Fabric-based multi-functional solar evaporator with all-weather efficient continuous evaporating capability through

photothermal and electrothermal effect

Chuanliang Chen[#], Minhan Cheng[#], Yuliang Qu, Ke Tian, Qianyang Li, Qiang Fu,

Hua Deng*

College of Polymer Science and Engineering, State Key Laboratory of Polymer

Materials Engineering, Sichuan University, Chengdu, 610065, China

#: Equal contributing authors

*: Corresponding authors: Hua Deng,

E-mail: huadeng@scu.edu.cn (H. Deng), Tel.: + 86-28-85460953

Experimental section

Materials

Commercialized Polyethylene terephthalate (PET) cloth was purchased from Zhongyan Trading Co., Ltd. in Jinzhou City, Hebei Province. Expanded Polystyrene (EPS) was purchased from Wuhan Qiwei Building Materials Co., Ltd. The carbon nanotube dispersion (CNT) was purchased from Beijing Carbon Oxygen Technology Co., Ltd. Dopamine (DA) and trimethylaminomethane (Tris) were provided by Aladdin Reagent Company. Copper sulfate (CuSO4 \cdot 5H₂O, GR), sodium thiosulfate (Na₂S₂O₃ \cdot 5H₂O, GR), and 30% hydrogen peroxide (H₂O₂, AR) and ethyl acetate were purchased from Chengdu Cologne Chemical Co., Ltd. Polydimethylsiloxane (PDMS) and curing agent were provided by Dow Corning Corporation. Hydrophobic gas-phase silica was purchased from Yingchuang Industrial Co., Ltd. Sodium chloride (NaCl) and hexane were obtained from Sigma-Aldrich. Bohai pure natural seawater is purchased from Bohai Liaoshen store. Mung bean seeds are provided by the Tiancube Seed Industry. Deionized water is obtained from a water purifier (UL pure KE0119) and used in all experiments.

Preparation of PET /PDA@CuS (gradient) evaporator

Firstly, the commercial PET cloth was cut into rectangular spline with a length of 16mm, a width of 5mm. Then 0.25g CNT solution with a concentration of 5wt% was sprayed on both sides of the spline, and then dried to obtain PET/CNT-X, where X represents the number of spraying. Then, the PDA coating was rapidly deposited on PET/CNT. Specifically, 0.61 g of tris was added to 500 ml of deionized water and stirred magnetically to dissolve, and 1 g of DA, 333.2 mg of H₂O₂, and 624.2 mg of CuSO₄ · 5H₂O were added to the above solution under stirring. After stirring for 1 min, it was immediately poured into a container containing PET/CNT, allowed to stand for 1 h, and then the PET/CNT was washed and dried to obtain PET/CNT/PDA.

Furthermore, CuS was generated by polymerization on PET/CNT/PDA. Specifically, CuSO₄·5H₂O and Na₂S₂O₃·5H₂O were dissolved in deionized water to prepare a solution with a concentration of 300 mM, respectively. Then, PET/CNT/PDA was put into the CuSO₄ solution, and then poured into the Na₂S₂O₃ solution. The solution was allowed to stand for two hours at 85 °C, and then the PET/CNT/PDA was washed and dried to obtain PET/CNT/PDA@CuS. For other initial reaction concentrations (100mM, 200mM, 400mM), the obtained PET/CNT/PDA@CuS was also prepared by a similar method. Further, the 5×1 cm (length×width) local part of PET/CNT/PDA@CuS was hydrophobic treatment. Specifically, 3wt% PDMS and 1wt% hydrophobic silica were ultrasonically dispersed in ethyl acetate, followed by the addition of a curing agent (PDMS/curing agent (10/1, wt/wt)) PDMS@SiO₂ disperse liquid, spray the dispersed liquid onto the surface of the fabric, and cure it under a hot bench at 80°C for 5 hours. Finally, PET/CNT/PDA@CuS with local hydrophobic treatment and EPS foam are combined to prepare solar evaporator, which was recorded as PET/CNT/PDA@CuS (gradient), and the obtained local treatment sample was recorded as PET/CNT/PDA@CuS/PDMS@SiO₂. As a comparison, for the preparation of the solar evaporator without PDMS@SiO₂ treatment, it is recorded as PET/CNT/PDA@CuS (uniform). The reaction mechanism for the generation of CuS may be as follows¹:

$$Cu^{2+} + S_2O_3^{2-} + 2H_2O \rightarrow Cu[(S_2O_3)(H_2O)_2]$$
(1)

$$Cu^{2+} + S_2 O_3^{2-} \rightarrow Cu[(S_2 O_3)_2]^{2-}$$
(2)

$$Cu[(S_2O_3)(H_2O_2)] \rightarrow CuS\downarrow + SO_4^{2-} + 2H^+ + H_2O$$
(3)

$$Cu[(S_2O_3)_2]^{2-} + 6H_2O \rightarrow CuS\downarrow + 3SO_4^{2-} + 12H^+$$
(4)

$$nCuS \rightarrow (CuS)n \tag{5}$$

Evaporation experiment

The $5 \times 5 \times 3$ cm (length×width×height) EPS foam was wrapped by the above local PDMS@SiO₂-treated sample and placed in a container filled with water to investigate evaporation performance of PET/CNT/PDA@CuS (gradient) evaporator. The local treatment surface was the irradiation surface of sunlight. The evaporator was tested at 0 ms⁻¹ convection velocity, 20 °C room temperature and 40 % humidity, and the mass change during the evaporation process was recorded with analytical balance (0.1 mg). At the same time, an infrared camera (FLIR-T600) is used to monitor the surface temperature of the evaporator. The evaporation performance of the

PET/CNT/PDA@CuS (gradient) evaporator in other modes (electrothermal, photoelectrothermal) and the evaporation performance of the PET/CNT/PDA@CuS (uniform) evaporator were also investigated using the similar method.

Characterization

The surface morphologies of PET and its composites were observed by SEM, and the corresponding surface composition was analyzed by energy dispersive spectrometer (EDS). X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) were used to analyze the structural composition of PET and its composites. AFM was used to analyze the surface morphology and surface roughness of PET and its composites. The hydrophilicity and hydrophobicity of PET and its composites were analyzed by contact angle tester. The conductivity of PET and its composites was measured by a four-probe tester. The thermal conductivity of PET and its composites was measured by laser scattering instrument. UV-Vis-NIR spectrophotometer was used to evaluate the absorption of sunlight and UV resistance of PET and its composites. The UV protection coefficient was measured according to GB/T18830-2009. Sandpaper, folding resistance tester (YN-MIT135) and water flow test were used to evaluate the stability of PET composite. The electric heating performance was measured by applying DC voltage at both ends of PET/CNT/PDA@CuS (5cm*2cm) with a DC power supply (HY3005ET, Hyelec). According to the GBT20944.1-2007 national standard, the antibacterial ability of PET and PET/CNT/PDA@CuS was evaluated by oscillation method. The ion concentration before and after purification was tested by inductively coupled plasma mass spectrometry.



Figure S1 SEM of neat PET (a), PET/CNT (b-b'), PET/CNT/PDA (c), (d-e) EDS element mapping of (c) and (f-f') PET/CNT/PDA@CuS/PDMS@SiO₂ and (g-j) EDS element mapping of

(f)



Figure S2 AFM 3D images of PET (a), PET/CNT (b), PET/CNT/PDA (c), PET/CNT/PDA@CuS (d) and PET/CNT/PDA@CuS/PDMS@SiO₂.



of PET, PET/CNT/PDA, PET/CNT/PDA@CuS Figure S3 FTIR PET/CNT, and PET/CNT/PDA@CuS/PDMS@SiO2 The Figure shows that for PET, the absorption peak at 1082 cm⁻¹ is attributed to C–O stretching vibrations, while the peaks at 1130 and 1280 cm⁻¹ correspond to the stretching vibrations of the O=C-O-CH₂ ester group. The absorption peak at 1710 cm⁻¹ is associated with carboxy carbonyl stretching, and the peaks at 2850 and 2920 cm⁻¹ are ascribed to the asymmetric and symmetric vibrations of -CH2 groups. Additionally, a broad absorption peak at 3320 cm⁻¹ corresponds to -OH stretching vibrations. For PET/CNT, the characteristic absorption peaks are similar to those of PET, but their intensity is significantly diminished, likely due to the loading of CNTs. In the case of PET/CNT/PDA, an absorption peak at 3431 cm⁻¹ is attributed to -OH and -NH2 stretching vibrations, with a slight redshift of the -OH peak resulting from the polymerization of PDA. For PET/CNT/PDA@CuS, in addition to the aforementioned features, a characteristic absorption peak for CuS appears at 654 cm⁻¹. Finally, for PET/CNT/PDA@CuS/PDMS@SiO2, a new characteristic absorption peak at 798 cm⁻¹ is attributed to the symmetric stretching vibrations of Si-O-Si from PDMS and SiO₂.



Figure S4 The flexibility of PET/CNT/PDA@CuS







Figure S6 (a-d) The wettability of PET/CNT with different CNT spraying times



Figure S7 (a) The UV-VIS-NIR absorption spectra, (b) surface temperatures evolution profiles, (c) conductivity and thermal conductivity and (d) TGA curves of PET/CNT with different spraying times



Figure S8 SEM of PET/CNT with different spraying times. (a-a') neat PET, (b-b') 1 times (c-c') 2 times, (d-d') 4 times, (e-e') 8 times. The figure shows that compared with neat PET, the surface of PET/CNT becomes rough after spraying CNT. When the number of spraying CNT is less than 8 times, the surface bonding between CNT and PET is relatively close. When the number of spraying CNT reaches 8 times, the surface bonding between CNT and PET becomes loose.



Figure S9 The comparison of wettability of PET, PET/CNT, PET/CNT/PDA and PET/CNT/PDA@CuS. The figure shows that the water droplets quickly wet and spread on the surface of pure PET; for PET/CNT, the spreading speed of water droplets on its surface is greatly reduced; when PDA was introduced, the spreading speed of water droplets on the surface of PET/CNT/PDA increased rapidly. After further in-situ polymerization of CuS, the spreading speed of water droplets on its surface did not decrease, showing good wettability and hydrophilicity.



Figure S10 water absorption experiments of PET/CNT/PDA@CuS



Figure S11 The photo of white ammonium chloride smoke from the mouth of glass container covered with PET/CNT/PDA@CuS



Figure S12 (a) TGA curves of PET/CNT/CuS and PET/CNT/PDA@CuS



Figure S13 SEM of PET/CNT/CuS (a-a'), (b-e) EDS element mapping of (a), SEM of PET/CNT/PDA@CuS (f-f'), (g-j) EDS element mapping of (f). The figure shows that for PET/CNT/CuS, the amount of CuS loaded on the fiber surface is less, and there is a gap between the fiber and CuS, showing easy shedding. For PET/CNT/PDA@CuS, the CuS loaded on the fiber surface increased significantly, and the fiber was tightly bonded to CuS. This is because the introduction of PDA makes CuS better anchored on the fiber surface.



Figure S14 (a) The conductivity and resistance and (b) surface temperatures evolution profiles of PET/CNT/PDA@CuS (5cm*2cm, length*width) with different CuSO4 concentration under dry



Figure S15 SEM of PET/CNT/PDA@CuS with different CuSO4 concentration. (a-a') 100 mmol/L, (b-b') 200 mmol/L, (c-c') 300 mmol/L, (d-d') 400 mmol/L



Figure S16 TGA curves of PET/CNT/PDA@CuS with different CuSO₄ concentration



Figure S17 The comparison of absorbance of PET/CNT/PDA@CuS and PET/CNT/PDA@CuS/PDMS@SiO₂ evaporator and literature ²⁻¹¹.



Figure S18 Absorption spectra (a), time-dependent curves (b) and conductivity (c) of PET, PET/CNT, PET/CNT/PDA and PET/CNT/PDA@CuS, (d) conductivity and resistance of PET/PDA@CuS, PET/CNT/CuS and PET/CNT/PDA@CuS. The light absorption of PET/CNT/PDA@CuS in the whole solar spectrum range is as high as 96.8%, the photothermal temperature is as high as 109°C, the conductivity is as high as 4490S/m, and the resistance is as low as 140hm, which is superior to PET/CNT and PET/CNT/PDA. In addition, its conductivity and resistance are also compared with PET/PDA@CuS and PET/CNT/CuS, showing obvious advantages.



Figure S19 (a) Electric heating curve (dry state) of PET/CNT/PDA, (b) conductivity comparison of PET/CNT/PDA and PET/CNT/PDA@CuS

Solar irradiation/electric heating fabrics	T (°C)	Light intensity	T (°C)	Voltage	Reference
PET/CNT/PDA@CuS	109	1.0 sun	127	4 V	This work
PAN/CuS	88	1 sun	/	/	12
AgNW/PDA/cotton	/	/	63	1.6 V	13
rGO/PET	/	/	50	6 V	14
MXene/aramid nonwoven fabric	76.8	1 sun	80	2 V	15
MXene@PPy/PDMS fabric	95.3	1.2 sun	66.3	6 V	16
PDMS/PEDOT: PSS/pen ink/cotton	50	1 sun	52	20 V	17
AgNPs-6@MNWF-5	61.3	1 sun	95	7.5 V	18
MXene@silk	44.3	1 sun	41	8 V	19
MXene@PDA/cotton fabric	53.8	0.5 sun	70	6 V	20
AgNW-MXene@PP	60	1 sun	44.1	2 V	21
MXene/TPU fabrics	54.4	1 sun	102	4 V	22

Table S1 The comparison of solar irradiation/electric heating fabrics between PET/CNT/PDA@CuS in this study and some fabrics reported in the literatures.



Figure S20 (a) The heating power under different voltage and (b) electrothermal adjustment curves of PET/CNT/PDA@CuS with 300mmol/L CuSO₄



Figure S21The conductivity changes of PET/CNT/PDA@CuS in friction cycles (a), bending cycles (b) and water washing cycles (c).



Figure S22 The water contact angle changes of PET/CNT/PDA@CuS/PDMS@SiO₂ in friction cycles (a), bending cycles (b) and water washing cycles (c).



Figure S23 The comparison of evaporation rate of PET/CNT/PDA@CuS (gradient) evaporator and most two-dimensional evaporators reported in the literature.^{7, 23-35}

Energy flow analysis

When the fabric-based evaporator evaporates under sunlight, the surface temperature of the evaporating sections on both sides (T₂) is higher than the corresponding environmental temperature (T₁). Most of the heat is used for water evaporation, while the remaining heat is dissipated through conduction ($q_{T, cond}$), radiation ($q_{T, rad}$), and convection ($q_{T, conv}$). It is noteworthy that throughout the photothermal evaporation process, the temperature T₃ of the hydrophobic section in the center of the fabric-based evaporator is higher than that of the hydrophobic sections on both sides. This allows the cooler evaporating sections on the sides to draw energy from the central hydrophobic section through conduction ($q_{C, cond}$), thereby enhancing evaporation. Additionally, the hotter central section can transfer heat to the evaporating sections on either side through radiation ($q_{C, rad}$) and convection ($q_{C, conv}$). On the other hand, the evaporator can also receive extra input energy E, further enhancing steam production. According to energy

flow analysis, the relationship between the input and output energy of the fabric-based A_1mh_{LV} evaporator during the evaporation process can be described by the following requisition $A_1(T_2 - T_1) + A_1(T_2 - T_1) +$

$$q_{\text{steam}} = \alpha q_i - q_{T, \text{ cond}} - q_{T, \text{ rate}} \sigma \left(q_{T_3, \text{ conv}} T_1^+ q_{T_3, \text{ conv}} + q_{Q} (T_{0, \text{rate}} - T_1^- q_{T_3, \text{rate}} + A_2 \mathcal{E} (T_3^- q_{T_3}^- q_{$$

Where A_1 represents the area of the evaporation zone (20 cm²), m is the evaporation rate, h_{LV} is the total enthalpy of sensible heat and phase change between liquid and gas, C_{opt} is the optical concentration, q_i is the solar irradiance power (1 kW m⁻²), c is the specific heat capacity of water (4.2 J g^{-1o}C⁻¹), and ΔT is the change in temperature of the water body before and after one hour of evaporation. The variable ϵ denotes the emissivity of the sample ($\epsilon = 1$), σ is the Stefan-Boltzmann constant (5.6703×10⁻⁸W m⁻² K⁻⁴), T₂ is the surface temperature of the evaporating sections of the evaporator, T₁ is the corresponding environmental temperature, h_{conv} is the convective heat transfer coefficient (5 W m⁻² K⁻¹), A₂ is the area of the central hydrophobic zone (5 cm²), T₃ is the temperature of the central hydrophobic section, U is input voltage, and I is input current density.

When the solar power is 1kwm⁻² and the input voltage is 5V, the energy conversion efficiency η of the entire evaporation system can be calculated by the following formula:

$$\eta = A_1 m h_{LV} / (A_1 C_{opt} q_{i+} A_2 C_{opt} q_{i+} UIA_1) = 81.5\%$$

At this time, the proportion of heat conduction loss of the whole system is: $cm_1\Delta T/(A_1C_{opt}q_{i+}A_2C_{opt}q_{i+}UIA_1)=2.9\%$

At this time, the proportion of thermal radiation loss of the whole system is: $[\varepsilon A_1 \sigma (T_2^4 - T_1^4) + \varepsilon A_2 \sigma (T_3^4 - T_1^4)]/(A_1 C_{opt} q_{i+} A_2 C_{opt} q_{i+} UIA_1) = 9.7\%$

At this time, the proportion of thermal convection loss of the whole system is: $[h_{conv}A_1(T_2 - T_1) + h_{conv}A_2(T_3 - T_1)]/(A_1C_{opt}q_{i+}A_2C_{opt}q_{i+}UIA_1) = 5.9\%$



Figure S24 The thermal conductivity of PET/CNT/PDA@CuS and PET/CNT/PDA@CuS/PDMS@SiO_2 $\label{eq:period}$



Figure S25 (a) The evaporation rate of the PET/CNT/PDA@CuS (gradient) evaporator with different voltages and only different voltages is input at the same time under 0.5 solar illumination. (b) comparison of evaporation rate of evaporator in different modes and (c) the heating power of evaporator under different voltage.



Figure S26 Surface photo of evaporator tested for 1 hour under 1Sun+5V (a) and 1Sun+7V(b) conditions. The figure shows that the surface of the evaporator after evaporation at 1sun+5V had almost no salt deposition compared to that at 1sun+7V. The reasons are as follows: the water transport capacity of the evaporator is the same. When tested under 1sun+5V conditions, because the electrically stable temperature of the evaporator under 5V wet conditions is significantly lower than that under 7V conditions, resulting in a lower stable temperature of the evaporator under 1sun+5V conditions. This ultimately leads to salt accumulation on the surface of the evaporator (1sun+7V) during the test, while there is no salt accumulation on the surface of the evaporator (1sun+5V), demonstrating good salt resistance.



Figure S27 Salt deposition photos of evaporator continuously tested for 24 hours in 3.5wt% NaCl solution



Figure S28 Self-cleaning behavior of evaporator on NaCl crystal



Figure S29 Original E.coli and S.aureus colony plate photos and corresponding antibacterial photos placed in PET/CNT/PDA@CuS in the evaporator against E.coli and S.aureus.



Figure S30 The comparison of UV-visible transmission spectra (a), UVA and UVB transmittance rates (b) of PET/CNT/PDA@CuS and PET/CNT/PDA@CuS/PDMS@SiO₂ in the evaporator



Figure S31 Cu²⁺ concentration after evaporator purification

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