Ultrablack Poly(vinyl alcohol)-Graphite Composite Xerogel with Vertically Arranged Pores for Highly Efficient Solar Steam Generation and Desalination

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Ultrablack materials have attracted wide attention due to their high light absorbance and efficient photothermal conversion used in the field of solar steam generation to alleviate the drinking water crisis. Herein, ultrablack and low-cost poly(vinyl alcohol)-graphite composite xerogels (PGCXs) that have vertically arranged pores and high thermal conductivities are fabricated. The PGCX-50% shows high light absorbance (95.44%), good wettability, and a water evaporation rate of 1.24 kg m⁻² h⁻¹ under 1 sun illumination when coupled in a two dimensional (2D) evaporator. To further improve the solar steam generation performance, the PGCX-50% is switched to a three dimensional (3D) evaporator by rotating it. Under 1 sun illumination, the 3D evaporator has a highest water evaporation rate of 3.80 kg m⁻² h⁻¹, which is 3.07 times that of the 2D evaporator, due to its larger evaporation area and higher surface area at subambient temperature. Finally, a heatsink-like 3D evaporator is designed and a water evaporation rate of up to 9.54 kg m⁻² h⁻¹ is achieved when coupled with wind energy. The high water evaporation rates of the PGCX even in concentrated brines ensure its great potential for drinking water production and seawater desalination.

1. Introduction

Ultrablack materials refer to the materials that absorb almost all of the incident light of a certain band without reflection and transmittance. Due to their high light absorbance and efficient photothermal conversion,[1–4] ultrablack materials are used for shading,[5,6] photothermal therapy,[7,8] photocatalysis,[9] detection,[10–12] solar steam generation,[13–20] and other fields.[21,22] Among these applications, solar steam generation, which is an economical technology that uses solar energy and the photothermal effect of ultrablack materials to promote evaporation of water and thereby solve the crises of drinking water shortage and water pollution, comes to the force in recent years.

In the past few years, some efficient evaporators based on different ultrablack materials such as metal nanoparticles,[23–25] semiconductors,[26–28] carbon materials,[29–34] polymers,[35–37] and others[38–42] have been reported. However, there are still one or more disadvantages of these evaporators in practical application, such as the use of expensive metals, the strict and complex chemical synthesis process to achieve high absorbance, synthesis process involving high temperature and pressure, and poor durability. To data, considerable efforts have been devoted toward the improvement in solar steam generation performances of evaporators. The design of macroscopic three dimensional (3D) structures of the evaporators brings the solar steam generation performances of evaporators to a new level. These spatial structure designs, such as waved,[43] origami,[44,45] sunflower disc-shaped,[46,47] cylindrical,[48,49] spherical,[16,30–32] cup-like,[53] heat-sink-like,[54] and Monstera-inspired,[53] significantly increase the solar steam generation performances through light and thermal
managements. However, the following problems are worth paying attention to when designing evaporator. How to improve the solar steam generation performance of the same material through macroscopic structure design and what are the mechanisms involved?

Herein, ultrablack and low-cost poly(vinyl alcohol)-graphite composite xerogels (PGCXs) that had different graphite content, vertically arranged pores, and high thermal conductivities were fabricated by directional freeze. The PGCX-50% was proved to have the highest water evaporation rate among PGCXs when coupled in two dimensional (2D) evaporator. To further improve the solar steam generation performance of the PGCX-50% through macroscopic structure design, the PGCX-50% was switched to a 3D evaporator by rotating it so that one end of the PGCX-50% is exposed to air. The solar steam generation performances and thermal management abilities of the 3D evaporator at different rotation angles were systematically studied. The 3D evaporator had a highest water evaporation rate of 3.80 kg m$^{-2}$h$^{-1}$ under 1 sun illumination due to its larger evaporation area and higher surface area at subambient temperature compared with 2D evaporator. Finally, a heatsink-like 3D evaporator was designed. When coupled with a wind flow of 4.5 m s$^{-1}$, the heatsink-like evaporator realized a water evaporation rate of up to 9.54 kg m$^{-2}$h$^{-1}$. Combined with its low-cost and durability, the evaporator shows a great application prospect of drinking water production and seawater desalination.

2. Results and Discussions

The fabrication strategy of PGCX with vertically arranged pores is shown in Figure 1a, which can be summarized by the following steps: 1) dissolution of poly(vinyl alcohol) (PVA) and dispersion of graphite to form a mixed suspension; 2) directional freezing of mixed suspension, which results in formation of directionally growing ice crystals in the frozen block;[55–57] and 3) freeze drying of the frozen block, which removes ice crystals and leaves directionally arranged pores in the final PGCXs. For comparison, PGCXs with different graphite content (10–70 wt%) were fabricated. The detailed preparation processes and parameters are shown in the Experimental Section and Table S1, Supporting Information.

Figure 1b shows the digital photo of the PGCXs with different graphite content. As the graphite content of the PGCX increases, the color of the PGCX becomes darker, which indicates its better visible light absorption. The microstructures of the PGCXs were

![Figure 1. Preparation and microstructures of the PGCXs with vertically arranged pores. a) Preparation of the PGCXs by directional freezing and subsequent freeze drying. b) Digital photo of the as-prepared PGCXs with different graphite content. c–f) SEM images of PGCX-10%, PGCX-30%, PGCX-50%, and PGCX-70%, respectively (scale bar: 20 μm). The insets are top-view SEM images of the corresponding PGCXs (scale bar: 5 μm). g) Raw mercury intrusion curves of the PGCXs. h) Pore size distribution of the PGCXs.](image-url)
characterized using scanning electron microscopy (SEM) to elucidate their artificial, vertically arranged, and interconnected pore structures, which contribute to light absorption and water transportation. As shown in Figure 1c–f, after drying and removal of ice crystals, vertically arranged pores were retained. Interestingly, as shown in the top-view SEM images (Figure 1c–f, insets), the vertically arranged pores are interconnected. The PGCX with low graphite content has a structure similar to PVA (Figure S1, Supporting Information), and its pore size is smaller and more regular. The PGCX with high graphite content exhibits the characteristic of graphite, which is composed of vertically arranged graphite and has a flat pore structure. It is obvious that the higher the graphite content, the larger is the pore size and the smoother is the pore wall of the PGCX. The porosity and pore size distribution of the PGCXs were measured using an automatic mercury porosimeter (Figure 1g,h). PGCXs have wide pore distributions, and their pore sizes are mostly in the range of tens to hundreds of micrometers (Figure 1h), which is consistent with the pore distribution characteristics observed in the SEM images. The porosity of the PGCX-10%, PGCX-30%, PGCX-50%, and PGCX-70% was 54.08%, 56.18%, 86.75%, and 69.32%, respectively, which contributes to solar absorption and water transport.

Solar absorption is one of the key factors that affect solar steam generation performance of the photothermal material. The digital photo of the PGCXs in Figure 1b has illustrated that PGCXs with different graphite content have different visible light absorbance. To accurately investigate the absorbance of the PGCXs, optical reflectivity and transmittance spectra of the PGCXs were measured using a UV–vis–near-infrared (NIR) spectrophotometer equipped with an integrating sphere. As shown in Figure 2a and S2, Supporting Information, the higher the graphite content, the lower is the reflectivity the PGCXs. Besides, all of the PGCXs exhibited negligible transmittance, which, combined with their low reflectivity, ensured their high absorbance across the measured spectra of 400–2000 nm. The strong absorption peak at ≈1450 nm comes from the absorption of the adsorbed water. The absorbance of the PVA, PGCX-10%, PGCX-30%, PGCX-50%, and PGCX-70% was calculated to be 7.91%, 90.91%, 94.24%, 95.36%, and 95.44%, respectively. The excellent light absorbance of the PGCXs can be attributed to the intrinsic property of graphite and the synergy effect between light and microstructure of the PGCXs. Graphite, as a kind of carbon material, has intrinsic light absorption ability for wide band electromagnetic wave. Besides, similar to the black-body model, the vertically arranged pores with size of dozens of micrometer in the PGCXs enable electromagnetic waves to penetrate deeply, which makes the electromagnetic waves trapped by multiple reflection and absorption inside the PGCXs instead of being reflected, which increases the skin depth of the PGCXs and thereby light absorbance.

The surface temperature changes of the dry PGCXs under 1 sun illumination were recorded using an IR thermal imager.
to evaluate the photothermal conversion abilities of the PGCXs. Due to the low light absorption of the PVA, its photothermal conversion ability and solar steam generation performance were not studied. As shown in Figure 2b, once illuminated by simulated sunlight, the surface temperatures of the PGCXs rise rapidly, indicating that the PGCXs have rapid photothermal response process. It is obvious that the higher the graphite content in the PGX, the higher is the surface temperature of the PGX. The thermal equilibrium was achieved in 150 s. The thermal equilibrium temperature of the PGX-10%, PGX-30%, PGX-50%, and PGX-70% was 53.6, 68.0, 76.5, and 81.0 °C, respectively, indicating their different photothermal conversion abilities. The temperature distributions of the surface of the PGCXs were uniform (Figure 2b, inset), indicating that the graphite was evenly dispersed.

Besides the solar absorbance and photothermal conversion, wettability is another important parameter that determines water evaporation process. The vertically arranged porous structures of the PGCXs are similar to vascular bundles found in many plants and help improve the water transport capacity and solar steam generation performance. PGXs are superhydrophilic and have high water transport rates. As shown in Figure 2c, take the PGX-50% for example, when the PGX-50% was placed vertically, water can be quickly transported from the bottom to the top. The initial temperature of cold bulk water, ambient, and the dry PGX-50% was 25.5, 26.1, and 28.6 °C, respectively (Figure S3, Supporting Information). The average water transport rate of the PGX-50% in first 30 s was 1.22 mm s⁻¹. Even in the subsequent process, the average water transport rate also reached 0.20 mm s⁻¹. The high water transport rates of the PGCXs were attributed to their vertically arranged porous structures, which, like the vascular bundles in plants, provide capillary forces to transport water from bottom of the PGCXs to the top at a high rate.

Once with high absorbance, good photothermal conversion ability, and good wettability, the PGCXs are expected to have good solar steam generation performances. Solar steam generation performances of the PGCXs coupled in 2D evaporators under 1 sun illumination were systematically studied using a homemade evaporator (Figure S4a, Supporting Information). The evaporator is consisted of an ultrablack PGX for photothermal conversion, a square ring made of foam (5 mm in thickness) to support the PGX, and a polymethylmethacrylate container filled with bulk water. It is worth noting that the PGCXs in the 2D evaporators have horizontal-channel-arrangement, while that in the 3D evaporators will be introduced later have vertical-channel-arrangement. As shown in Figure 2d, the mass changes of water using different PGCXs were recorded in detail. Obviously, the PGCXs with higher light absorbance showed higher mass change of water. The water evaporation rates calculated according to the mass change curves in steady state of different samples are shown in Figure 2e. The pure water exhibited low water evaporation rate of only 0.40 kg m⁻² h⁻¹ under 1 sun illumination. For the PGX-10%, PGX-30%, PGX-50%, and PGX-70%, the water evaporation rate was 1.11, 1.17, 1.24, and 1.23 kg m⁻² h⁻¹, respectively. The highest water evaporation rate of the PGCXs was 3.1 times that of the pure water. As shown in Figure 2e and Table S2, Supporting Information, the efficiency of pure water was only 20.47%, while that of the PGX-10%, PGX-30%, PGX-50%, and PGX-70% was 66.54%, 70.35%, 74.87%, and 73.66%, respectively. Note that the water evaporation rate in the dark (Figure S5, Supporting Information) was subtracted from the mass flux under illumination when calculate the efficiency.

The low water evaporation rate and efficiency of pure water were attributed to its low light absorbance and thereby low evaporation temperature (Figure S5, Supporting Information). The low efficiencies of the PGCXs can be attributed to the following aspects (Table S3, Supporting Information). First, according to the reactivity spectra, about 4.56–9.09% of the input energy was reflected by the PGCXs. Second, as the surface temperature of the PGCXs was 12.6–14.2 °C hotter than the ambient temperature adjacent to the evaporation surface (Figure 2f), the hot surfaces of the PGCXs will release a lot of energy to the ambient through radiation (7.93–9.15%) and convection (6.30–7.10%). Finally, due to the high thermal conductivities of the PGCXs (Figure S7, Supporting Information), especially when completely wet, the PGCXs will release a large amount of heat into the bottom bulk water (8.80–12.80%) in the absence of a thermal insulation layer. The total energy loss of the PGX-10%, PGX-30%, PGX-50%, and PGX-70% was 36.12%, 33.17%, 29.69%, and 30.89%, respectively, which indicates their efficiency of 63.88%, 66.83%, 70.31%, and 69.11%, respectively. The efficiency calculated by law of conservation of energy is almost the same as that calculated by the traditional equation.

PGCXs have been proved to have low water evaporation rates and efficiencies. How to further improve the solar steam generation performance of the PGCX remains a problem. The design of biface evaporator may be an alternative. As shown in Figure 3a, a 3D evaporator was obtained only by rotating the PGX so that one end of the PGX is exposed to air. First, the 3D evaporator with biface has higher evaporation area compared with 2D evaporator. Second, the 3D evaporator had both a sunny side and a shady side, which has low surface temperature and may absorb energy from the warm environment to increase the water evaporation rate and efficiency of the 3D evaporator. Finally, the PGCXs had high thermal conductivities in wet state, which leads to rapid heat transfer from the hot sunny to the cold shady side. In other words, the hot sunny side was cooled due to its high thermal conductivity, which reduced the temperature difference between evaporation surface and ambient and thereby reducing radiation and convective heat loss. A PGX-50% with an exposed size of 4.05 × 2.80 × 0.80 cm³ was selected as the photothermal material of the 3D evaporator due to its high water evaporation rate and efficiency when coupled in 2D evaporator. Figure 3b shows the projection area of the 3D evaporator at different rotation angle. The solar steam generation performances of the 3D evaporators with different rotation angle were systematically studied. As shown in Figure 3c,d, the evaporation rates of the 3D evaporators increase with the increase of the rotation angle and are much higher than that of 2D evaporator. The water evaporation rate calculated by the projection area was 1.65, 1.66, 1.75, 1.90, 2.15, and 3.80 kg m⁻² h⁻¹ at a rotation angle of 15°, 30°, 45°, 60°, 75°, and 90°, respectively.

The improvement of the water evaporation rates of the 3D evaporators can also be analyzed by law of conservation of energy combining with surface temperatures of the 3D evaporators in
the steady state. According to the Stefan–Boltzmann law and Newton’s law of cooling, when the surface temperature of the evaporator is higher than the ambient temperature, the evaporator releases energy to the ambient through radiation, convection, and conduction. Conversely, if the surface temperature of the evaporator is lower than the ambient temperature, the evaporator will absorb energy from the warm ambient. As shown in Figure 3e,f, obviously, the surface temperature of the sunny side of the 3D evaporator was higher than that of the shady side. In addition, as the tilt angle increases, the temperature difference between the evaporator and ambient gradually decreases (Figure 3f), resulting in the decrease of energy loss through radiation, convection, and conduction. A decreased energy loss may lead to a higher evaporation rate. For 3D evaporators with a tilt angle of 75° and 90°, the surface temperature of evaporators is lower than ambient, indicating a heat gain from the warm ambient, which leads to rapid increase in water evaporation rates. Three pieces of PGCXs were assembled into a 3D evaporator that looks like a heatsink. Detailed schematic diagram and dimension parameters of the heatsink-like evaporator are shown in Figure 4a and S8, Supporting Information. To further increase the water evaporation rate, wind energy was coupled into the steam generation system. As shown in Figure 4b,c, the heatsink-like evaporator exhibited a high water evaporation rate of 2.00 kg m⁻² h⁻¹ in the absence of wind energy. The heatsink-like evaporator exhibited a high water evaporation rate of 0.48 kg m⁻² h⁻¹ even in the dark (Figure S9, Supporting Information). When coupled with wind energy, the water evaporation rates of the heatsink-like evaporator increased quickly. The water evaporation rate of the heatsink-like evaporator was 5.92, 8.00, 9.09, and 9.54 kg m⁻² h⁻¹ when coupled with wind energy with a velocity of 1.5, 2.5, 3.5, and 4.5 m s⁻¹, respectively.

As shown in Figure 4d,e, when there is no wind flow, the temperatures at the top and side of the heatsink-like evaporator were higher than the ambient temperature, which leads to heat loss to the ambient and resulting in a low water evaporation rate. When coupled with wind flow, the temperatures at the top and side of the heatsink-like evaporator were lower than the ambient temperature, which leads to heat gain from the ambient and resulting in a higher water evaporation rate. Besides, in the absence of wind flow, the air layer on the evaporator surface can easily reach vapor saturation, resulting in a limited evaporation process. When there is a wind flow, the air is flowing, so the air with high humidity on the evaporator surface is constantly replaced by
new air with low humidity. The vapor on the evaporator surface has been in an unsaturated state, which is conducive to the evaporation process. As the escape of vapor takes away a large amount of heat, the temperature of the evaporator is easy to reach the subambient temperature, leading to energy gain from the warm environment and enhancement of water evaporation rate.

Solar desalination performance is crucial in actual application scenarios of an ideal evaporator. Salt-rejection capability, water evaporation rate in brine, and long-term performance are key factors to evaluate the solar-powered desalination performance of evaporator. As shown in Figure 5a, the heatsink-like evaporator exhibited high water evaporation rates in different brines. The water evaporation rate of the heatsink-like evaporator in 3.5 wt% NaCl solution, 10.0 wt% NaCl solution, and real seawater was 2.05, 2.04, and 2.05 kg m\(^{-2}\) h\(^{-1}\), respectively. Besides, long-term solar desalination test in the 10 wt% NaCl solution showed continuous and highly efficient water evaporation process (Figure 5b), confirming the excellent salt-rejection capability and long-term performance of the heatsink-like evaporator. After 12 h desalination in 10 wt% NaCl solution, no NaCl crystals were found on the surface of the heatsink-like evaporator (Figure S10, Supporting Information), further confirming the excellent salt-rejection capability of the heatsink-like evaporator. The excellent salt-rejection capability of the heatsink-like evaporator can be attributed to the superhydrophilicity, interconnected porous structure, and rapid water supply ability of the PGCXs. A closed container consisting of bell glass and culture dish was used to collect desalted water in seawater desalination experiment (Figure S11, Supporting Information). As shown in Figure 5c, after desalination, the contents of metal ions, including Na\(^{+}\), Mg\(^{2+}\), K\(^{+}\), and Ca\(^{2+}\), in desalted water are below 1.21 mg L\(^{-1}\) and are all significantly lower than the safe salinity levels defined by standards set by the World Health Organization, confirming the excellent solar desalination performance of the heatsink-like evaporator.

To further demonstrate the solar desalination and water collection performance of the heatsink-like evaporator when coupled with wind energy, a hermetic water evaporation and collection device that can introduce wind energy was designed (Figure 5d and S12, Supporting Information). After 1 sun illumination for 4 h, the mass change of the brine (10 wt% NaCl solution) was 10.61 g when there was no wind flow, whereas that was 17.01 g when coupled with wind flow of 1.5 m s\(^{-1}\). The evaporation rate was calculated as 3.03 kg m\(^{-2}\)h\(^{-1}\) when coupled with wind flow of 1.5 m s\(^{-1}\), which was 60.3% higher than that when there was no wind flow. The decreased rate compared to that of the open system may be attributed to the unsmooth wind flow and the reduced light transmittance of the box caused by condensation of water droplets at the top of the box (Figure 5e,f). The highly efficient solar steam generation and desalination performances of the PGCX, combining with its low cost (Table S4, Supporting Information), make it possible to provide sufficient drinking water in homes and industry.

Figure 4. Solar steam generation performances of the heatsink-like evaporator. a) A schematic diagram of the heatsink-like evaporator. b) Mass change curves of water in the heatsink-like evaporator. c) Water evaporation rates of the heatsink-like evaporator. d) IR thermal images of the heatsink-like evaporator. e) Surface temperatures of the heatsink-like evaporator.
3. Conclusion

In summary, ultrablack PGCXs with different graphite content and vertically arranged pores were fabricated by directional freeze. The ultrablack PGCXs had high light absorbance up to 95.44% due to the intrinsic light absorbance of graphite and the synergy effect between the light and vertically arranged porous microstructure of the PGCXs. With high light absorbance, good photothermal conversion ability, and good wettability, the PGCX-50% coupled in 2D evaporator was proved to have the highest water evaporation rate of 1.24 kg m$^{-2}$ h$^{-1}$ among PGCXs. To further improve the water evaporation rate, the PGCX-50% was switched to a 3D evaporator only by rotating it so that one end is exposed to air. It was proved that this simple rotation was highly effective in improvement of the water evaporation rate. The 3D evaporator had a highest water evaporation rate of 3.80 kg m$^{-2}$ h$^{-1}$, which is 206.5% improvement compared with 2D evaporator. The excellent solar steam generation performance of the 3D evaporator was attributed to its large evaporation area and subambient surface temperature, which contributes to energy absorbance from the warm ambient. To further improve the water evaporation rate, a heatsink-like 3D evaporator was designed and a high water evaporation rate of 9.54 kg m$^{-2}$ h$^{-1}$ was achieved with a wind flow of 4.5 m s$^{-1}$. Besides, the heatsink-like evaporator had good salt rejection capability in different brines. The highly efficient solar steam generation performance of the PGCX, combining with its low cost and durability when used for solar desalination, makes it possible to provide sufficient drinking water in homes and industry.

4. Experimental Section

Materials: Graphite powder (>99.85%), PVA 1788 (alcoholysis: 87.0–89.0%), nitric acid (65.0–68.0%), glutaraldehyde (25% aqueous solution), hydrochloric acid (36.0–38.0%), and sodium chloride (≥99.5%) were purchased from the Shanghai Chemical Reagent Company and were used without further purification.

Pretreatment of Graphite Powder: In order to increase the hydrophilicity of graphite powder, graphite powder was pretreated with nitric acid as follows. Graphite powder (10 g) was dispersed into nitric acid solution (5 vol%, 100 mL) and heated in an oven at 90°C for 24 h. After heating, the graphite powder was filtered and washed with deionized water several times until the pH of the solution reached neutral. After washing, the graphite powder was dried in an oven at 90°C for further use.

Preparation of PGCXs: First, PVA, graphite powder, and glutaraldehyde were added to deionized water to form a mixed solution. The mixture was stirred at room temperature until the PVA was completely dissolved. Next, hydrochloric acid solution (1.2 mol L$^{-1}$) was added to the mixture and stirred for 5 min to promote polymerization. Finally, the mixture was poured into a mold and frozen directionally in a liquid nitrogen bath to form vertically arranged pores. PGCXs with different graphite contents were obtained by freeze-drying. The detailed raw material parameters are shown in Table S1, Supporting Information. To distinguish, the different PGCXs were named PGCX-wt% according to the content of graphite.

Solar Steam Generation and Solar Desalination Experiments: The sunlight was provided by a Xenon-lamp (300–2500 nm, H5X-F300, China) coupled with an AM1.5 filter. The size of the light spot was controlled via an aperture, avoiding exposure to areas other than evaporator. Before taking any measurements, the lamp was warmed up to a point where stability was attained. Then, a solar power meter (VLP-2000, China) was placed in the working area to measure the solar irradiation intensity. For seawater desalination experiments, sodium chloride was directly dissolved in deionized water to form different simulated seawater (3.5 and 10 wt%). A real
seawater sample collected from the East China Sea was also used for solar desalination experiments.

**Calculation of Evaporation Rate and Efficiency** The evaporation rate was obtained by linear fitting in the steady-state region of the mass change curve based on the projection area. The efficiency ($\eta$) was calculated according to the following equation:[2,35,62]

$$\eta = \frac{m \times (C \times \Delta T + \Delta H_{\text{vap}})}{C_{\text{optical}} \times I}$$

(1)

where $m$ is the mass flux (kg m$^{-2}$ h$^{-1}$); $C$ is the specific heat capacity of water, which is a constant (4.18 J kg$^{-1}$ K$^{-1}$); $\Delta T$ is the difference between the evaporator temperature and ambient temperature; $C_{\text{optical}}$ is the optical concentration (1 in this work); and $I$ is the normal direct solar illumination (1 kW m$^{-2}$). The value of $\Delta H_{\text{vap}}$ is temperature-dependent and is listed in Table S2, Supporting Information. Note that the mass flux under dark condition is subtracted from the mass flux under illumination.

**Calculation of Efficiency by the Law of Conservation of Energy** According to the energy balance in the solar steam generation system in the steady state, the energy efficiency of the evaporator can be analyzed in detail. The total input energy ($Q_{\text{total}}$) is provided by the simulated sunlight

$$Q_{\text{total}} = C_{\text{optical}} \times I \times A_{\text{projection}}$$

(2)

where $A_{\text{projection}}$ is the projection area.

In a typical solar steam generation system in the steady state, in addition to the reflected solar energy, the rest of the solar energy is converted into Joule heat by the ultrablack material. The Joule heat generated is mainly used for steam generation, and the rest is dissipated by radiation, convection, and conduction. Therefore, the energy loss of the system can be summarized as the following parts:

- Reflected solar energy ($Q_f$) by the ultrablack material, which can be calculated with the following equation

$$Q_f = R \times Q_{\text{total}}$$

(3)

where $R$ is the reflectivity of the ultrablack material.

- Radiation energy loss ($Q_{\text{radiation}}$) from the ultrablack material to the ambient, which can be calculated by the Stefan–Boltzmann equation

$$Q_{\text{radiation}} = \sigma \times \varepsilon \times A_{\text{evaporation}} \times (T_{\text{evaporation}} - T_{\text{ambient}})$$

(4)

where $\sigma$ is the Stefan–Boltzmann constant (5.67 $\times$ 10$^{-8}$ W m$^{-2}$ K$^{-4}$), $\varepsilon$ is the emissivity of the ultrablack material, $A_{\text{evaporation}}$ is the evaporation area of the ultrablack material, $T_{\text{evaporation}}$ is the evaporation surface temperature of the ultrablack material, and $T_{\text{ambient}}$ is the ambient temperature adjacent to the evaporation surface of the ultrablack material. For most 2D evaporators, the projection area $A_{\text{projection}}$ is equal to evaporation area $A_{\text{evaporation}}$.

- Convection energy loss ($Q_{\text{convection}}$) from the ultrablack material to the ambient, which can be calculated by the Newton’s law of cooling

$$Q_{\text{convection}} = h \times A_{\text{evaporation}} \times (T_{\text{evaporation}} - T_{\text{ambient}})$$

(5)

where $h$ is the convection heat transfer coefficient (5 W m$^{-2}$ K$^{-1}$).

Energy loss from the ultrablack material to the bulk water, which can be regarded as the energy that heats the bulk water from the initial state to the steady state, that is, the increment of the heat capacity of the bulk water ($Q_{\text{water}}$):

$$Q_{\text{water}} = C \times m \times (T_{\text{steady}} - T_{\text{initial}})$$

(6)

where $C$ is the specific heat capacity of water (4.18 J kg$^{-1}$ K$^{-1}$), $m$ is the mass of the remaining bulk water, $T_{\text{steady}}$ is the temperature of bulk water in the steady state, and $T_{\text{initial}}$ is the temperature of bulk water in the initial state.

**Characterization:** The morphology of the sample was characterized by SEM (Hitachi S-4800, Japan). The porosity and pore size distribution of the PGCKs were measured using an automatic mercury porosimeter (PoreMaster 33, USA). The reflectance ($R$) and transmittance ($T$) spectra of the samples were measured using a UV/vis/NIR spectrophotometer (JASCO V-570, Japan) equipped with an integrating sphere. The absorbance of the samples was calculated as 100% $-$ $R$ $-$ $T$. The room temperature thermal conductivities were measured using a Hotdisk thermal analyzer (TPS 2500S, Sweden). The IR thermal images and temperature variation curves were recorded using an IR thermal imager (FOTRIC 220s, China). The temperature measured by the IR thermal imager was calibrated by a contact thermocouple (UT-T07). The mass changes in water were measured using an electronic balance (BS124S, 0.0001 g, Germany). The contents of metal ions in solution were measured using an inductively coupled plasma emission spectrometer (Optima 210DV).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

Research data are not shared.

**Keywords**

desalination, photothermal conversion, solar steam generation, submerged temperatures, ultrablack

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[1] W. Sun, A. Du, Y. Feng, J. Shen, S. Huang, J. Tang, B. Zhou, ACS Nano 2016, 10, 9123.

[2] H. Wang, A. Du, X. Ji, C. Zhang, B. Zhou, Z. Zhang, J. Shen, ACS Appl. Mater. Interfaces 2019, 11, 42057.

[3] J. Guo, D. Li, Z. Qian, H. Luo, M. Yang, Q. Wang, J. Xu, N. Zhao, Adv. Funct. Mater. 2020, 30, 1909877.

[4] X. Huang, X. Liu, Z. Jia, B. Wang, X. Wu, G. Wu, Adv. Compos. Hybrid Mater. 2021, 4, 1398.

[5] H. Wang, A. Du, Z. Zhang, B. Zhou, J. Shen, J. Mater. Res. 2017, 32, 3524.

[6] H. Wang, C. Zhang, B. Zhou, Z. Zhang, J. Shen, A. Du, Adv. Compos. Hybrid Mater. 2019, 2, 743.

[7] S. Dong, Y. Zhang, J. Wan, R. Cui, X. Yu, G. Zhao, K. Lin, J. Mater. Chem. B 2020, 8, 368.

[8] Y. Li, G. Bai, S. Zeng, J. Hao, ACS Appl. Mater. Interfaces 2019, 11, 4737.

[9] H. Wang, X. He, B. Zhou, J. Shen, A. Du, MRS Commun. 2018, 8, 521.
