam Generation under Low Solar Flux

Chao Chang, Peng Tao*, Benwei Fu, Jiale Xu, Chengyi Song, Jianbo Wu, Wen Shang, Tao Deng*

State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

*Email: taopeng@sjtu.edu.cn; dengtao@sjtu.edu.cn
Heat loss analysis of 3D porous interfacial evaporator

The energy transfer model of the 3D porous interfacial evaporator is shown in Figure S1. Based on energy conservation principle, the following equation can be obtained

\[ q_{solar} \cdot T_{quartz} \cdot \alpha_{abs} = q_{rad,abs} + q_{conv,abs} + q_{cond,water} + q_{evap} \quad (S.1) \]

where \( T_{quartz} \) is the quartz transmittance (0.93), \( \alpha_{abs} \) is the absorber absorptance (0.95), \( q_{rad,abs} \) and \( q_{conv,abs} \) are the radiation and convection heat loss of the selective absorber, \( q_{cond,water} \) is the conduction heat loss from the PDMS foam to the water underneath. Among them, \( q_{rad,abs} \), \( q_{conv,abs} \) and \( q_{cond,water} \) can be calculated by

\[ q_{rad,abs} = \varepsilon_{abs} \sigma (T_{s}^4 - T_{\infty}^4) \quad (S.2) \]

\[ q_{conv,abs} = h_{abs} (T_{s} - T_{quartz}) \quad (S.3) \]

\[ q_{cond,water} = \frac{k_{f}}{d_{f}} (T_{top} - T_{down}) \quad (S.4) \]

where \( \varepsilon_{abs} \) is the emittance of the spectrally selective absorber (0.05), \( \sigma \) is the Stefan-Boltzmann constant \( 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \), \( T_{s} \) is the selective absorber temperature, \( T_{\infty} \) is the ambient temperature (20 °C), \( T_{quartz} \) is the temperature of quartz, \( h_{abs} \) is the convection heat transfer coefficient between the quartz and absorber (5.8 W/(m²K)),\(^1\) \( k_{f} \) is the thermal conductivity of the PDMS foam (0.03 W/(m K)) and \( d_{f} \) is the thickness of the PDMS foam (3 cm), \( T_{top} \) and \( T_{down} \) are the temperature at the top surface and bottom surface of the PDMS foam, respectively.

The steam generation efficiency (\( \eta \)) can be calculated by

\[ \eta = T_{quartz} \cdot \alpha_{abs} - \frac{q_{rad,abs} + q_{conv,abs} + q_{cond,water}}{q_{solar}} \quad (S.5) \]

In this case, the surface temperature of the absorber (\( T_{s} \)) is 100 °C. The top surface temperature (\( T_{top} \)) and bottom surface temperature (\( T_{down} \)) of the PDMS foam were measured to be 80 °C and 40 °C under 1 sun. The temperature at the quartz
cover surface \( T_{\text{quartz}} \) was measured to be 50 °C. According to Eq. (S.2)-(S.4), the radiation, convection and conduction heat loss is 34 W/m², 290 W/m² and 40 W/m², respectively. Based on Eq. (S.5), the theoretical solar-to-steam conversion efficiency of the 3D porous interfacial evaporator model was calculated to be 51%.

**Influence of copper foam surface wettability**

For the hydrophilic copper foam, it is modeled as a composite foam material with homogeneously adsorbed water on the whole surface (Figure S6a). For the spectrally selective solar absorber, the energy balance gives:

\[
q_{\text{solar}} \cdot \alpha_{\text{abs}} = q_{\text{conv}} + q_{\text{rad}} + q_{\text{cond}}
\]  

(S.6)

where \( q_{\text{solar}} \) is the solar flux, \( \alpha_{\text{abs}} \) is the absorbance of the absorber, and \( q_{\text{conv}}, q_{\text{rad}} \) and \( q_{\text{cond}} \) are the convection, radiation and conduction heat transfer, respectively. The convection, radiation and conduction heat transfer can be calculated by

\[
q_{\text{conv}} = h(T_s - T_{\infty})
\]  

(S.7)

\[
q_{\text{rad}} = \varepsilon_{\text{abs}}\sigma(T_s^4 - T_{\infty}^4)
\]  

(S.8)

\[
q_{\text{cond}} = \left(\frac{1}{R_t} + \frac{k_{cw}}{d}\right)(T_s - T_w)
\]  

(S.9)

where the \( k_{cw} \) is the effective thermal conductivity of the copper foam and water composite, and \( d \) is the thickness of copper foam (5 cm). The thermal contact resistance between the selective absorber and copper foam \( R_t \) is approximately estimated as \( 7 \times 10^{-4} \) m² K/W². By defining the \( \varepsilon_{\text{abs}}\sigma(T_s^2 + T_{\infty}^2)(T_s + T_{\infty}) \) term as the radiation heat transfer coefficient \( (h_r) \), the radiation can be written as

\[
q_{\text{rad}} = h_r(T_s - T_{\infty})
\]  

(S.10)

Substituting Eq. (S.7)-(S.10) into Eq. (S.6), the surface temperature of the absorber \( T_s \) can be calculated by
In the hydrophobic copper foam or the copper foam with hybrid surface wettability, water is only partially adsorbed onto the surface (Figure 6b). We defined the water wicking thickness as \( l \) \( (0 \leq l < d, \ d \) is the thickness of copper foam), and the temperature at water interface as \( T_i \). Different from the hydrophilic copper foam, the conduction heat loss term in the partially wetted copper foam is expressed as

\[
q_{\text{cond}} = \left( \frac{1}{R_t} + \frac{k_c}{d-l} \right) \cdot (T_s - T_i)
\]

(S.12)

where \( k_c \) is the copper foam thermal conductivity. Through similar derivation, \( T_s \) can be expressed as

\[
T_s = \frac{q_{\text{solar}} \cdot \alpha_{\text{abs}} + (h + h_r) \cdot T_\infty + \left( \frac{1}{R_t} + \frac{k_{cw}}{d} \right) \cdot T_W}{h + h_r + \frac{1}{R_t} + \frac{k_{cw}}{d}}
\]

(S.11)

To generate steam, the water on the copper foam should reach its boiling temperature, and thus \( T_i \) is equal to 100 °C. In the system, the heat loss mainly includes convection loss \( q_{\text{conv}} \) and radiation loss \( q_{\text{rad}} \), and most of \( q_{\text{cond}} \) is used to generate steam. Therefore, the overall solar-to-steam energy conversion efficiency can be approximately estimated by

\[
\eta = T_{\text{quartz}} \cdot \alpha_{\text{abs}} - \frac{q_{\text{conv}} + q_{\text{rad}}}{q_{\text{solar}}}
\]

(S.14)

Based on Eq. (S.12) - (S.14), we can obtain the evolution of evaporation efficiency with \( l \) (Figure S7).

**COMSOL model**

A 3D COMSOL model was built to analyze the temperature distribution of the steam generator with hybrid hydrophilic-hydrophobic copper foam. The following assumptions are made: (1) the model is considered as two dimensional axisymmetric;
the interfacial thermal resistance between each component of the evaporation system is not considered; (3) the physical parameters of materials are constant.

The transparent quartz cover with a diameter of 42 mm was placed on top of the solar-steam generator to reduce the convection heat loss. The convection heat transfer coefficient between the quartz surface and atmosphere was assumed to be 10 W/m²K. The solar power absorbed by the selective absorber \( (q_{abs}) \) can be calculated by

\[
q_{abs} = q_{solar} \cdot T_{quartz} \cdot \alpha_{abs}
\]

where \( q_{solar} \) is the solar flux, varying from 1000 W/m² to 5000 W/m², \( T_{quartz} \) is the transmittance of the quartz (0.93) and \( \alpha_{abs} \) is the absorptance of the spectrally selective absorber (0.95).

By measuring the weight of the copper foam before and after adsorbing water, it was determined that the amount of water adsorbed by the hydrophobic, hybrid wettability and hydrophilic copper foam are 0, 20 and 50 vol\%, respectively. A rule of mixture model was used to evaluate the influence of adsorbed water on the physical properties of the copper foam. The physical properties of copper foam with different wettability can be calculated by:

\[
\rho_{cw} = \eta_c \rho_c + \eta_w \rho_w
\]

\[
c_{pw}^{cw} = \eta_c c_p^c + \eta_w c_p^w
\]

\[
k_{cw} = \eta_c k_c + \eta_w k_w
\]

where \( \rho, c_p, k \) represent the density (kg/m³), special heat capacity (J/kg K) and thermal conductivity (W/m K), and \( \eta_c \) and \( \eta_w \) are the volume faction of copper and water, respectively. Among them, \( \eta_c \) is 4\% based on the porosity of the copper foam (30 ppi).

The transient heat transfer in the 3D model is governed by:

\[
\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = q
\]
where $\rho$, $c_p$, $k$, $T$ and $q$ are the density, special heat, thermal conductivity, temperature and input energy in each simulation unit, respectively. Among them, the specific heat $c_p$ includes both the sensible heat and the latent heat $h_{lv}$. The dependence of evaporation latent heat on the temperature of the evaporator was established by Equation (S. 20) and Equation (S. 21) as shown below.

The evaporation phase-change energy $q_e$ can be calculated by:

$$q_e = \dot{m} \cdot h_{lv} \quad \text{(S. 20)}$$

where $\dot{m}$ is the mass flux and $h_{lv}$ is the enthalpy of phase change. Here, the evaporation process was considered to have a stable evaporation mass flux and gradually increased latent heat with increasing vapor temperature.

At the vapor-liquid interface, the phase change heat transfer can also be described by

$$q_e = \left[ \frac{2\tilde{\sigma}}{(2-\tilde{\sigma})} \right] \left( \frac{h_{lv}^2}{T_v \nu_{lv}} \right) \left( \frac{\tilde{M}}{2\pi R T_v} \right)^{1/2} \left[ 1 - \frac{P_v \nu_{lv}}{2h_{lv}} \right] (T_v - T_l) \quad \text{(S. 21)}$$

where the $\tilde{\sigma}$ is constant (0.03), $\tilde{M}$ is the molecular weight of water (18 g/mol), $\tilde{R}$ is Avogadro’s number (8.314), $\nu_{lv}$ is the specific gravity of water vapor (1.672 m$^3$/kg), and $P_v$ is the atmospheric pressure. By solving Equation (S. 19), the time-dependent temperature distribution of the evaporation system can be calculated.

**Supporting References:**

(1) Elenbaas, W. Heat Dissipation of Parallel Plates by Free Convection. *Physica* 1942, 9, 1-28.

(2) Ji, Y.; Li, G.; Ma, H.; Sun, Y. Experimental Study of VACNT Arrays as Thermal Interface Material. *in Proc. ASME International Conference on Micro/Nanoscale Heat and Mass Transfer, The American Society of Mechanical Engineers, Hong Kong 2013.*

(3) Carey, V. P. Liquid-Vapor Phase-Change Phenomena: An Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer
Figure S1. Theoretical heat loss analysis of 3D porous solar-driven interfacial evaporator. (a) Schematic structure for the 3D porous interfacial evaporator. (b) Schematic energy transfer diagram.

Figure S2. Transmittance spectrum of transparent quartz cover.
**Figure S3.** Contact angle measurements for (a) untreated copper foam surface and (b) fluorosilane-treated hydrophobic copper foam surface.

**Figure S4.** Temperature evolution of spectrally selective absorber in steam generators with different surface wettability.
Figure S5. Temperature evolution of different components in the steam generator with hybrid surface wettability.

Figure S6. Schematic heat transfer in the evaporator with different surface wettability. (a) Hydrophilic evaporator in which water is fully adsorbed onto the copper foam surface. (b) Copper foam with hybrid wettability where water is partially adsorbed. The blue color represents water.
Figure S7. Evaporation efficiency of the 3D porous solar-driven interfacial evaporator as a function of the wetted thickness of the copper foam ($l$).