Review Article

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Design and optimization of solar steam generation system for water purification and energy utilization: A review

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Abstract: Solar steam generation with low-cost and excellent energy efficiency is of great significance for alleviating an energy crisis, reducing water pollution and promoting seawater desalination. However, there are still numerous challenges for solar steam generation system to practical energy utilization. In this review, based on our previous research, we summarize various methods of solar steam generation, photothermal conversion mechanism and efficiency. We studied a series of effecting factors for solar steam generation. Our systematic investigation provided a clearer understanding of how to design and optimize the photothermal conversion system to improve the steam generation rate and energy conversion rate, including improving light absorption, reducing heat loss, and optimizing water supply. This article aims to make a comprehensive review of present solar steam technology, so that people can better apply photothermal conversion technology. Meanwhile, it also provides a route for the selection of photothermal materials, the design and optimization of the photothermal conversion system.

Keywords: solar steam generation; photothermal conversion; solar utilization; seawater desalination; water purification

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1 Introduction

Due to world population increment, socioeconomic development, and the depletion of traditional fossil fuels, people have called for more sustainable ways to acquire clean and safe water urgently [1, 2]. Production of potable water on a large scale from renewable resources is a significant global challenge that needs to be addressed, in order to alleviate the crisis of water shortage in the near future [3]. Solar irradiation is the most promising source of renewable energy. The energy that the sun radiates to the surface of the earth every hour can satisfy the annual energy consumption of human beings [4]. As a representative of renewable energy, solar energy is an indispensable source for thrusting the evolution of sustainable and renewable energy technology [5]. At present, solar energy utilization mainly includes photothermal [6], photovoltaic [7] and photochemical fields [8]. Light-to-heat, also known as photothermal conversion [9, 10], is an effective mean of utilizing solar radiation energy through reflection, absorption and converting it to high enough temperature to meet the requirements of different loads [11]. Among a range of ever-evolving technologies, solar vapor generation has been proven to be a promising and green strategy to alleviate water shortage [12–17]. As a fundamental thermal process [18], solar-driven evaporation is not only used to produce clean water, but also to drive a great deal of significant industrial processes of various applications worldwide [19, 20]. For example, electricity of generation [21], sterilization of waste [22], sewage disposal [23], oil-water separation [24] and so on. However, current solar steam generation process suffers from poor efficiency [13] due to weak light absorption of water and sharp heat loss [25]. In

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Figure 1: Schematic drawing of two photothermal evaporation systems: (a) the volumetric system and (b) the interfacial system [137]

Figure 2: Schematic illustration for effect factors of solar-driven evaporation system

order to reduce heat losses, volume solar absorption methods using optical nanofluids has been achieved moderate increase in evaporation efficiency [26]. A new concept, named “air-water interface solar heating” has been intensively studied in the field of seawater desalination [27–29], which restrains heat loss to the bulk water. Many advanced designs and applications with high efficiency have been invested through the unique designs of photothermal nanomaterials and evaporation systems that take advantage of the concept of interfacial heating [20, 30–32]. This suggests that the solar steam generation technology has the enormous potential to increase opportunities for freshwater and green energy generation.

According to the location of photothermal materials in the liquid, solar-driven evaporation system can fall into two categories. The first one is the volumetric system (Figure 1a) where photothermal materials are dispersed in large volumes of water, which is widely known as nanofluids [26, 33]. In this review, we discuss the development of the mechanism of the suspension thermal system. First, the initial hypothesized mechanism of the suspension thermal system was the nanobubble model [30]. When the nanoparticles are exposed to sunlight, the surface temperature of these nanoparticles can quickly exceed the boil-

ing point of liquid water. Then, the steam forms a thin layer of steam at the interface of granular liquid. Since steam is a poor conductor of heat, the transfer of heat from the heated particles to water is inhibited. As light continually irradiates the nanoparticles, the steam shell grows until it reaches a critical thickness of several hundred nanometers, so the steam/nanoparticle is less dense than an equivalent amount of water and rises to the surface. The bubbles then burst, releasing steam from the surface and returning the nanoparticles to the water itself. However, particle models and molecular dynamics simulations show that it is impossible to achieve local temperature gradient that leads to the generation of nanobubbles around nanoparticles at a feasible solar concentration and illumination intensity. By simulating the array of nanoparticles, Keblinski *et al.* [34] found that heating at the macroscopic scale was due to the overall heating of the liquid, and pointed out that the formation of nanobubbles requires a laser power density equivalent to 3×10^7 Suns. Chen’s group used the scale lumped capacitance model to better predict the volumetric temperature response of the nanoparticle receiver [35]. So far, plenty of interpretations have been demonstrated that the solar steam generation of nanofluids is caused by the global heating of the bulk fluid [36]. This system typically relies on high optical density systems to achieve a large amount of liquid heating that add complexity and cost [29]. However, heat energy rapidly transfers from nanoparticles to the water when the water directly contacts with nanoparticles resulting in relatively low evaporation efficiency in this suspending system. In addition, the steady dispersion and pumping of nanofluids is still a problem for long-term intense solar radiation [2, 17]. The second one is the interfacial system (Figure 1b) with the photothermal materials separated from the bulk water, which confining heat to air/water interface and forming heat localization [29]. This concept is considered to be an extremely promising approach, which minimizes the heat losses on account of the reduction of heat transmission to the non-evaporative parts [37, 38]. Studies have been reported in recent years [39–43] that solar-to-steam conversion efficiencies are up to more than 90%. Owing to these advantages, interfacial solar steam generation (ISSG) system [33] with highly efficient and sustainable photothermal materials would inspire new paradigms of applications relevant to water handing, electricity generation [21], seawater desalination [44], sterilization [45] and clean energy generation [46]. Here, we mainly summarize the solar-driven evaporation system from several aspects: mechanism and efficiency, thermal management, water supply regulation and solar steam collection (Figure 2).

Table 1: Comparison of the performance of photothermal conversion systems with different design concepts

Materials	Solar intensity (KW m ⁻²)	Absorbance (%)	Insulation layer	Water channel	Evaporation rate (kgm ⁻² h ⁻¹)	Efficiency (%)	Refs
Porous N-doped graphene	1	90-98	-	-	1.50	80	[1]
MXene-PVDF-PS membrane	1	-	PS	PVDF membrane	-	84	[7]
rGO/PU	1	91	PU	PU	0.9	65%	[11]
Carbonized conjugated microporous polymers	1	99	-	-	1.4406	86.8	[12]
rGO-MWCNT/PVDF membranes	1	95.3	PVDF membrane	MWCNT/PVDF membranes	1.22	80.4	[13]
TiN/carbonized wood	1	96	Carbonized wood	Carbonized wood	1.47	92.5	[23]
Black TiO ₂ /rGO airlaid paper	1	90	Polyethylene foam	Airlaid paper	-	69.1	[25]
SWNT-MoS ₂ film	5	82-95	-	-	6.6	92.5	[38]
Gold-deposited nanoporous template	4	99	-	nanoporous template	-	90	[39]
Defect-abundant graphene aerogel	1	99	PS foam	Cotton bars	1.78	91	[40]
Hierarchical graphene foam	1	95	-	-	-	93.4	[41]
GO foam	1	95	-	-	1.4	93.4	[41]
rGO/PVA hydrogel	1	98	-	-	2.5	95	[42]
Porous hydrogel(p-PEGDA-PANi)	1	98.5	EPE foam	Cellulose	1.4	91.5	[43]
MoS ₂ -loaded carbon foam	1	99.58	-	-	1.458	90.4	[44]
Ti ₂ O ₃ nanoparticle	1	92.5	-	Cellulose	1.32	92.1 ± 3.2	[52]
CB/PMMA-PAN membrane	1	97	-	PAN	1.3	72	[58]
GO film	1	94	Polystyrene foam	Cellulose	1.45	80	[61]
Black Ag nanostructures	1	~100	-	-	1.38	68.3	[62]
Ag nanoparticles	1	93.5	-	-	-	80	[63]
MoS ₂ /C @ PU sponge	1	98	PU sponge	PU sponge	1.95	88	[64]
Cotton-CuS-agarose aerogel	1	94-95.5	cotton rod	cotton rod	1.63	94.9	[69]
MoNx film	1	96	Polystyrene foam	Nylon66 film	1.69	97	[70]
MoOx membrane	1	90	PTFE membrane	PTFE membrane	1.255	85.6	[71]
CB	1	98	Polystyrene foam	Porous paper	1.28	88	[73]
Black titania/GO	1	90	EPE foam	Airlaid paper	-	69.1	[74]
Functionalized carbonblack	1	96	Polystyrene foam	Cellulose film	-	85	[75]

Table 1: ...continued

Materials	Solar intensity (KW m ⁻²)	Absorbance (%)	Insulation layer	Water channel	Evaporation rate (kgm ⁻² h ⁻¹)	Efficiency (%)	Refs
Vertically aligned CNT	1	98-99	-	-	-	90	[76]
F-Wood/CNTs	1	98	Natural wood	Natural wood	0.95	65	[77]
CB/GO	1	99	EPS	GO pillars	1.27	87.5	[78]
GO/Au	1	-	-	-	-	59.2	[79]
RGO/PFS sponges	1	95.5	-	-	1.375	88.8	[80]
Graphene aerogels	1	-	-	-	-	76.9	[81]
rGO	1	-	paper fibers	paper fibers	-	89.2	[82]
rGO	1	-	Cellulose film	Cellulose film	-	60	[83]
rGO aerogel	1	-	-	-	-	53.6	[84]
PPy gel	1	95	-	-	3.2	94	[85]
Flame-treated wood	1	99	Natural wood	Natural wood	1.05	72	[87]
Carbonized daikon	1	95.5	PS foam	-	1.57	85.9	[90]
Carbonized lotus seedpods	1	98-99	-	-	1.3	86.5	[91]
Carbonized mushrooms	1	96	-	-	1.475	78	[92]
3D cross-linked honeycomb GO	1	97	-	-	2.6	87	[93]
Carbonized lotus seedpods	1	98-99	-	-	1.30	86.5	[94]
PDA/carbonized cotton	1	97.5	Cotton	Cotton	1.54	88	[95]
Modified PDA/PVDF membrane	0.75	96.2	-	-	0.58	53	[96]
RGO-SA-CNT aerogel	1	92	-	-	1.395	83	[97]
Oligoanilines	1	95.2	-	-	1.1687	80.5	[99]
PDA/BNC	1	98	BNC	BNC	1.13	78	[102]
CNF-CNT aerogel	1	97.5	CNFs	CNFs	1.11	76.3	[103]
Graphite/anisotropic mesopowood	1	95	Wood	Wood	1.2	80	[104]
Carbon particles/ air-laid paper	1	98	Air-laid paper	Air-laid paper	0.964	70	[105]
Nanoink-stained PVA sponges	1	96.48	-	-	2.15	-	[115]
3D-CG/GN(CNT/GO film	1	97.2	GO/NFC wall	GO/NFC mesh	1.25	85.6	[117]
GO/NFC mesh GO/NFC wall)	1	-	-	-	1.39	90	[122]
Nitrogen-enriched carbon sponge	1	-	-	-	-	-	-
Graphite/nonwoven film	22	98	PS foam	Nonwoven film	24.3	72.2	[123]
mG/PNIPAm membrane	< 1	99	-	-	1.66	-	[127]

Table 1: ...continued

Materials	Solar intensity (KW m ⁻²)	Absorbance (%)	Insulation layer	Water channel	Evaporation rate (kgm ⁻² h ⁻¹)	Efficiency (%)	Refs
Functionalized rGO	1	-	-	-	0.47	81	[128]
Nitrogen-doped graphene/carbon aerogel	1	89	Melamine form	Melamine form	1.558	90	[132]
AuNP/PBONF composite films	1	49.0-67.4	PBONF films	PBONF films	1.424	83	[135]
AuFs/silica gel	1	-	-	-	1.356	85.1	[137]
VA-GSM	1	98	Polystyrene	Cotton bar	1.62	86.5	[138]

The performance of photothermal conversion systems have been summarized in Table 1.

2 Photothermal conversion mechanism and efficiency

2.1 Mechanism of photothermal conversion

A large number of photothermal materials have been explored in recent years, including metal nanoparticles, semiconductor materials and carbon-based materials. Photothermal conversion is caused by the strongly driven the electromagnetic field of solar radiation in the carrier of the solar absorber, so that the carrier produces heat [47, 48]. According to the properties of photothermal materials, there are three types of photothermal conversion mechanisms. (1) For metal nanoparticles, when the sunlight radiates metal nanoparticles, the collective motion of large numbers of free electrons causes the surface plasmon resonance, resulting in a large amount of heat [49–51]. (2) For nano-structured semiconductor, light with the appropriate wavelength can stimulate electron-hole pairs, and the energy in the excited electrons is dissipated in a nonradiative manner, thus generating heat [52]. (3) For carbon-based nanomaterials and polymer, these materials have exceedingly good natural light absorption ability. The absorbed solar energy is dissipated through photon scattering/lattice vibration to generate heat [53].

2.2 Photothermal conversion efficiency

Photothermal conversion efficiency is an index to evaluate the performance of photothermal conversion system. It is the system's ability to convert solar energy into effective water evaporation.

The photothermal conversion efficiency (η) is calculated according to the following equation [54–59]:

$$\eta = mh_{LV}/q_i \quad (1)$$

Where η stands for photothermal conversion efficiency, m is evaporation rate of water under illumination after subtracting evaporation rate of water in the dark environment, h_{LV} is made up of the enthalpy of liquid-vapor phase change and the sensible heat, and q_i the incident power density of solar irradiation.

The photothermal conversion efficiency can also be analyzed by energy losses of the system, including radiation losses, convection losses and conduction losses.

The energy consumed by solar-driven evaporation (Q_c) is equal to the light input energy (Q_i) subtract energy losses of the system. Q_c can be described as the following equation: [55, 60, 61]

$$Q_c = Q_i - Q_1 - Q_2 - Q_3 \quad (2)$$

1. Radiation losses:

$$Q_1 = \epsilon A \sigma (T_1^4 - T_2^4) \quad (3)$$

Where Q_1 represents the radiation losses, ϵ is the optical emission, A is the area of the evaporation, σ is the Stefan-Boltzmann constant, T_1 is the temperature at the surface of the evaporative material, and T_2 is the environment temperature.

2. Convection losses:

$$Q_2 = hA(T_1 - T_2) \quad (4)$$

Where Q_2 represents the convection losses, A is the area of the evaporation, h is the convection heat transfer coefficient, T_1 is the temperature at the surface of the evaporative material, and T_2 is the environment temperature.

3. Conduction losses:

$$Q_3 = kA(T_1 - T_2)/L \quad (5)$$

Where Q_3 is the conduction losses, k is the conduction coefficient of the medium, A is the area of the conduction, T_1 is the temperature of water after solar illumination, and T_2 is the temperature of water before solar illumination, L is the thickness of the material.

3 Sunlight absorption regulation

Photothermal materials can absorb incident sunlight through photoexcitation and convert part or all of it into heat (input energy). Adjusting the surface nanostructure and morphology of photothermal materials can be considered as an effective strategy to increase input energy.

3.1 Metallic nanoparticles

Many metal nanoparticles, such as Au [22, 39], Ag [62, 63], Al, Cu and so on, can carry out photothermal conversion because of the surface plasmon resonance. Metal nanoparticles absorb sunlight at specific wavelengths and convert

Figure 3: SEM images and absorption spectra of: (a) AgNPs assemblages [62]; (b) self-assembled AuNPs [39]; (c) narrow bandgap Ti_2O_3 [52]; (d) h-G foam [41], (e) VA-GSM [60]; (f) HNGs [85]

it into heat. Nevertheless, conventional metal nanoparticles have the narrow resonance band, causing low energy utilization and limiting their application.

Yin's group synthesized a rod-like aggregation of silver nanoparticles (AgNPs) (Figure 3a), which could effectively absorb visible and near-infrared light. Integrating small AgNPs in a limited space ensures greater absorbance (about 100%) and more efficient broadband absorption, which is conducive to the utilization of solar energy [62]. The performance of traditional plasma absorbers, which are mainly made by the top-down method, need to be improved. The absorber could be prepared by self-assembly of Au nanoparticles onto a porous template by one-step deposition (Figure 3b), having an absorbance of ~99% across the wavelength range of 400 nm to 10 mm [39]. Besides, Zhu's group demonstrated a plasma structure that is self-assembled from tightly packed nano-silver into a porous template with double-sided performance of water purification and pollution detection [63]. The average absorption of the upper surface was 93.5% in the range of 400–2500 nm.

3.2 Nano-structured semiconductors

Semiconductor materials are regarded as a new type of photothermal conversion materials because of their

low cost and low toxicity [64]. The most critical factor in the absorbency of semiconductor materials is the bandgap energy, but traditional semiconductor materials only respond to ultraviolet radiation due to their large bandgap [65–68]. Various research has been carried out to narrow the energy band gap of semiconductor materials in recent years, expanding the capability of absorption from ultraviolet to visible light.

Wu's group reported a novel narrow bandgap Ti_2O_3 nanoparticle (Figure 3c) with the ability to absorb sunlight across a full spectrum range, which has a much lower bandgap energy than TiO_2 . Under the irradiation of sunlight, overwhelming majority of photons radiated from the solar show higher energy than the band gap of Ti_2O_3 nanoparticles, resulting in the generation of electron-hole pairs in Ti_2O_3 [52]. Therefore, the narrow-bandgap Ti_2O_3 nanoparticles can absorb almost 92.5% of sunlight across a full spectrum range. Metal oxides and chalcogenides have shown a good application prospect in the near infrared region. Xu's group developed a novel photothermal gel, consisting of cotton, CuS and agarose, was prepared by a simply casting method [69]. After the cotton-CuS-agarose aerogel was wetted by water, the light absorption was further increased to 97%. Molybdenum-based semiconductor materials have also been considered as effective photothermally evaporating materials. Yu's group reported that the bi-phase molybdenum nitride (MoN_x)

nanoparticles was synthesized by a simple method [70]. The MoN_x nanoparticles has the light absorption of 96%. Similarly, Wang's group introduced an oxygen-defected molybdenum oxides hierarchical nanostructure (MoO_x HNS), consisting of ultrafine nanosheets of atomic thickness [71]. The light absorption of the MoO_x HNS membrane exceeds 90% across a full spectrum range. Transition metal oxide is considered to be a promising alternative to photothermal conversion among the light-harvesting materials. Our group showed that the novel two-dimension WO_x nanosheets can be used as high performance of light absorption for high efficiency solar steam generator [72].

3.3 Carbon-based materials and polymers

Carbon-based materials have excellent sunlight absorption, which have attracted much attention from researchers. Black nanomaterials include carbon black [73–75], carbon nanotubes (CNT) [76, 77], graphene oxide (GO) [78, 79], reduced graphene oxide (rGO) [80–84], polymers [56, 59, 85], carbonized materials [86–92] and so on. Carbon black and graphite are often used to develop low-cost absorbers. To improve the solar energy absorption capacity of carbon-based materials, the focus is not on the absorption range, but on increasing the intensity and reducing the surface light reflection. Because one of the main motivations behind solar thermal energy consists in developing more environmentally friendly technologies, it does not make sense to neglect the environmentally benign photothermal materials.

CNT can reduce the effective refractive index and the angular dependence of incident light. Zhang's group reported that the vertically aligned carbon nanotube (VACNT) array makes it performance most similarly to a blackbody [76]. The light absorption of the VACNT array is about 0.98–0.99 over a spectral range of 250–2250 nm, and the solar thermal conversion efficiency reached 90% under solar illumination of 1 sun. Besides, Hu's group showed a CNT-modified wood membrane (F-Wood/CNTs), leading to a light absorption of ~98% and the thermal efficiencies of 65% at 1 Sun [77].

The light absorption and photothermal conversion rate of graphene materials are comparable to those of CNT materials. Chen's group described an extremely simple and independent solar steam generator consisting of a 3D cross-linked honeycomb graphene (3DG) foam material, achieving with 87% under one sun illumination and 97% absorption across 200–2500 nm [93]. Liu's group reported that hierarchical graphene foam (h-G foam) (Figure 3d), having 95% absorption of sunlight and ~93.4%

energy conversion under 1 kW m^{-2} [41]. Zheng's group fabricated reduced graphene oxide wrapped plant fiber sponges (PFS@rGO). The PFS@rGO possessed excellent solar absorption (95.5%) and efficiency of 88.8% under one sun illumination [80]. Moreover, vertically aligned 2D structures have also been adopted for improved optical properties. Qu's group fabricated the vertically aligned graphene sheets membrane (VA-GSM) (Figure 3e), possessing a blackbody-like performance with 98% light absorption [60].

Besides, carbonized materials and polymer nanomaterials also reveal excellent sunlight absorption ability. Zhou's group reported that natural wood treated by simple flame could be regarded as an ideal solar absorbing material. With excellent light absorption (99%), the flame-treated wood can enable a photothermal conversion efficiency of 72% under solar illumination of 1 sun [87]. Fang *et al.* found that hierarchical porous carbonized lotus seedpods could obtain 86.5% photothermal conversion efficiency under a sun density and provide 98–99% absorption over a spectral range of 250–2250 nm [91]. Yang's group demonstrated that a double-network hydrogel with a porous structure (p-PEGDA-PANi) for efficient solar steam generation, exhibiting excellent photothermal conversion efficiency of 91.5% under 1 kW m^{-2} and 98.5% absorption across 200–2500 nm [43]. Multilayer polypyrrole (PPy) nanosheets with self-formed surface structures, which can enhance light absorption across 200–2500 nm and reach photothermal conversion efficiency of 95.33% [59]. Meantime, Bae *et al.* [56] showed a natural design containing through-pore black diatom frustules with introducing PPy that could effectively absorb broadband solar energy. Yu's group proposed a hierarchically nanostructured gel (HNG) (Figure 3f) for high-efficiency solar steam generator. These unique properties of the HNGs presented over 95% absorption across 200–2500 nm, with an energy efficiency of up to ~94% [85].

For practical applications, environmentally benign photothermal material is a key factor that will determine the competitiveness of solar steam generation [94]. Interestingly, Asinari's group synthesized coffee-based colloids, which consists of distilled water, Arabica coffee, glycerol and copper sulphate [47]. The coffee-based colloids not only provide enhanced properties along with biocompatibility but also may encourage increasing environmentally benign photothermal material apply to state-of-the-art solar evaporation systems. As a biodegradable material, polydopamine is the main constituent of proteins in the adhesive plaque of mussels. Xu's group reported a solar-steam generation system using a polydopamine-

Figure 4: Thermal management design for solar steam generation system: (a) single-layered and (b, c) double-layered floating evaporation structure [35]; (d) conventional evaporation structure; (e) thermal insulator devices with water supply [53]

coated cotton strand, leading to an impressive solar-thermal conversion efficiency of 88.8% [95].

4 Thermal management

As a significant factor to affect the photothermal conversion efficiency, the design of thermal management includes not only the photothermal properties of the materials itself, but also their micro and macro design. It is inevitable that occur the heat losses of conduction, convection and radiation to the surroundings in the process of generating solar steam by photothermal conversion. Thermal concentration, another intelligent strategy for generating steam directly by ambient solar fluxes, is to concentrate the heat generated from a large area of light absorbers in a small evaporative region. Due to the complexity and cost of optical concentrators, it is seldom used in practical application. So, the design of the thermal management structure, which does not require additional facilities, will provide a better alternative considering the economic benefit for utilizing natural solar flux. In order to reducing heat losses, the thermal management structure is divided into

three parts: single-layered, double-layered structure and 3D structure. In this review, we focus on the thermal management structure design of solar evaporators.

4.1 Single-layered floating evaporation structures

In ISSG system, localizing heat to the air/liquid interface is crucial to high evaporation rate and steam generation efficiency [96]. In principle, single layered floating evaporation structure (Figure 4a) for heat localization are expected to the material with broadband solar absorption, open porosity, buoyancy and low thermal conductivity. Thermal conductivity is vital for thermal management that can effectively prevent the heat loss and contribute to heat confinement. Such as sodium alginate (SA) aerogels with low thermal conductivity ($<0.05 \text{ W m}^{-1} \text{ K}^{-1}$) [97], the single-walled nanotube-MoS₂ film ($0.06 \text{ W m}^{-1} \text{ K}^{-1}$) [38], the F-Wood/CNTs membrane ($0.21 \text{ W m}^{-1} \text{ K}^{-1}$) [77], RGO wrapped plant fiber sponges ($0.103 \text{ W m}^{-1} \text{ K}^{-1}$) [98], a polymer foam consisting of mainly aniline trimer ($0.057 \text{ W m}^{-1} \text{ K}^{-1}$) [99], conjugated microporous polymers aro-

gels ($0.022 \text{ W m}^{-1} \text{ K}^{-1}$) [100]. The thermal conductivity of those single-layered floating evaporation structure is much lower than the pure water ($0.6 \text{ W m}^{-1} \text{ K}^{-1}$), lead to a low conduction heat loss.

4.2 Double-layered evaporation structures

In single-layered floating evaporation structure, the photothermal layer that in direct contact with the underlying water can produces a great deal of the downward heat conduction loss. However, this structural design has stimulated numerous further studies. Appropriate thermal insulation design is essential to locate heat at the air/liquid evaporation interface, achieving better heat localization effect and the evaporation efficiency. A floating evaporation structure with double-layered, which contains photothermal layer and thermal insulation layer (Figure 4b). The double-layered evaporation structure supported by a floating porous thermal insulation layer. In general, the thermal insulation layer is usually made of melamine foam [101], bacterial nanocellulose [102, 103], the porous carbon foam [104], paper [105], cotton cloth [106], geopolymer [107], kapok fibers [108], silk fabric [109], plant stems [110]. The above-mentioned floating porous thermal insulator contains air, which availably reducing the downward heat conduction. Those porous thermal insulators, however, also contained open pores as a channel for water to be transported to the air-liquid interface. Therefore, the thermal conductivity of the wet thermal insulation layer is higher than the dry one. As shown in Figure 4c, a solar absorber was placed on a closed-cell insulator (polyethylene foam), and the foam was wrapped with hydrophilic cellulose as a water transport passage. Zhu's group reported an efficient solar desalination device, of which the solar absorber is not in direct contact with bulk water (Figure 4d) because it separated by a thermal insulator (a polystyrene foam, thermal conductivity of $\sim 0.04 \text{ W m}^{-1} \text{ K}^{-1}$). The foam only has closed pores. Additionally, the water path is limited to two dimensional (2D) by a thin cellulose layer wrapped over the surface of the foam (Figure 4e) and water is pumped through the capillary effect in the cellulose [61]. In this way, the double-layered evaporation structure supported by a closed-pore thermal insulator can suppress the downward heat loss. Heat insulating materials also include polyethylene (EPE) foam. For example, Yin *et al.* [43] reported a double-network hydrogel solar steam generator with a 2D water supply component.

4.3 3D structures

Over the past five years, interfacial solar water evaporation for a 2D solar-energy evaporator has been investigated intensively and the energy efficiency verge on the theoretical upper limit. The main energy losses in 2D system come from diffuse reflection and thermal radiation. However, the relatively low-power density distribution of natural solar radiation limits the practical application of solar energy. In order to maximize the utilization of solar energy by a variety of feasible means and exploit all kinds of heat localization techniques to decrease the heat loss are of great significance to the practical application of solar steam.

4.3.1 3D structure design

The solar absorptance of light absorbing materials should be as high as possible in the process of photothermal conversion, and it determines the initial energy input. Solar evaporation claims that photothermal materials have broadband optical absorption across the full solar spectrum (from 250 to 2500 nm). Thus far, many achievements have been devoted to exploit superior structures with minimal transmittance and reflectance. Almost or even greater than 100% solar steam efficiency has been reported by changing the absorber structure from a conventional planar device to a macroscopic 3D structure. Accordingly, Wang's group made a 3D cylindrical cup-shaped solar evaporator with mixed metal oxide [111]. Since the capability of the cup wall to restore the diffuse reflectance and thermal radiation heat loss from the 2D cup bottom (Figure 5a), the water evaporation efficiency of the cup-shaped 3D structure was closed to 100% under one-sun illumination. In addition, inspired by a Miura-ori tessellation, Wang's group reported a deployable, three-dimensional (3D) origami-based solar steam generator with a nanocarbon composite of graphene oxide and carbon nanotubes (Figure 5b) [112]. The 3D origami device showed an extraordinary solar energy efficiency close to 100% under 1 sun illumination owe to efficiently recover radiative and convective heat loss, as well as capturing solar energy through its periodic concavity pattern, which consist of rigid parallelogram faces like mountain and valley folds. Similarly, Wang *et al.* [113] developed a bio-inspired 3D photothermal cone (Figure 5c) with minimum light reflection and heat conduction loss for solar driven evaporation. Multiple reflections are displayed in the photothermal cones with an appropriate apex angle. The cone- 56° showed a higher temperature than the cone- 121° , the cone- 86° and

Figure 5: Schematic illustration of 3D structural design of thermal management: (a) 2D disk and 3D cup [111]; (b) Miura-ori tessellation [112]; (c) photothermal cone [113]; (d) lamp-like [95]; (e) salt-rejecting evaporation [108]; (f) CP-air-foam structures and thermal distribution [114].

the cone-70°. The 3D cone with rationally designed structure had an ideal absorbance about 99.2% across the solar spectrum. The photothermal cone were fixed in the hole of polystyrene (PS) plate, which can float in the air-liquid interface and control the location. The PS foam rings were used to alter the contact area by adjusting inner diameter of the hole to optimize the evaporation performance. When the contact area is reduced by a ring having a smaller inner diameter, a higher evaporation rate can be obtained in a shorter illumination time. For instance, undergoing less than 2 min illumination, Cone-70° achieved an evaporation rate over $1.70 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun illumination aided by the hole with 4 mm inner diameter. Xu's group designed a solar-steam generation system that inspired by the traditional oil lamp (Figure 5d). This system was realized by a cotton strand coated with an optical absorption layer of polydopamine as a wick, a cylinder to hold water and a cap with a hole was used to fix the cotton strands [95]. In the desalination application of solar steam, salt accumulation at the heating interface leads to increased solar reflection and blockage of water channels both of which

result in a significant decrease in evaporation efficiency. The salt rejection properties and anti-fouling of solar evaporators are therefore highly wanted. Chen's work demonstrated a small-scale floating desalination system could remove excess salts from evaporation (Figure 5e) and critically maintaining heat localization [108]. The evaporation structure was coupled with a polymer film condensation cover to produce freshwater while floating in a saline body of water such as an ocean. Beneath the black fabric was an insulating structure that composed by the alternating structure of polystyrene foam and cellulose fabric. The expanded polystyrene limits downward heat transferred from the evaporation surface above because of low thermal conductivity ($0.02 \text{ W m}^{-1} \text{ K}^{-1}$). Apparently, the more efficient the better for all energy collection and conversion applications. However, for practical outdoor solar energy applications, adequate solar illumination cannot be achieved in most areas of the earth due to different climatic conditions and the rotation of the sun. The 3D absorbers can extract energy from the environment to improve solar evaporation performance, which is a potential energy cap-

ture means. Gan's group used solar energy to generate cold vapor below room temperature by adopted the reverse approach [114]. The environment could provide extra energy for vapor generation when the evaporation temperature is lower than the room temperature. In order to realize this strategy under one Sun illumination, they used thermally isolated carbon-coated paper (CP) on polystyrene foam with the degrees of 22.4° (Figure 5f) by increase the actual surface area. The system extracted 20.7% energy from the environment for vapor generation and the obtained vapor generation rates reached $2.2 \text{ kg m}^{-2} \text{ h}^{-1}$. The work demonstrated how to use environmental energy to generate solar steam in low intensity light. The measured total evaporation capacity is higher than the upper limit of given input solar energy, which brings a unique ideas and perspectives for exploring the evaporation mode and direction of solar steam. Based on the above, the 3D morphology controlling can inspire a new insight into design novel high-efficiency solar steam generator, as well as it provides new opportunities in practical application [95, 112, 113, 115].

4.3.2 Three-dimensional (3D) printing

The three-dimensional (3D) printing technique has promising to transform the conventional photothermal solar evaporator fabrication as a revolutionary technology [116], which can quickly, automatically and precisely manufacture ideal shape material what we need. For the first time, Hu's group made an all-in-one evaporator (Figure 6a-b) by adopted 3D printing technique for high-efficiency solar steam generation [117]. The 3D-printed porous evaporator has a high solar steam efficiency of 85.6% under 1 kW m^{-2} owe to the thin and porous CNT/GO layer was used for heat localization and vapor escape. The air surrounded by the GO/NFC wall acted an effective thermal barrier to significantly reduce thermal losses to the bulk water (Figure 6c). Furthermore, Hu's group also designed a jellyfish-like solar steam generator (Figure 6d) using the vertical 3D printing technique [78]. The evaporator was composed by porous carbon black/graphene oxide (CB / GO) composite layer, aligned GO column and foamed polystyrene (EPS) matrix with low thermal conductivity ($0.08 \text{ W m}^{-1} \text{ K}^{-1}$). The EPS matrix served as a thermal insulator to suppress the downward heat loss. Therefore, the well-designed evaporator showed satisfactory energy conversion efficiency of 87.5% under one-sun illumination. But more than that, photothermal mechanisms of various processes such as light converts into heat, thermal energy heats water into steam, heat transfer, water transport, demands further research to better assess the ma-

terial or system performance. As an advanced technique, theoretical simulation can be used as an important supplement to experimental analysis. By using theoretical models and software tools to simulate these processes, we can better understand the properties of materials and structures. Hu's group studied the heat-transfer behavior of the jellyfish-like evaporator based on ANSYS simulation (Figure 7a-c) [78]. Zhou *et al.* [42] further clarified the energy limitation near the hydrogel evaporation surface by using COMSOL Multiphysics (Figure 7d-e) [118]. So, the advanced 3D printing technique offers a brand-new way to solar energy harvesting for efficient steam generation and numerical simulation of various mechanisms of thermal management deserves further exploration. These techniques will help guide and optimize material structure design and continue to play a key role in future research.

4.3.3 Natural materials

Using biomass-based structures strategy is an unmatched and promising method for solar steam generation. Natural creatures have evolved fine nanostructures on multiple scales and dimensions in a hierarchical, organized way to achieve controllable absorption, water supply, heat localization [119, 120]. The similarities between the natural structure of plants and the solar evaporation structure have inspired many bionic designs. Hu's group demonstrated a reverse-tree design was a cost-effective, expandable and highly efficiency steam generation device (Figure 8a-b), which was fabricated by cutting natural trees along the longitudinal direction, then followed by surface carbonization (called as C-L-Wood) [88]. The localization of heat occurred because of the dry C-L-Wood with low thermal conductivity ($0.11 \text{ W m}^{-1} \text{ K}^{-1}$), in which the layered empty channels could block the heat effectively. In another work of Hu's group, they reported an anisotropic mesoporous wood satisfied the requirements of heat loss suppression and efficient water supply by separating the preferred heat transfer direction and the microfluidic channels, which covered with a layer of graphite (Figure 8c) [104]. As shown in Figure 8d-e, rapid water transport was facilitated by the cross-transport of nanoscale pits on wood lumens. The thermal energy generated by the light-absorbing at the vapor generation interface was located by the wood with anisotropic thermal conductivity. Given all that the vertical cutting wood has better thermal insulation capability and the wood with anisotropic thermal conductivity contributes to the heat localization in the solar receiving layer by hindering the transfer of heat into the wood matrix.

Figure 6: 3D printing for thermal management: (a) schematic showing the process of 3D printing fabrication and (b, c) structure of the 3D-printed evaporator [117]; (d) the vertically 3D printed evaporator [78].

Figure 7: Numerical simulations for thermal management: (a) bottom view; (b) temperature distribution and (c) Heat flux distribution of the CG-HG evaporator [78]; (d-e) temperature distribution of CTH [42].

Figure 8: Thermal management of natural wood: (a) graphical illustration of the natural tree; (b) longitudinal wood blocks; (c) surface carbonization [88]; (d) manufacturing process; (e) SEM image of mesoporous wood; (f) the solar steam generation mechanism [104]

Figure 9: Thermal management of natural biological materials (a) schematics of the carbonized daikon device [90]; (b) top view and (c) heat management of carbonized lotus seedpods [91]; (d) the mushroom-based device and (e) the heat behavior [92]

In addition to natural wood as a solar evaporator, Zhu *et al.* [90] prepared a localized heating device (Figure 9a) consisted of carbonized daikon and PS foam with cotton gauze layer for steam generation. The carbonized daikon was supported by PS foam could float on the water and realize localized heating by the gauze wrapped PS foam. Researchers have found that the insulation can improve evaporation efficiency such as polystyrene foam. But the use of polymer foams is not environmentally friendly. Fang *et al.* [91] found carbonized lotus seedpods were an efficient solar steam generator (Figure 9b) for the first time. The excellent performance of carbonized lotus seedpods was attributed to the natural hierarchical mesopore and macropore structures and the efficient heat management, which markedly reduced heat loss without any extra insulation measure (Figure 9c). Because of the large internal surface area of local heat exchange, a fine-scale pore structure also effectively reduces the heat loss caused by heat convection and radiation. Zhu's group have found that mushrooms with umbrella-shaped black pileus, porous context and fibrous stipe were efficient solar steam generation systems due to their unique structures (Figure 9d) [92]. The geometry of mushrooms is also naturally optimized to minimize the heat loss of all three components, including conduction, convection and radiation due to a large surface-projected area ratio, the low thermal conductivity of carbonized mushrooms ($0.45 \text{ W m}^{-1} \text{ K}^{-1}$) and the quasi-1D conductive path (Figure 9e). These biomaterials inspired by nature not only reveal the hidden potential of biomaterials as low-cost materials for solar steam generation, but also provided inspiration for the design and future development of high performance photothermal conversion devices [90–92, 120].

4.4 Latent heat reuse

From the perspective of energy conversion, as an effective energy collection method, solar evaporation converts solar energy into heat energy, which is stored in the form of hot steam or water. However, there is a huge waste of energy between the solar input and the condensate water we collect. We are surprised to find that the use of waste heat to generate electricity in the solar steam process is an attractive way to improve energy utilization efficiency [121]. This approach with advanced thermal management can provide a promising approach to produce electricity and clean water in a personalized way, particularly suitable for remote areas/emergency needs. Ho's group [122] reported a 3D elastic cellular solid, an ultralight weight nitrogen enriched carbon sponge (CS) that performed sepa-

rate heat localization for in situ photothermal vaporization (Figure 10a). Subsequently, for the first time, they demonstrated solar steam could induce electric potential by a ferroelectric fluoropolymer polyvinylidene fluoride (PVDF) to obtain the thermomechanical responses of the CS solar vaporization (Figure 10b). During the evaporation transition, the coupling of the pyroelectric and piezoelectric effects was measured by heating-cooling and slight oscillation of PVDF film. The electrical signal outputs of CS with piezo-pyroelectric responses and the temperature variations caused by water evaporation were recorded. Since the measured electrical signals are closely related to the temperature changes experienced by PVDF thin films, the pyroelectric effect is the main mechanism for solar steam generation-induced electricity. This system obtained the maximum open circuit voltage (V_{oc}) is $\sim 80 \text{ nA}$ (Figure 10c) and the short circuit current (I_{sc}) is $\sim 20 \text{ V}$ (Figure 10d). In most interfacial solar vapor generation studies, the internal enthalpy of steam is typically lost to the environment during condensation of steam to form water (Figure 10e). Recently, Zhu's group [123] reported a device that simultaneously produced both clean water and electricity by storing and recycling steam enthalpy from the solar steam process (Figure 10f). This system was composed of three parts: solar evaporator, thermoelectric module (based on Bi_2Te_3 materials) and steam collection. The output of a thermoelectric module was depended largely on the temperature difference on both sides of the module. When the light source was turned on, the open circuit voltage and short circuit current increased with the temperature of the chamber, until it reached a stable state. More steam is generated and more condensing latent heat is transferred to the thermoelectric module with the increase of solar lighting which can further increase the open-circuit voltage and short-circuit current, up to 3.87 V and 0.55 A under 30 kW m^{-2} (Figure 10g-h). After the light source was turned off, the thermoelectric module releases sensible heat to maintain power generation. Using solar energy as the only energy input, this device proved to produce both clean water (72.2% efficiency) and electricity (1.23% efficiency) by storing and recycling the internal enthalpy of steam. At present, more and more attention has been paid to the use of staged cells to realize better latent heat utilization [124]. As shown in Figure 10i, Asinari's group presented a passive multi-stage solar distiller for seawater desalination. Each unit stage of the multistage integrated system consists of two hydrophilic layers separated by a hydrophobic microporous membrane. The design is used to reduce the gap between the hydrophilic materials and thus significantly increase the permeability of water vapor, which allows doubling the productivity of other solar-driven desalina-

Figure 10: Thermal management of latent heat reuse: (a) solar steam generation; (b) steam generation-induced electric; (c) the piezoelectric output currents and (d) voltages [122]; (e) condensation processes; (f) storage and recycling of solar steam enthalpy; (g) open-circuit voltage and (h) short-circuit current [123]; (i) schematic of the modular distiller [125]; (j) schematic of high-efficient solar-thermal membrane distillation system [126]

tion systems [125] Zhou's group proposed a compact solar-thermal membrane distillation system with salt rejection that can recycling the latent heat (Figure 10j). The absorber is heated by solar flux to produce vapor from the polyvinyl alcohol sponge containing saltwater. The vapor is then forced through the hydrophobic membrane and condense on the collector, which is driven by the high temperature difference between the vapor and the collector [126].

Therefore, in addition to the design of material microstructure and macroscopic structure, the numerical simulation of material temperature, heat conduction for further study, and the utilization of waste heat is also an advanced heat management method. Progress in combining solar evaporation with power generation offers greater promise and potential to address the challenges of global water and energy shortages due to its sustainability and ability to meet both freshwater and energy needs.

5 Water supply regulation

Under the irradiation of sunlight, the photothermal conversion material rapidly change the water on its surface into steam. Therefore, a good photothermal system needs to have a good water supply, so that water can be rapidly and continuously transported to the surface of the photothermal material for high performance water evaporation. The improvement of water supply can be started from two aspects: 1. Design of water transport channel; 2. Improvement of hydrophilicity.

5.1 Design of water transport channel

Water is transported in a 1D channel by capillary force, similar to water in the natural wood channels. Hu's group used 3D printing technique to design the evaporator having a series of vertical porous structures with one-

Figure 11: Schematic illustration of: (a) 1D water transport channels [78]; (b) 2D water transport channels [43]; (c) 3D water transport channels [42]; (d) self-regulating water transport channels [127].

dimensional water transport Figure 11a). Water is transported from the porous GO column to the evaporation surface by the capillary effect [78], which leads to a constant evaporation rate of $\sim 1.27 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun illumination. Two-dimensional waterways can provide fast water supply for evaporation systems by wrapping hydrophilic materials on the side of the insulator. Yang's group integrated the p-PEGDA-PANi hydrogel with the two-dimensional water compensation (Figure 11b). Through the capillary effect of cellulose, water is delivered to the upper hydrogel, exhibiting an evaporation rate of $1.40 \text{ kg m}^{-2} \text{ h}^{-1}$ under one-sun illumination [43]. The intrinsic layered pores of three-dimensional water channels play a significant role in the water supply of photothermal materials. Yu's group showed that a solar steam generator is composed of three-dimensional hydrogel-based polymer framework (Figure 11c). Together with capillary effect and osmotic expansion, the polymer framework transports water from the underlying body of water to the evaporating surface, which leads to evaporation rate of $2.5 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun [42]. Inspired by the self-control of plant stomata, Hu's group developed an intelligent solar water evaporation membrane (Figure 11d) that automatically opens and closes water transport channels depending on the intensity of sunlight. Because of the hydrophilicity of the

polymer chain, these bionic pores could facilitate water transport quickly, displaying an excellent evaporation performance under weak light condition [127].

5.2 Improvement of hydrophilicity

Improvement of hydrophilicity accelerates the water flow from bulk water to the evaporating surface of the solar absorber, enabling steam generation system to continuously supply water. Luo's group showed that specially functionalized graphene can improve the evaporation efficiency [128]. The hydrophilic properties of functionalized graphene could thin the water film near the three-phase contact line, promoting the capillary effect and leading to more efficient evaporation. With the increase of graphene hydrophilicity, the photothermal conversion efficiency was increased by 10% under one sun illumination.

Figure 12: (a) Changes of four main ions in seawater before and after solar desalination [130]. (b) Rejection performance of organic and heavy metal ions [131]

6 Water purification and solar steam collection

6.1 Water purification

Water purification usually represents two aspects: desalination of seawater and purification of wastewater. The solar steam water purification device can produce good drinking water by using simulated seawater, real seawater, laboratory wastewater, river water, lake water and sewage [129].

Desalination of seawater is the process of converting seawater into drinkable fresh water. At present, seawater desalination is realized by reverse osmosis and distillation in industry. Reverse osmosis can remove almost all the salt in seawater. However, the high operating pressure, high energy consumption and serious membrane pollution hinder the further popularization of reverse osmosis technology. Distillation is also a traditional method to purify water, but it has high energy consumption and cost. Generating fresh water from solar steam is a low-cost, renewable and environmentally friendly solution to desalination. As shown by Figure 12a, seawater desalinated by solar steam can effectively reduce the concentration of various salt ions [130].

Wastewater purification is also of urgent significance to solve the problem of water shortage. Wastewater purification is the separation of impurities from wastewater to obtain water with low pollution. Water that can be used directly for irrigation, flushing, flushing, and other purposes (but is not yet drinkable). After purification by solar steam, typical pollutants, including heavy metal ions, organic pollutants, inorganic salt ions and microorganisms, can be removed to obtain water that can be directly drunk. As shown by Figure 12b, wastewater purification by solar

steam can effectively reduce the concentration of heavy metal ions and organics [131].

6.2 Solar steam collection

In order to achieve high efficiency of solar steam generation, several design criteria must be satisfied, including excellent light absorption, thermal management strategy [77, 132] and efficient water supply [5, 103]. In recent years, after putting forward the concept of interface photothermal evaporation, solar-driven clean water production is developing rapidly. Although the current photothermal conversion efficiency is relatively high, it's absolutely crucial to the collection of solar steam from laboratory to practical large-scale [133].

As shown by Figure 13a, Deng's group [134] fabricated a prototype device with a sewage tank and a condensate tank. A large piece of photothermal absorption layer (rGO/paper-based composites) was floating at the contaminated solution surface to receive sunlight and convert it into heat. The transparent quartz plate was used as the upper inclined plate to reduce light absorption loss and the rest of the device is made of glass. For further continuous collection of condensed water, Xu's group designed a simple solar desalination device (Figure 13b) with a water inlet and outlet for constant use [69]. The photothermal aerogel was placed on a cotton rods in a rack that was located at the top of a seawater container. However, under light irradiation, a thin water film was formed on the wall of the device and the humidity was increased in the limited space, resulting in a decrease of the light intensity during the testing process. Similarly, Chen *et al.* [135] fabricated a solar desalination device (Figure 13c) that consists of two chambers: the inner evaporation chamber and the outer condensation chamber. Photothermal composite film was floated on the surface of seawater in the evaporation chamber. Further, Ren *et al.* [41] designed a sectional typed solar-vapor desalination unit with collection cap and steam generation chamber (Figure 13d). The upper part is collection cap (quartz slope) and the lower part is a steam generation chamber with ongoing inlet and outlet, which can provide a steady stream of sea water. The device used for condensing steam is a cone-shaped ceiling except the upper inclined plate. Li *et al.* [64] designed a solar steam collection system, as shown in Figure 13e. In this device, contaminated water was stored in an inner bottle that included a thermally insulating layer coated with cellulose paper, the sponge at the top of the thermally insulating, the produced water steam condensed on the cone-shaped ceiling and flowed down. Some condensed water

Figure 13: Schematics of solar steam collectors

droplets inevitably adhered to the surface of the glass and affected the incident density of light. Furthermore, Wu *et al.* reported a direct contact membrane distillation (DCMD) module (Figure 13f) that the water evaporated on the hot feed water side of the membrane surface, diffused through the microporous film and condensed on the cold distillate side [96]. Membrane distillation (MD) is a beneficial thermally-driven membrane technology, based on the vapor pressure difference between the two sides of a porous hydrophobic membrane, which can produce clean water at a lower temperature than boiling and lower pressures than reverse osmosis [94]. However, the conversion efficiency of photothermal MD membranes is relatively lower because of the interference of top water layer to sunlight and conductive heat loss. Especially, Ho's group designed a prototype reactor (Figure 13g) that combined with clean energy and water production for the first time [136] and advantageously made use of photothermic enhanced catalysis and desalination. Under the sun's illumination, hydrogen was produced on the left side of the reactor and steam was produced on the right side. In order to collect the produced water vapor, a steam collecting device containing water condenser coil was designed on the right side where the water vapor generated. The condenser could be passed through cold water so that the steam condensed into water through the water condenser coil and fell into the collecting device, which sped up the condensation of steam. Subsequently, Ho's group designed the first integral prototype design (Figure 13h) for parallel production of fresh water and triboelectricity [137]. The prototype included inclined walls and around bottom vessel lined with PTFE energy using triboelectric nanogenerator (TENG) de-

vices. When light was transmitted through the window to the photothermal material (gold nanoflowers solar absorber gel) in the sealed prototype, the water vapor condensed on the wall to form tiny water droplets and accumulated into larger droplets that overcame the friction of the wall surface and flowed down on account of gravity. Condensate produced electrical signals during downward flow and swinging in any direction with the device due to the electrification of the water and the PTFE. So, the condensed water was collected at the bottom of the vessel. Steam collection should not only take into account the light transmission of the collected material itself, but also consider that the most common and important problem that the loss of light absorption caused by the condensation of water droplets from condensed plates during the collection process [98, 138]. In future research, the design of new materials and structures which can mitigate the reflection of incident light needs to be further exploration and development.

7 Conclusion and prospects

In this review, we clearly present the fundamental concept, classification, mechanism, efficiency calculation, influence factors and solar steam collection. Starting with the fundamental concept, a comprehensive summary of interfacial solar-driven steam generation system is reviewed. Compared with the conventional bulk heating-based evaporation, interfacial solar-driven steam generation system can limit the heat to air/water interface and form the heat

localization, reduce thermal loss and improve energy conversion efficiency. We also list the light absorption rate and photothermal conversion efficiency of photothermal materials in the literature related to interfacial water evaporation in recent years. Thus far, interfacial solar-driven steam generation systems has been made a great deal of remarkable progress due to the advanced idea of thermal management, which not only have presented various class of materials with high solar absorptivity, but also have expanded the application fields of interfacial solar-driven steam generation system by the innovative photothermal system designs. For instance, multifunctional systems would be used to desalination, water purification, sterilization, photocatalysis and energy generation. Although extremely high conversion efficiency has been achieved under practical conditions (> 90%, even beyond the theoretical limit) in recent years, the utilization ratio of light absorption and the actual production efficiency of pure water under natural solar illumination still needs to be further improved in order to inspire the research work of solar steam generator from small to large scale. In practical applications, solar evaporator must consider durability, low-cost and chemical stability.

In addition, by studying the structural design of natural biological systems and the intelligent adjustment of its conversion process, it would provide a unique inspiration for the exploration of efficient solar evaporation device. In order to achieve better performance, solar-driven interfacial evaporation requires further basic research on the mechanism of various processes, for example, photo-physics, solar-heat conversion, heat transfer, vapour diffusion kinetics. Modelling of thermal transport behavior, water transport and vapour flow circulation are also invaluable for better prediction, acquisition and optimization of material-system performance. Moreover, effective condensation of water vapor, collection strategies and the use of its latent heat are critical to the production of clean water, which would increase energy efficiency.

Finally, we believe that the rational and efficient integrated application design of the interfacial solar-driven steam generation system will flourish in the future. By further exploring photothermal characteristics and understanding, solar steam devices interlinked water, energy and environmental, providing sustainable solutions for steam generation and energy generation.

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