All-in-one and scalable carbon fiber-based evaporator by weaving craft for high-efficiency and stable solar desalination

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Materials and Methods

Fabrication of Carbon fiber and cotton yarn mixture fabrics (CCMFs)

CCMFs were fabricated from commercial carbon fiber bundles and cotton yarns through conventional textile weaving. First, pristine cotton yarns underwent hydrophilic treatment involving immersion in a 4 mg/L aqueous detergent solution at 100 °C for 0.5 h. The specific fabricating procedure of CCMF is as follows: the cotton yarns are first arranged in the warp direction, and then the carbon fiber bundles and cotton yarns are arranged in the weft direction. For the CCMF, four levels of fabrics were used, i.e., 1/1 plain, 2/1 twill, 3/1 twill, and 4/1 satin, with the corresponding CCMFs termed as CCMF-1, CCMF-2, CCMF-3, and

CCMF-4.

Characterization

The morphologies of all the samples were observed through a field-emission SEM (Sigma 500, Zeiss, Germany) and a digital microscope (DSX510, Olympus, Japan). The light absorption of fabrics was obtained through a UV–vis–NIR spectrometer (UV-3600Plus, Shimadzu, Japan) equipped with an integrating sphere.

Experiment for Solar Steam Generation

Steam generation experiments were conducted in the laboratory, where the temperature and humidity were controlled at ~22 °C and ~60%, respectively. A solar simulator (Xenon lamp, CELHXF300, Education Au-light Co Beijing, China) was applied to simulate sunlight. Then, the real-time mass loss of water was recorded through an electronic balance with an accuracy of 0.0001 g to determine the evaporation rate and energy-conversion efficiency.

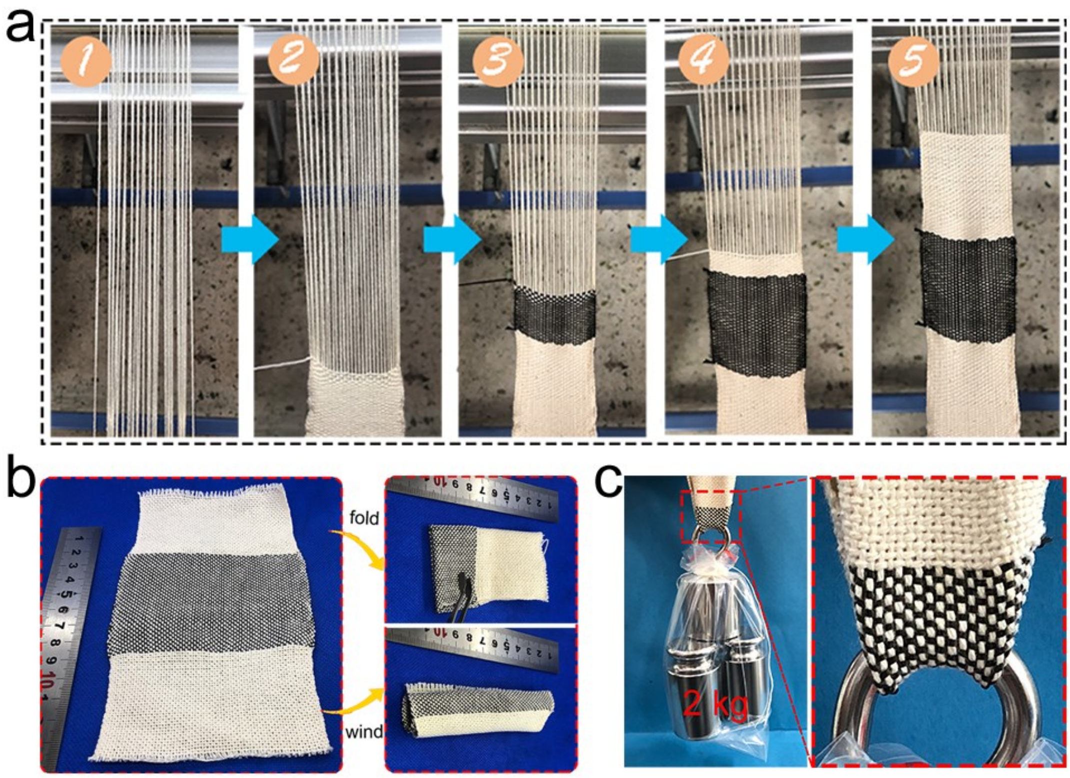

Figure S1. (a) Optical images of the fabrication process of CCMF-1. The flexibility (b) and mechanical property (c) of CCMF-1.

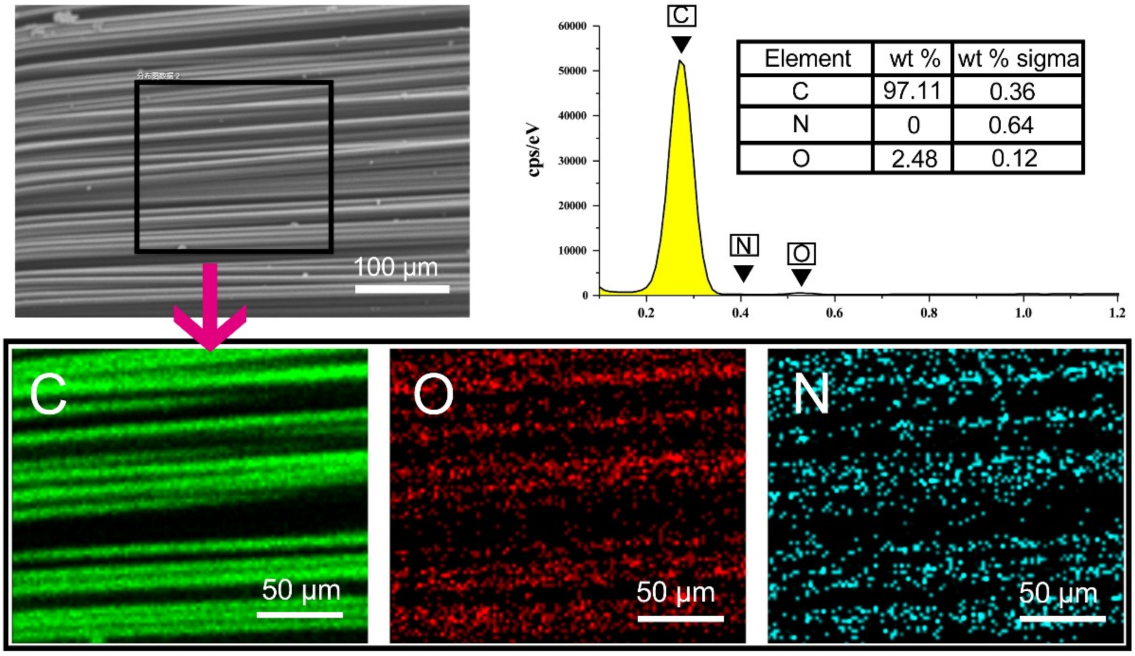

Figure S2. Elemental composition (C, O, and N) and (c) maps of carbon fiber bundle.

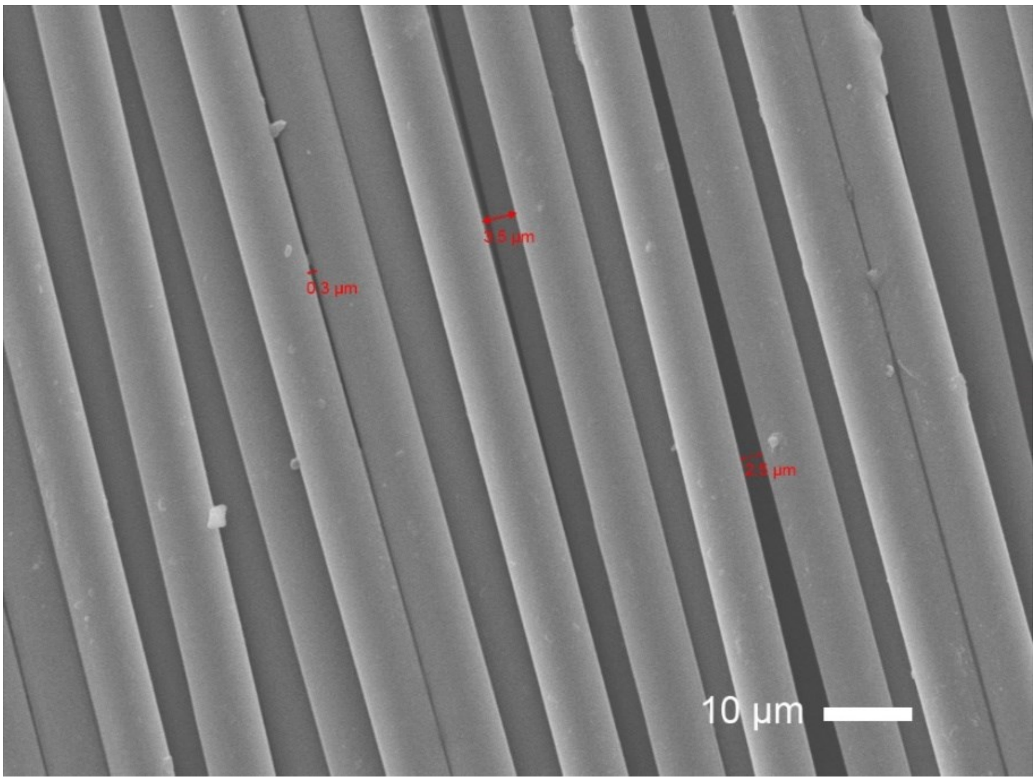

Figure S3. The size of the gap between the adjacent carbon in carbon fiber bundle.

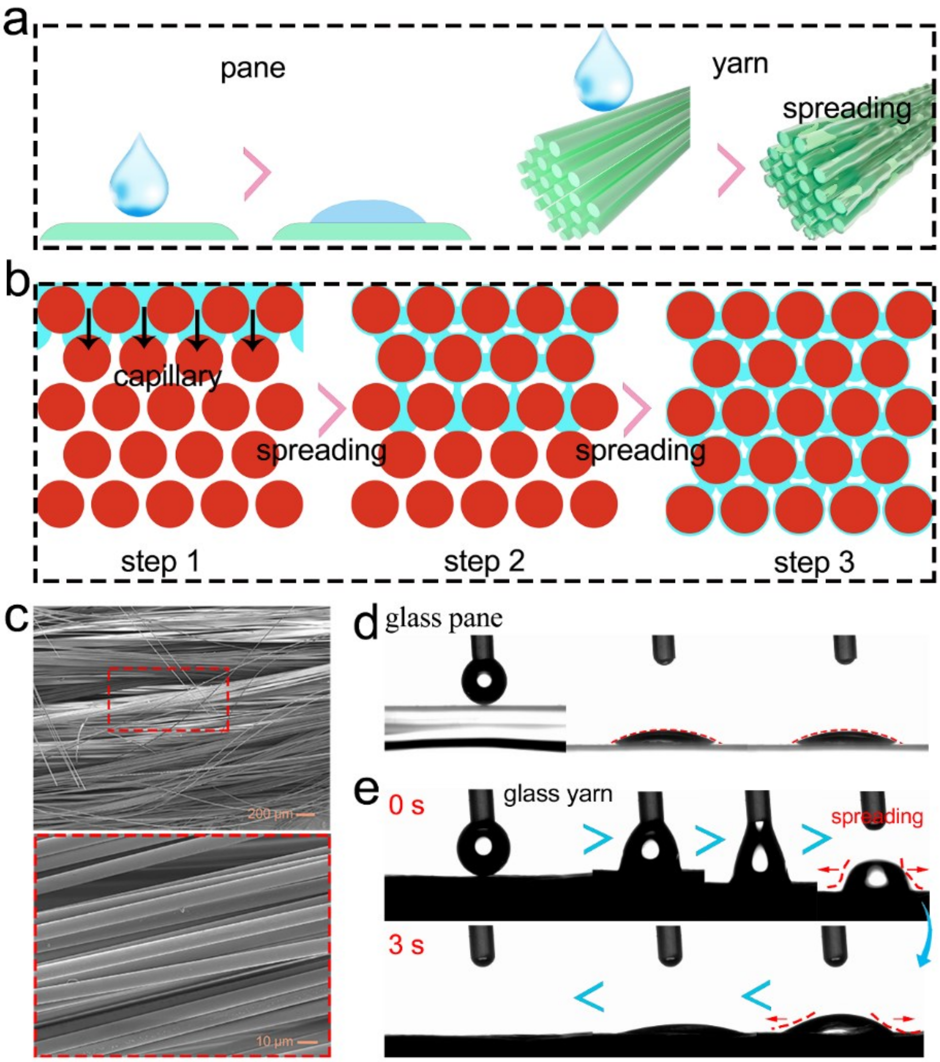

Figure S4. (a) Schematics showing that the water spreading on the pane and yarn when water drop contacts the corresponding surfaces. (b) A series of cross-sectional views showing the dynamic formation of the water wetting process on yarn. (c) SEM images of glass fiber yarn. The water contact angle of glass pane (d) and glass yarn (e).

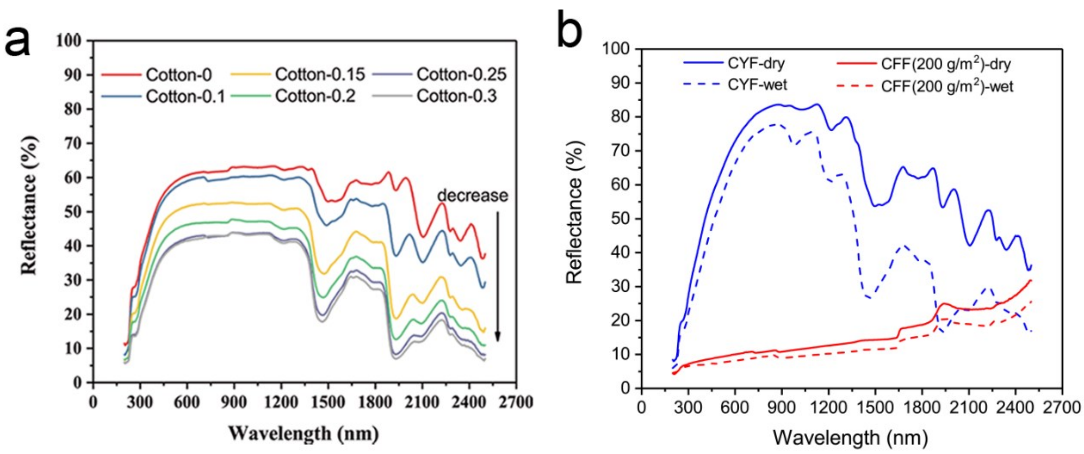

Figure S5. (a) Reflectance spectra of the wet cotton fabric in the wavelength range of 250~2500 nm (cotton-X is regarded as cotton fabric with different water weight (X) in volume (ml)). (b) Reflectance spectra of the wet and dry CYF and CFFs in the wavelength range of 250~2500 nm.

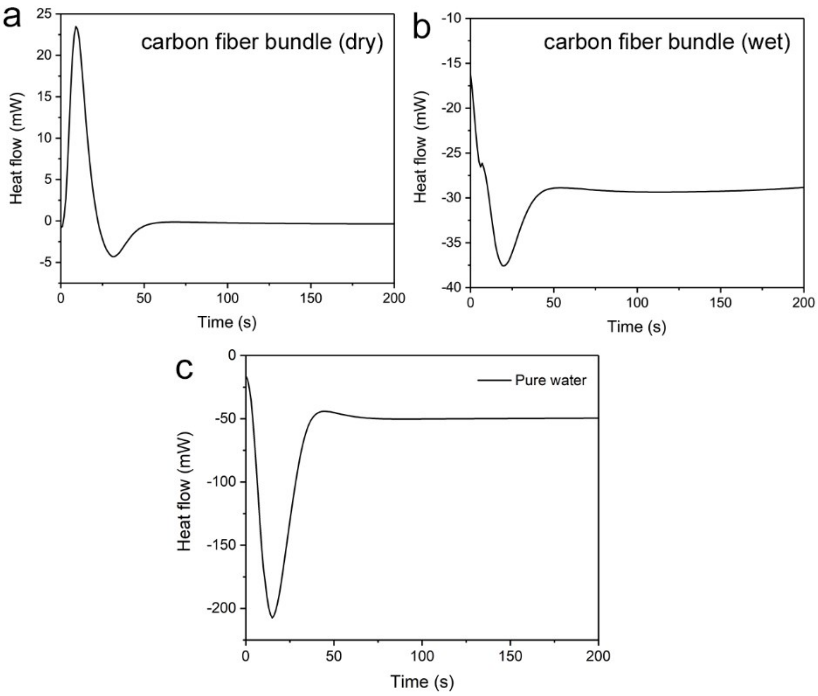

Figure S6. DSC spectra of carbon fiber at (a) dry and (b) wet state in the temperature range from 25 to 40 °C. (c) DSC spectra of pure water in the temperature range from 25 to 40 °C.

Vaporization enthalpy of water in carbon fiber bundle

The vaporization enthalpy of water in the carbon fiber bundle was estimated by DSC measurement.[1] During solar steam generation, the surface temperature of the most absorbers is about 40 °C in solar interfacial evaporation stills, which is far below 100 °C.[2] Hence, during the vaporization enthalpy measurements, samples were placed in an open Al crucible and measured in the temperature range from 25 to 40 °C. The vaporization enthalpy of water in carbon fiber bundle (H_T) at 40 °C was calculated by the following equation:

$$H_T = \frac{\Delta Q}{\Delta m} \tag{1}$$

Where ΔQ is the heat energy required for evaporating water in the wet carbon fiber bundle, Δm (4.78 mg) is the weight of the evaporated water in this experiment.

$$\Delta Q = Q_1 - Q_2 - Q_3 \tag{2}$$

Where Q_1 (8835 mJ) and Q_2 (95 mJ) that are calculated according to DSC spectra of carbon fiber at dry and wet state are the adsorption heat for the wet carbon fiber and dried carbon fiber in this experiment, respectively. These values of the adsorption heat are calculated according to the DSC spectra of the dried and wet carbon fiber (Figure S6). Q_3 (378 mJ) is the sensible heat of the wet carbon fiber from 25 to 40 °C.

$$Q_3 = Cm\Delta T \tag{3}$$

C is the specific heat capacity of water (4.2 kJ °C^{-1} kg^{-1}), m (6 mg) is the weight of water in wet carbon fiber bundle used in this experiment. ΔT (15 °C= 40-25 °C) is the different value in this experiment.

The corresponding vaporization enthalpy of water in carbon fiber bundle is 1749 J g^{-1} according to DSC measurement.

Vaporization enthalpy of bulk water

Fig. S6c was the DSC spectra of pure water. The vaporization enthalpy of bulk water (H_T) at 50 °C was calculated by the following equation:

$$H_T = \frac{\Delta Q}{\Delta m} \tag{1}$$

Where ΔQ is the heat energy required for evaporating water, Δm (32 mg) is the weight of the evaporated water in this experiment.

$$\Delta Q = Q_1 - Q_2 \tag{2}$$

Where Q_1 (85283 mJ) calculated according to DSC spectra of pure water is the adsorption heat in this experiment, respectively. These values of the adsorption heat are calculated according to the DSC spectra of the dried and wet carbon fiber (Figure S6c). Q_2 (3360 mJ) is the sensible heat of the wet carbon fiber from 25 to 50 °C.

$$Q_2 = Cm\Delta T \tag{3}$$

C is the specific heat capacity of water (4.2 kJ °C^{-1} kg^{-1}), m (32 mg) is the weight of water used in this experiment. ΔT (25 °C= 50-25 °C) is the different value in this experiment.

The corresponding vaporization enthalpy of bulk water is 2560 J g^{-1} according to DSC measurement, which is close to the theoretical value.

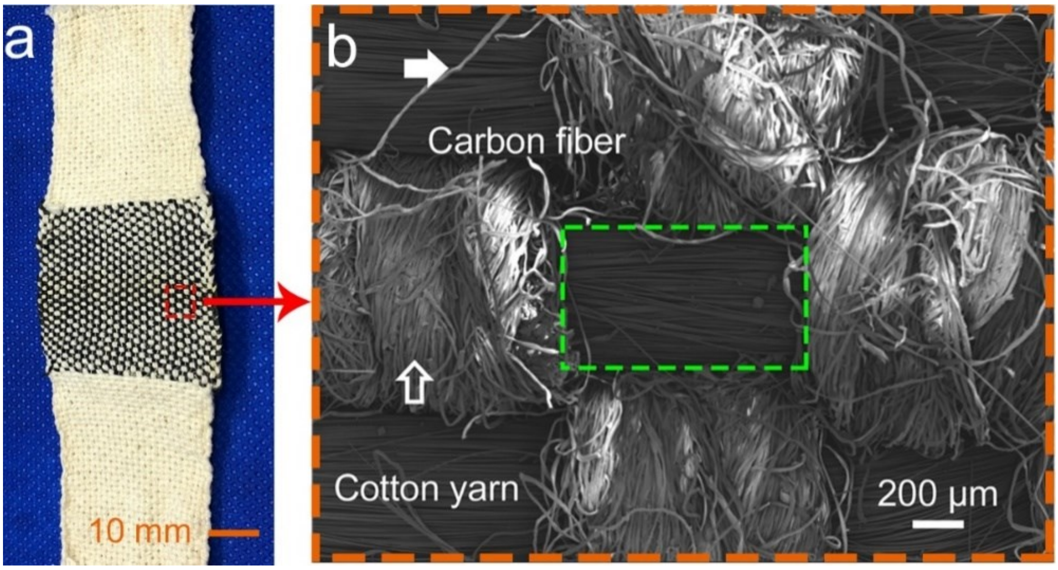

Figure S7. (a) Optical images of CCMF-1. (b) The SEM image of the obtained CCMF-1.The solid arrows and hollow arrows indicate carbon fiber bundle and cotton yarn, respectively.

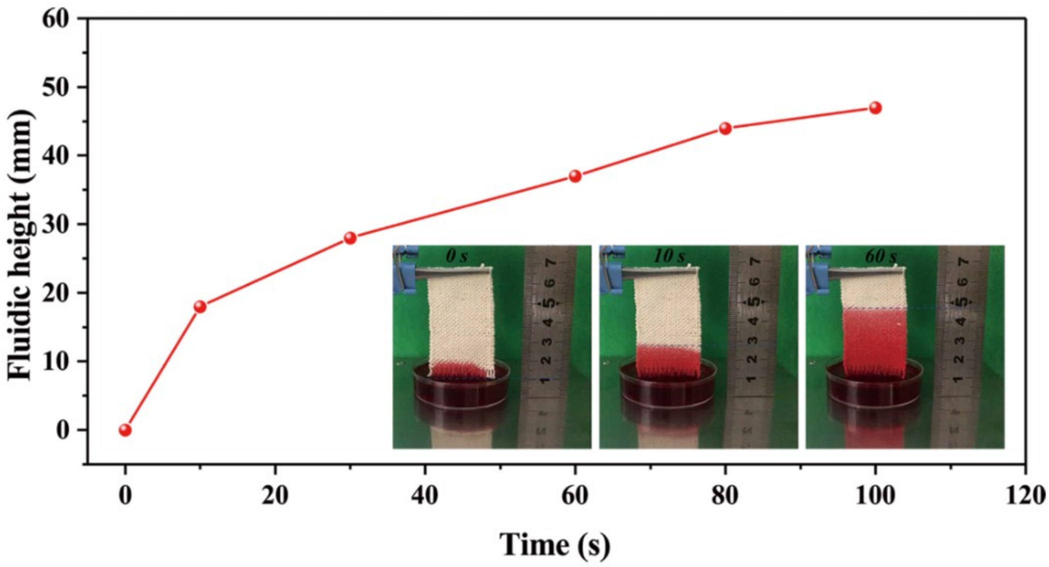

Figure S8. The rate of fluidic transport of cotton yarn fabric in the warp direction.

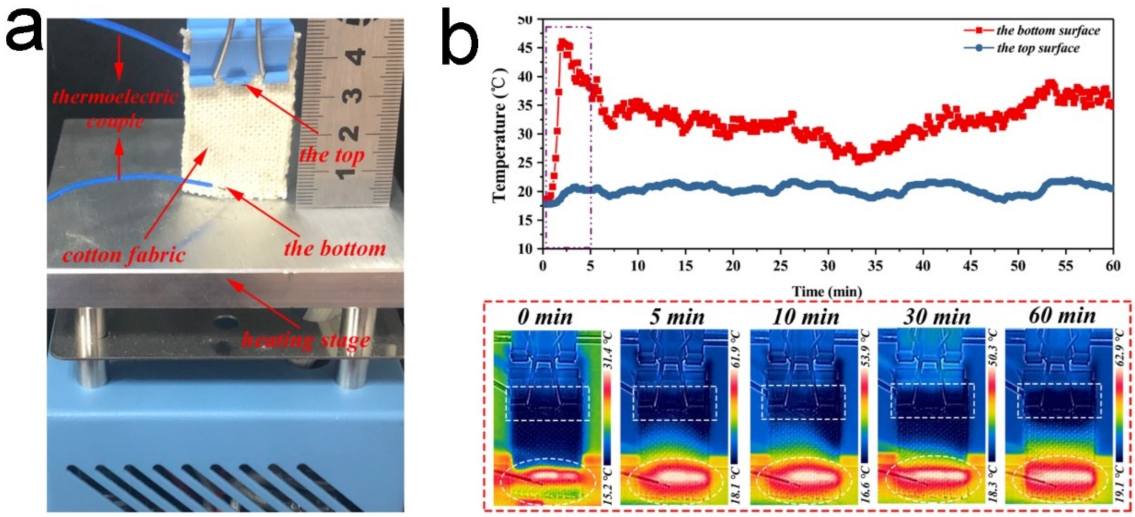

Figure S9. (a) The optical image of a device for the property of thermal conductivity of cotton yarn fabric. (b)The real-time temperature of the top and bottom of cotton yarn fabric in the warp direction. (c) The corresponding infrared images.

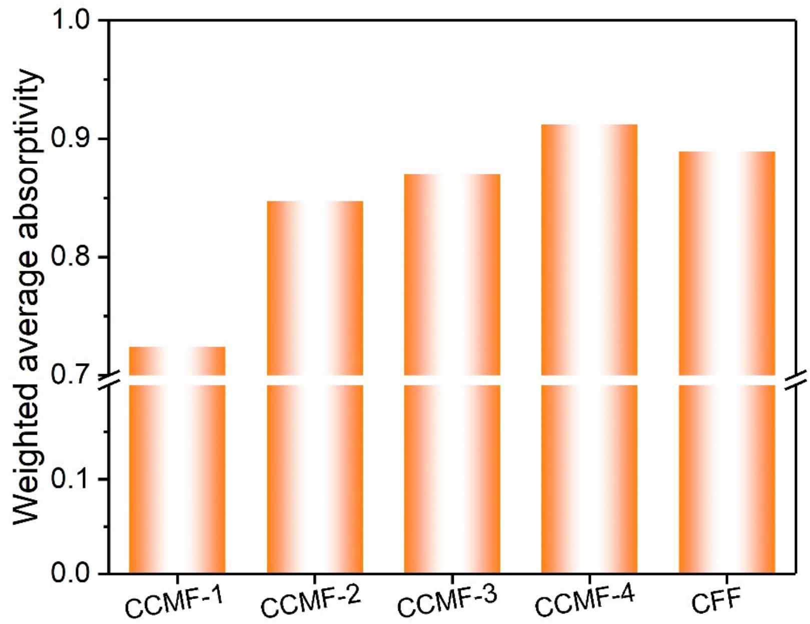

Figure S10. The weighted average absorptivity of various samples in solar spectrum region (280-2500 nm).

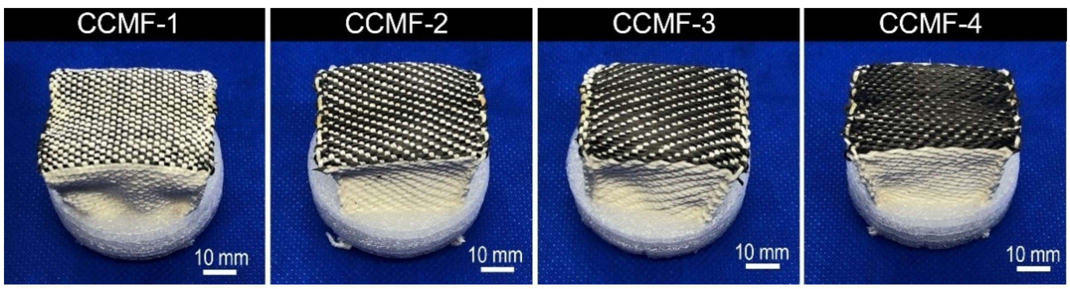

Figure S11. Optical images of CFFs based evaporator.

Figure S12. The tissue paper placed on the top of CCMF-4 can be wetted before and after 8 h illumination under 1 sun.

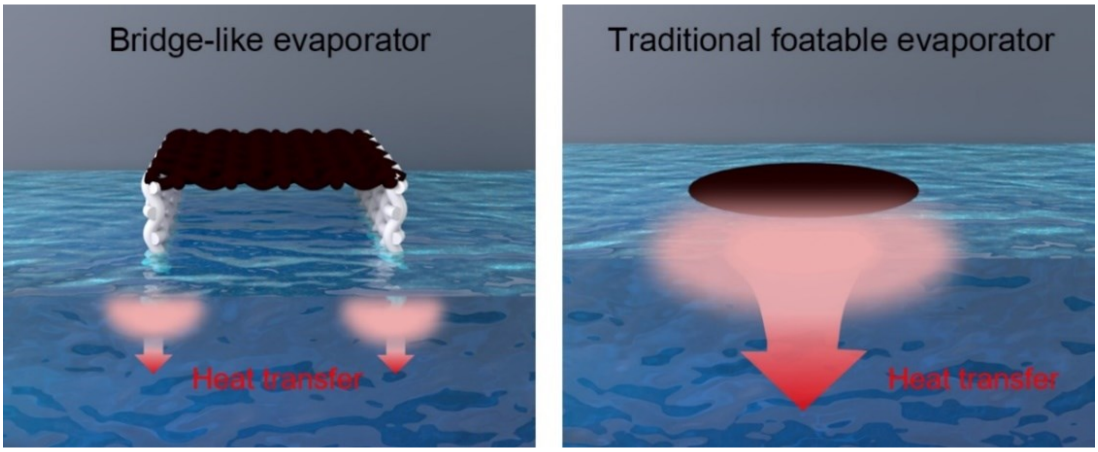

Figure S13. Schematic illustration of heat loss of bridge-like evaporator and traditional evaporator. Heat loss can be controlled by minimizing the contact area with the bulk water in a bridge-like evaporator.

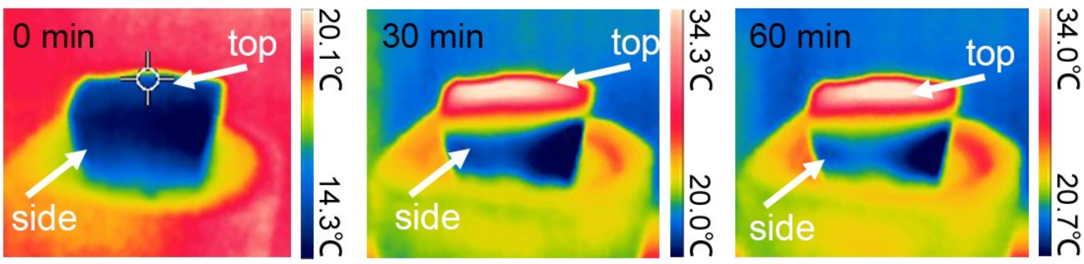

Figure S14. Side and top view of Infrared images of the CCMF-4 based evaporator under 1 sun.

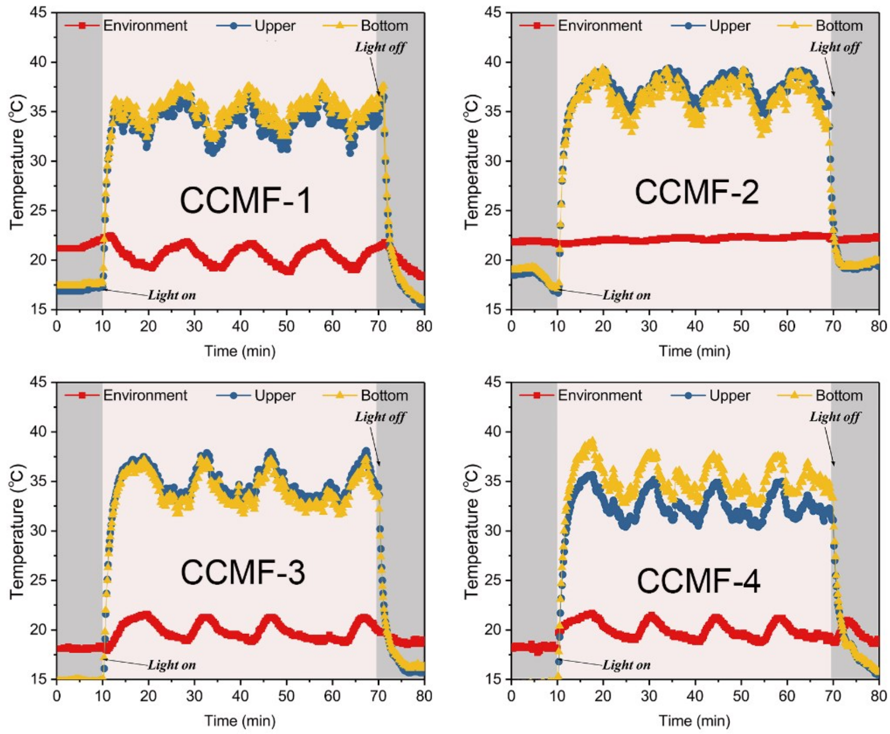

Figure S15. Temperature changes of CCMFs resulting from switching 1 sun illumination on and off.

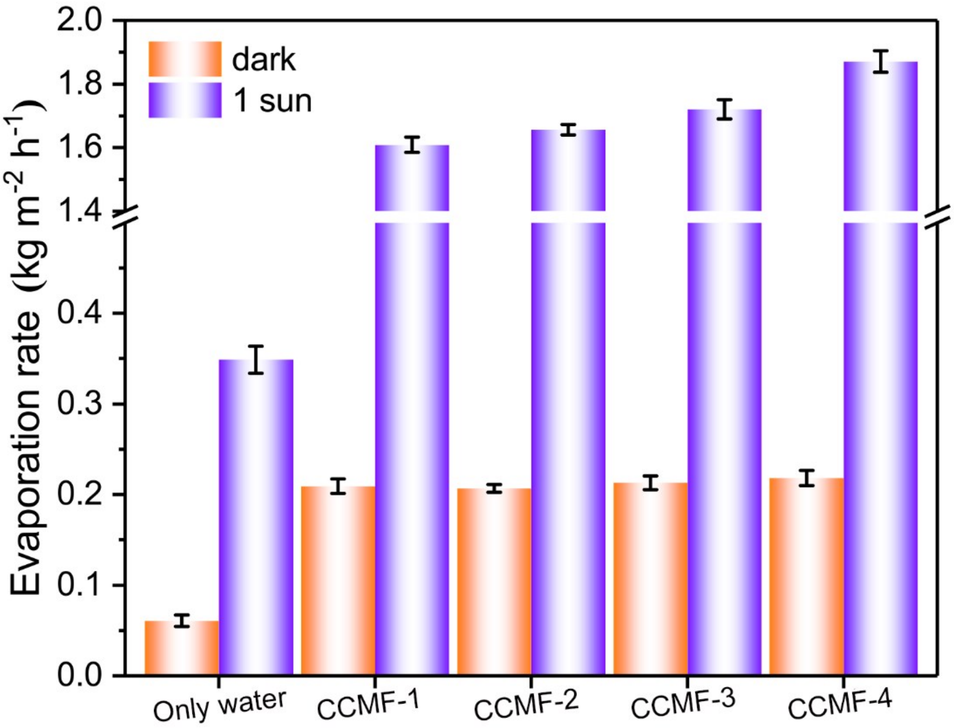

Figure S16. The average evaporation rate of water and CCMFs under the dark condition and 1 sun.

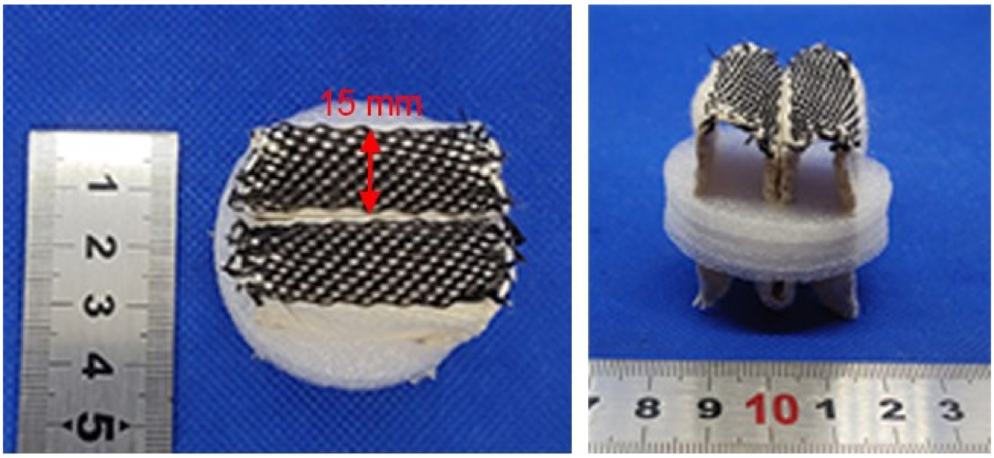

Figure S17. Optical image of CCMF-4 based solar generation device with salt resistance.

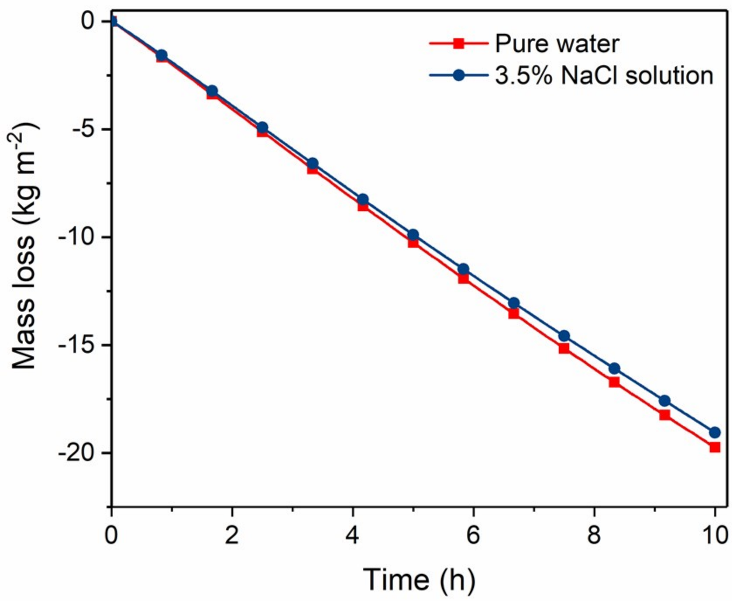

Figure S18. Mass loss of pure water and 3.5% NaCl solution through CCMF-4 under 1 sun illumination as a function of time (10 h).

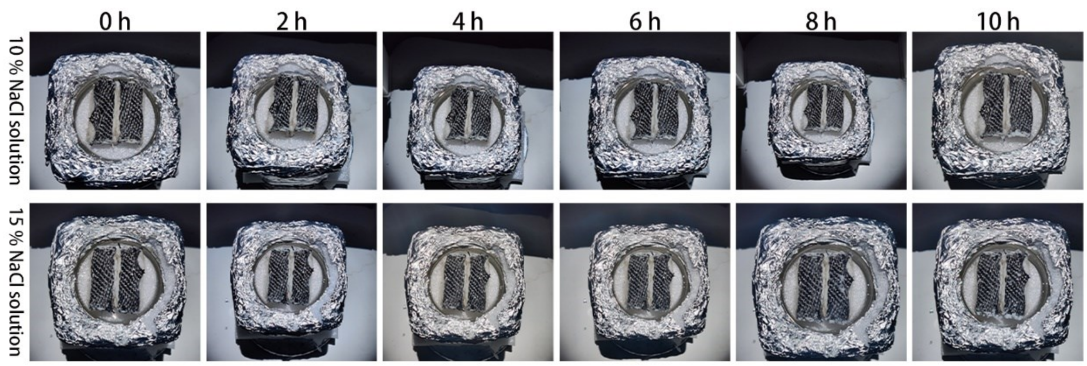

Figure S19. Optical images of salt precipitation on the surface of CCMF-4 in 10% and 15% NaCl solution.

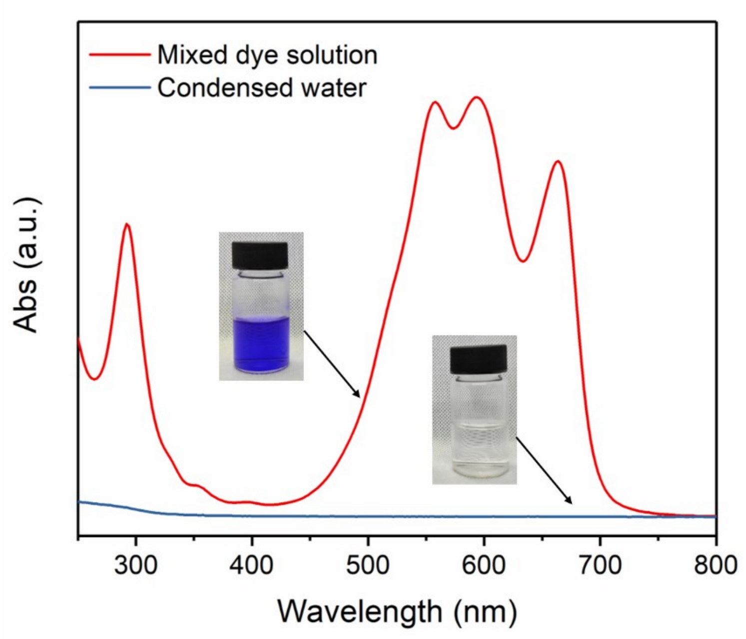

Figure S20. UV–vis absorption spectra of mixed dye solution and the condensed water through steam. The insets show the corresponding optical photos.

Calculation S1. The energy conversion efficiency.

The energy conversion efficiency (η) is calculated as follows[3]:

$$\eta = \frac{\dot{m}\, h_{LV}}{q_i} \qquad (1)$$

where $\dot{m}$ is the water-evaporation rate (note that the dark evaporation rate should be subtracted), and h_{LV} and q_i are the total evaporation enthalpy (including the vaporization enthalpy of water and sensible heat) and the power density of the simulated sunlight on the absorber surface (1 kW m^{-2}), respectively. In this study, we employed the obtained vaporization enthalpy of water in the carbon fiber bundle at 40 °C to calculate η. Note that η ignores the impact of cotton yarn on the vaporization enthalpy of water in our designed fabric-based solar-generation stills.

Calculation S2. Energy analysis of CCMF-4 in the evaporation process[4-6]

(1) Radiation flux be calculated by Stefan-Boltzmann law

$$\Phi=\varepsilon A\sigma(T_1^4-T_2^4) \qquad (1)$$

Where Φ represents heat flux, ε is the emissivity, and emissivity in this equation is supposed has a maximum emissivity of 1. A is the surface , σ is the Stefan-Boltzmann constant, T_1 (37 ℃) is the average surface temperature of absorber at a steady state condition, and T_2 (22 ℃) is the ambient temperature upward the absorber. Under the illumination of constant solar flux (1 sun). The radiation heat loss is calculated to be ~9.4%

(2) Convection flux is defined by Newton' law of cooling.

$$Q= hA\Delta T \qquad (2)$$

Where Q represents the heat energy, h is the convection heat transfer coefficient, which is about 5 W m^{-2} K as reported,[7] and ΔT (15 ℃) is different value between the average surface temperature of absorber (CCMF-4) and the ambient temperature upward the absorber. The connection heat loss is calculated to be ~7.5%

(3) Conduction flux was calculated based on

$$Q=Cm\Delta T \qquad (3)$$

Where Q is the heat energy, C is the specific heat capacity of water (4.2 kJ $^{o}C^{-1}$ kg^{-1}), m is the weight of pure water (20 g) used in this experiment. ΔT (1 ℃) is the average temperature difference of pure water after and before solar illumination under 1 sun after 1 h. The conduction heat loss is calculated to be ~2.5%

Supplementary References

[1] F. Zhao, X. Zhou, Y. Shi, X. Qian, M. Alexander, X. Zhao, S. Mendez, R. Yang, L. Qu, and G. Yu, *Nat. Nanotechnol*, 2018, **13**, 489.

[2] P. Tao, G. Ni, C. Song, W. Shang, J. Wu, J. Zhu, G. Chen, T. Deng, *Nat. Energy*, 2018, **3**, 1031.

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[6] G. Ni, G. Li, S.V. Boriskina, H.X. Li, W.L. Yang, T.J. Zhang, G. Chen, *Nat. Energy*, 2016, **1**, 16126–16132.