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Solar-thermal Conversion and Steam Generation: a Review

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Highlights

- Solar absorbed materials and their photo-thermal conversion mechanism are reviewed.
- The evaluation principle of photo-thermal conversion process are investigated.
- Different solar absorbed evaporation methods and system are summarized.
- The prospects and challenges of photo-thermal conversion and steam generation are discussed

Abstract: Recently, steam generation systems based on solar-thermal conversion have received much interest, and this may be due to the widespread use of solar energy and water sources such as oceans and lakes. The photo-thermal desalination system becomes attractive as it can convert absorbed solar light energy into thermal energy and realise the desalination and water purification of saline water through the evaporation process. In this paper, the research status of solar-thermal conversion materials such as metal-based materials, semiconductor materials, carbon-base materials, organic polymer materials, composite photo-thermal materials and their solar-thermal conversion mechanism in recent years are reviewed. The physical process and evaluation principle of solar-thermal conversion are both carefully introduced. The methods of optimising thermal management and increasing the evaporation rate of a hybrid system are also introduced in detail. Four main applications of solar-thermal conversion technologies (seawater desalination, wastewater purification, sterilisation and power generation) are discussed. Finally, based on the above analysis, the prospects and challenges for future research in the field of desalination are discussed from an engineering and scientific viewpoint to promote the direction of research, in order to stimulate future development and accelerate commercial application.

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Keywords: Solar steam generation; Solar-thermal conversion; Solar-absorbed materials; Evaluation principle

1. Introduction

Solar energy is a green, stable and universal source of renewable energy, with wide spectrum and broad area characteristics [1]. It is regarded as being one of the renewable energy sources with the greatest potential to achieve sustained, high intensity energy output [1,2]. The conflict between population growth and water shortage has become one of the most challenging problems of the 21st century [3,4]. Evaporation based on solar technology, as a fundamental component of the water circulation system in nature, has gradually become an essential method of using solar energy [5]. Solar-powered evaporation, as a foundational mass and heat transfer process, plays a pervasive role in driving applications around the globe, and humans have used it since ancient times in order to harvest fresh water [6]. In addition to improving the utilisation efficiency of existing freshwater resources, the integration of wastewater treatment, seawater desalination and electricity generation are also considered as key means for alleviating the current water and energy shortage [7,8]. Therefore, in order to promote highly efficient solar utilisation, it is necessary to adapt its characteristics and transform light energy into other forms of energy in an efficient way [9]. Currently, the conversion and utilisation of solar radiation mainly include photo-electric, photo-thermal, photo-catalytic and photo-biological energy [10,11]. To date, solar-thermal conversion and steam generation (SCSG) is the most direct utilisation method, and this has been widely used in fields such as photo-thermal power generation [12], photo-thermal energy storage [13], seawater desalination [14] and sewage treatment [15]. It converts solar power directly into heat for evaporation at an operating temperature which is lower than that of boiling temperature [16]. Despite this, it still remains high cost due to system complexity and high concentrations of light [17].

In Fig. 1, the global horizontal irradiation of solar energy distribution is shown, which indicates that it is abundant in most regions and countries, and it is a wise choice to develop related technologies which are based on solar energy. Through the development of the world in the past ten years, solar energy technology, in particular solar driven interface evaporation technology, has achieved an unprecedented level of development and made remarkable achievements [18]. In searching for “solar-thermal conversion” and “solar steam generation” respectively on the Web of Science based on Science Citation Index, the results show (Fig. 2) that there has been a stable booming trend in the past two decades and that it has gradually become a research hotspot. In particular, the number of papers during the past ten years has increased in leaps and bounds, and this

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has laid a theoretical foundation and shown a development direction for this field [19]. According to thermodynamic theory, liquid water in dry air can evaporate to saturate the surrounding air in order to reach an equilibrium where the partial pressure of evaporation in a natural environment is equal to the liquid saturation pressure [20]. Increasing the liquid temperature through solar heating results in a higher saturation pressure, and this requires an increase in partial pressure in order to promote vapour generation [21]. In recent years, pioneering works of SCSG from Chen et al. [22] and Halas et al. [23] on low light intensity have attracted widespread attention due to their high efficiency and low cost. Their method, which can be called equilibrium evaporation, has become an essential topic for harvesting solar energy, and it is suitable for the application and establishment of seawater resource separation to meet the needs of domestic and industrial water in places with abundant solar energy [24]. It has changed the original physical cognition for equilibrium from evaporation to boiling. Immediately following the research on SCSG using carbon black light absorption and insulation design, it showed that the photo-to-steam efficiency is higher, and for the purpose of maximising thermal efficiency, extensive follow-up research was conducted in order to discover new materials within the field of thermal engineering [25]. Almost all solar applications require absorbing materials in order to receive solar radiation and conduct thermal management programmes. SCSG thermal applications also require receptors for absorbing light and transforming it into thermal forms, which is then transferred to liquid in order to realise the increase in temperature [26].

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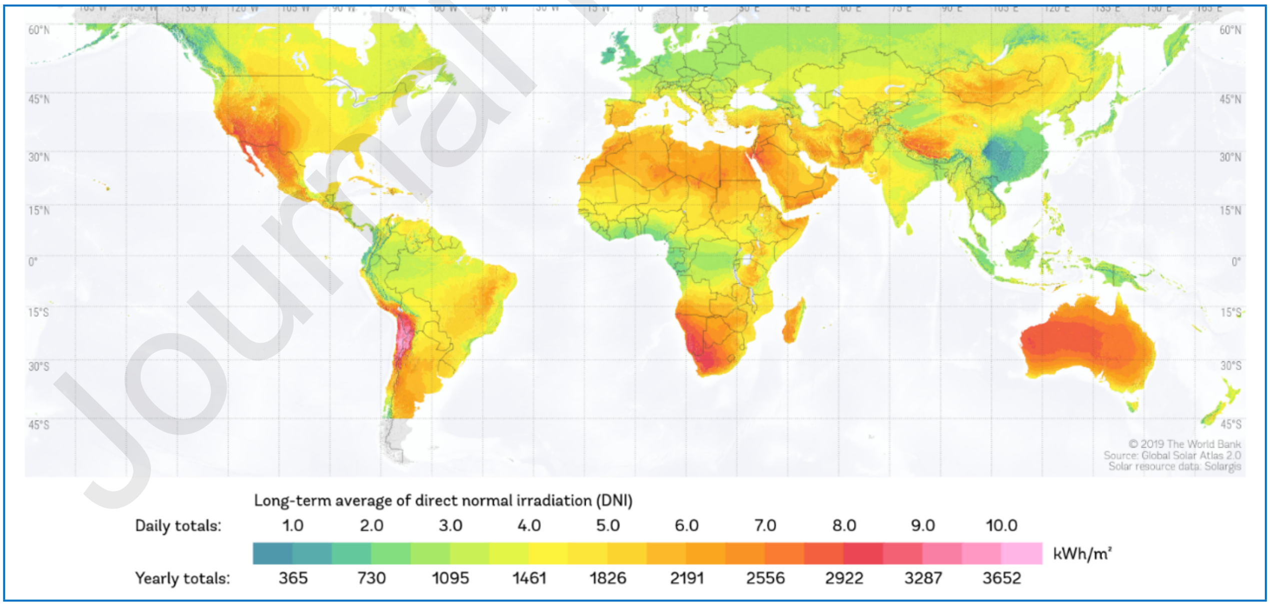

Fig. 1 Global horizontal irradiation of solar energy distribution, which was obtained from a widely recognised organisation based on the Solargis GIS map as a data source with permission (2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis)

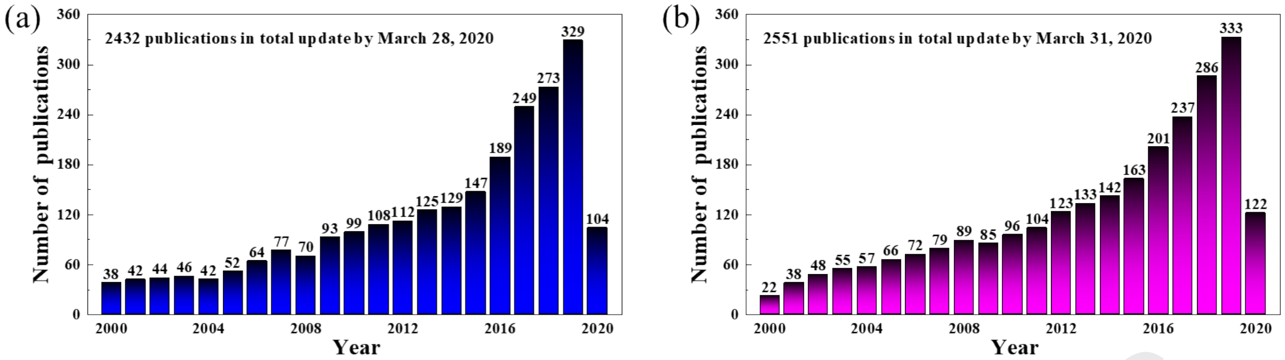

Fig. 2 Published article statistics in the past two decades using the keywords (a) “solar-thermal conversion” and (b) “solar steam generation”, which was obtained from a widely accepted literature using the Web of Science as a data source

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The key component of solar material innovation is the improvement of the absorption of sunlight [27,28]. High-quality solar absorbed materials are characterised by a wide absorption spectrum range, high solar-thermal conversion efficiency, low cost, strong surface hydrophilicity, multi-pore structure, good self-floating property and independent incident direction of light source [29]. They exhibit good application prospects in desalination and saltwater treatment [30]. When selecting solar-thermal conversion materials for desalination with salt water, single material is rarely selected, but two or more materials are hybridised or undergone other composite treatment in order to improve the thermal conductivity of materials, enhance the resistance of corrosion, saline-alkali resistance and thermal stability of materials, and further improve solar-thermal conversion and desalination efficiency [31]. SCSG can be divided into three technologies based on the methods of receiving solar energy and heat transfer methods [32]: (1) Heat produced at the device surface and steam generated in the device [33]. The solar-to-heat transfer efficiency is suboptimal due to the reflection of the surface of the heat absorber, so that the heat used for evaporation is much less than the actual solar thermal power. (2) Efficiency is improved by reducing heat losses on the device surface based on volumetric solar absorption, which relies on stable nanofluid dispersion and a long-term pumping process [34]. (3) The heat localisation is improved by interfacial evaporation technology and can achieve high solar-thermal conversion efficiency [35]. This approach not only utilises efficient heat for water evaporation compared to the first two methods, it also optimises the used photo-thermal materials and suppresses volumetric heating [36]. In addition, due to the rapid development of the SCSG system, different designs and materials are regularly invented and discussed [37,38]. Therefore, it is necessary to communicate the latest challenges and progress with the wider scientific community [39,40].

In this review paper, solar-thermal conversion mechanisms based on the absorber’s materials (plasmonic nanoparticles, carbonaceous materials and composite materials) and evaluation standards are discussed. Then, based on general design considerations of solar-driven interfacial evaporation system, water transport, thermal insulation and hybrid devices are systematic introduced. Next, in terms of application, traditional applications in desalination, purification, sterilisation and power generation are discussed. Finally, in view of the shortcomings of existing research, the outlook of the SCSG field is presented, which points out the direction for future research on SCSG and provides suggestions for further development. In summary, the purpose of this paper is not only to summarize the research literature on high-efficiency SCSG in recent years, but also to provide new research ideas for the development and application of highly-efficient SCSG in the future.

2. Solar-thermal conversion mechanisms and evaluation standards

As previously mentioned, solar-thermal conversion mechanism is a major part in SCSG research, with the main purpose of improving light absorption efficiency, as well as involving water delivery and heat losses [41,42]. SCSG developed based on solar-absorber materials can affect photo-thermal mechanisms and some typical model categories have been established [43]. Photo-thermal mechanisms include local heating of surface plasmon resonance, thermal vibration of molecules, and production and relaxation of electron holes, which are shown in Fig. 3 [44]. Typically, a single solar absorption material follows one of the photo-thermal mechanisms [45]. However, such a physical process may involve multiple mechanisms in composite solar absorption materials [46]. In order to design a solar absorption material with excellent solar-thermal evaporation performance, three primary factors must be considered: proper thermal management, effective solar-to-heat conversion and effective solar absorption [47].

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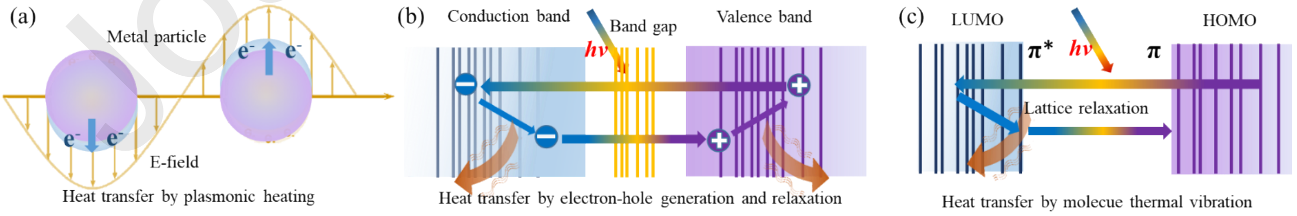

Fig.3 Photo-thermal conversion mechanisms of different kinds of solar absorption materials [10]: (a) Metal particles with plasmonic heating, (b) Semiconductor materials with electron-hole generation and relaxation, and (c) Carbon-based materials with thermal vibration of molecules

Sunlight heats objects using radiation within a wide wavelength region. In Fig. 4a and Fig. 4b, the solar spectrum includes the ultraviolet (UV) region (300-380 nm), visible light region (380-760 nm) and near infrared region (760-2500 nm) at AM 1.5 (standard solar spectrum), which represents the solar spectrum at the zenith angle of 48.2° and covers most countries. The power distribution on the surface of earth is 3% (UV region), 45% (visible light region) and 52% (near infrared region). Different utilisations, such as solar-electric, solar-thermal, solar-catalytic, and solar-biological energy, are actually used for production at selected spectral ranges [48]. Heat is generated from the interaction between incident sunlight and photo-thermal materials. The photo-thermal material first scatters and absorbs the photons in the upper fluid, and then photons are partly incident on the lower fluid [49]. Heat is generated on the surface of the photo-thermal material and transferred to the fluid molecules by the medium. The generation of heat is related to the size, shape and dielectric constant of the metal particles which are heated locally by the molecular fluids [50]. The Columbic charge or thermal relaxation caused by non-radiative relaxation and type semiconductor band gap energy between nanoparticle materials is linked to the phonon-phonon intramolecular coupling phenomenon [51]. Finally, thermal energy diffuses in the water.

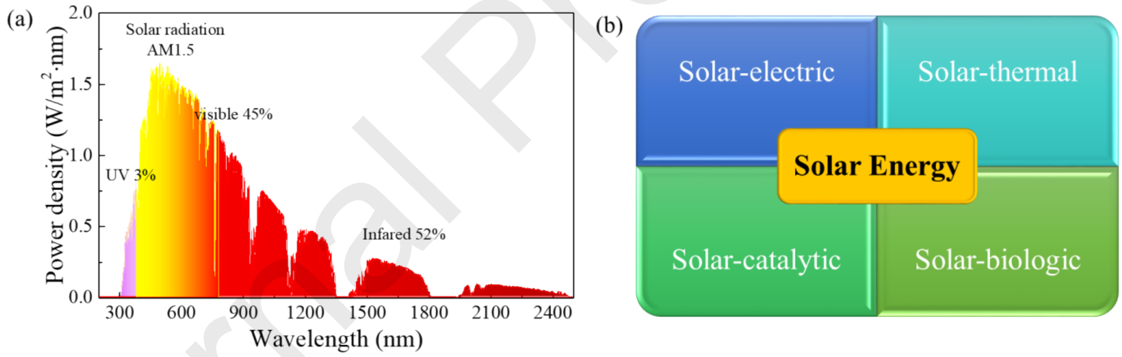

Fig. 4 (a) Solar spectral irradiance (AM 1.5): The power density of UV, visible light and near infrared region with a wavelength from 300 to 2500 nm [35,45]; (b) The four main conversion forms of solar energy [24]

During the thermal energy conversion process of solar energy, system heat losses are inevitable, and measures must be taken to reduce such losses caused by conduction, convection or radiation [52]. It can be concluded that in practical applications of SCSG, due to thermal management and material cost considerations, solar suspension absorbers may be superior to solar body devices [53]. Better heat regulation may reduce thermal loss to the environment to a great extent, thereby collecting more solar energy and converting it directly into the enthalpy of liquid evaporation and improving the efficiency of thermal evaporation. In order to suppress radiation loss, the ideal solar absorber must possess low thermal emissivity and high incident light absorption, which can be

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realised by high reflectance at the long-wave infrared region [54]. The heat loss of a solar absorber is caused by heat radiation, which increases at high temperatures. The selective spectral absorption materials can be matched with sunlight in order to match the best absorption wavelength required by the material spectrum.

In a solar-powered system for steam generation without a concentrating device, such as a solar distiller, heat and steam are not generated in the same place. The former is generated on the surface of the container, while the latter is normally generated inside the device [55]. This method of separating steam and heat leads to the generation of heat gradients which causes the temperature of the evaporation surface to hinder the lowering temperature of evaporation, which in turn leads to inevitable heat losses and relatively low evaporation efficiency in solar distillers (30-45%). The method in the above statement is known as “bottom heating” [56]. According to the relative position of the solar absorber and the heated water, it can be further categorised as bulking heating and interfacial heating, which are consistent with dispersed absorbers and surface absorbers [57,58]. The first one is considered by physicists to be excited by the interaction of light, mostly to improve the absorption efficiency of light and further improve the heat conversion efficiency of sun illumination [59]. The latter uses mostly low-cost materials such as carbon in order to achieve higher solar steam production efficiency [60]. Some simulations relating to the topic were used to assist the analysis, and an explanation was obtained by comparing the experimental values. All the photo-thermal methods in the above statement can be summarised by Fig. 5.

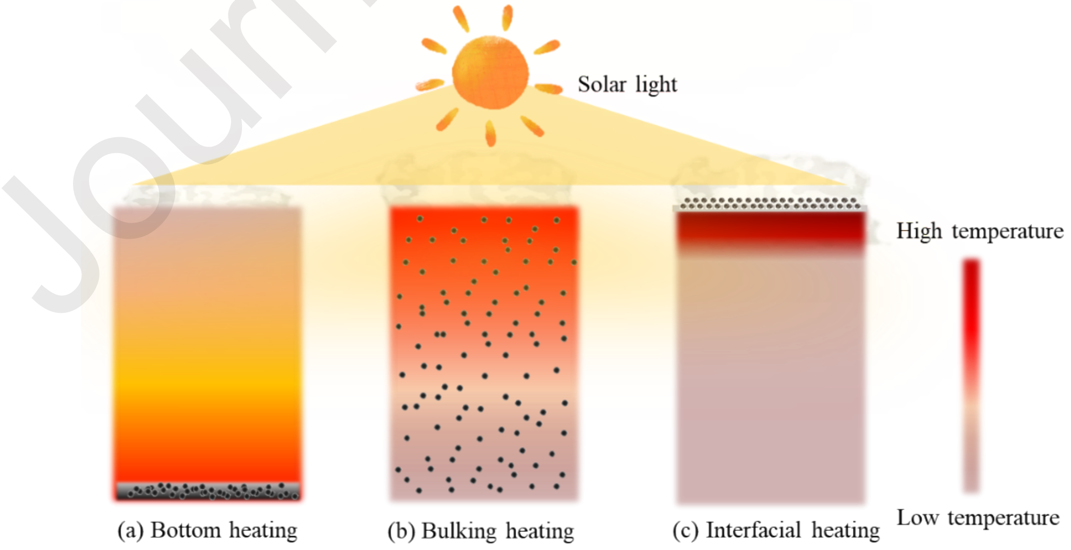

Fig. 5 Physical processes and solar-thermal conversion and solar steam generation methods based on three different heat

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transfer methods: (a) Bottom heating [27], (b) Bulk heating [32] and (c) Interfacial heating [24]

The same materials, particularly composite materials, can be used in any of the two allocations, and their combination has also been researched [61]. We discuss two photo-absorption principles and the strategies based on research activities of the material in this section. A long-term challenge is to evaluate the performance of solar evaporation devices correctly and uniformly. The current research has a programmatic calculation formula, but it lacks standardised measurement techniques and evaporation calculation efficiency [62]. Therefore, it is unscientific to directly compare the results of different jobs, as even the same material will demonstrate significant differences in evaporation efficiency during different seasons and at different times of the day. This has become a difficulty which hinders the development of the SCSG system [63]. A convincing approach is to subtract the rate of natural evaporation in the final evaporation rate calculation in order to eliminate environmental effects such as ambient temperature, humidity and wind [64]. In addition, the specific calculation formula and ways of determining the relevant parameters should be clearly explained in detail. Nonetheless, the solar evaporation research project will formulate more widely recognised and stricter guidelines as standards for the measurement and calculation [65]. Steady-state solar-thermal evaporation efficiency (SEE) is applied to evaluate steam production performance. This is defined as enthalpy of evaporation of light-to-heat conversion divided by the total solar heat received, which can be calculated using equation (1): [66]

$$\mathrm{SEE} = \frac{\dot{m} h_{\mathrm{lv}}}{q} \tag{1}$$

where $\dot{m}$ denotes the water flux of steam generation, which is equal to the absolute value of the linear gradient of the mass change during sunlight radiation time, h_{lv} is the enthalpy of the water phase change from liquid to gas, and q denotes the illumination density of light power. Under the condition of neglecting heat loss to the environment, two factors cannot be ignored which affect the steam generation process: one is that part of the heat causes the temperature of the volume of water in the collector to rise, and the second is that water is heated to become water vapour to reach the dehydration surface and enter the air. Therefore, in order to quantify the light-to-heat conversion performance of these devices, most work defines the total thermal efficiency (TTE) of the device, which represents the heat-receiving efficiency of the device over time [67].

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$$\mathrm{TTE} = \frac{m_{\mathrm{v}} c_{\mathrm{p,l}} \Delta T + m_{w} \mathrm{h}_{\mathrm{lv}}}{qAt} \tag{2}$$

where t is the evaporation time, A is the area of sunlight illumination, m_{v} is the total amount of evaporated water, m_{w} is the mass of bulk water, $c_{\mathrm{p,l}}$ is the specific heat of water at standard atmosphere pressure, and ΔT is the temperature increase of the bulk liquid. Heat dissipation to the surrounding environment will be accelerated when the surface temperature is too high which causes an increase of heat loss. The heat absorbed by nanoparticles and solar energy is transferred into the fluid to achieve effective absorption [68].

Volume heating is not specifically designed for applications which require evaporation, so no higher surface temperature is required. Near-infrared energy is also easily absorbed by water and directly diffused into nanofluids, while ultraviolet-visible energy is mostly absorbed or scattered by nanoparticles. The inherent absorption rate of the particle itself determines the solar energy which it can obtain. First-order scattering changes the direction of energy and enters the next particle, which results in irradiance distribution in different directions in the nanofluid [69]. According to transmission law, secondary scattering is caused by the collision of light waves with adjacent particles. As this process continues to become higher-order scattering, the energy escapes from the collector wall or dissipates in the nanofluid. Scattered light emitted from adjacent nanoparticles is absorbed by each other, although the final energy will be dissipated with the scattering. From the above discussion, it can be noted that during the irradiation process, the nanoparticles provide several nucleation sites during heating, and this promotes the generation of water vapour. When the illumination is absorbed by solid particles, temperature difference is produced between the nanoparticles and the surrounding medium, and the local temperature rise is sufficient to directly convert the liquid into steam. Due to the plasmonic resonance effect of the nanoparticles, the liquid forms isolated bubbles on the surface of the particles, the thermal conductivity of the particle-liquid interface is reduced, and the particles are encased in steam with low thermal conductivity during the non-equilibrium process [70].

Following a sufficient period of illumination, the heat dissipated in the steam generation process is significantly higher than that consumed by the fluid temperature rise, and the water temperature near the nanoparticles reaches the vaporisation temperature of liquid water and produces a non-equilibrium influence between the surface hot suspension and the bottom cold liquid [71]. Once

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the steam bubble forms on the particle surface, the force balance of the nanoparticles is destroyed, and the nanoparticles then rise with the vapour bubble. As they rise, the bubbles grow, merge with one another, and eventually escape from the surface of nanofluid, where the nanoparticles fall back into the suspension to reheat the nanofluid. In addition, strong dispersion and pumping of nanofluids during long-term periods of strong solar radiation remains challenging. Exciting progress has recently been made with the designing of nanomaterials, light absorption, thermal management and water supply, and they are expected to be widely used in the fields of water purification, solar desalination, groundwater extraction and power generation interfaces.

Previous work in the field of interfacial solar-thermal conversion has focused on its thermodynamic advantages, namely the high energy conversion efficiency of solar-steam. As the absorbers can localise the absorbed solar energy to the water's surface in order to promote evaporation, this can greatly suppress the water's conduction heat loss. Scientists have proposed an interface evaporation method to improve the thermal location of the liquid surface, and successfully achieved approximately 90% evaporation efficiency under the condition of reducing the optical concentration [72]. This method selectively heats the evaporated part of the water, rather than the whole body. Solar-driven interface evaporation averts the heating of volume devices, saves raw materials and costs, and provides a new path to dynamically adjust the steam generation performance, including the steam flow rate and temperature [43,56]. Due to these advantages, solar interface evaporation has the potential to expand the application of solar thermal technology in intensive, self-sufficient and portable systems [73]. A typical solar interface evaporation system includes a light absorber, a substrate and a water reservoir which separates light and shade. The external conditions include incident light and steam. The incident light is absorbed by the light absorber and then converted into heat. Fig. 6 shows the heat transfer process of a typical solar interface locally heating to generate steam, and thermal resistance analysis facilitates the researchers to quantitatively calculate the corresponding heat loss and heat transfer efficiency. During the process of desalting, water is absorbed by the substrate and transmitted to the evaporation surface of the absorber through the capillary force of the interconnected water path. The expansion of moisture generated on the evaporation surface causes the substrate to absorb water continuously, and the temperature of the water increases in order to continuously promote the evaporation process. During the past ten years, due to the rapid development of new types of photo-thermal materials and

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structures, in addition to the rapid development of water transport materials and thermal insulation materials, interface solar evaporation efficiency has increased by 190% at a low solar power [74].

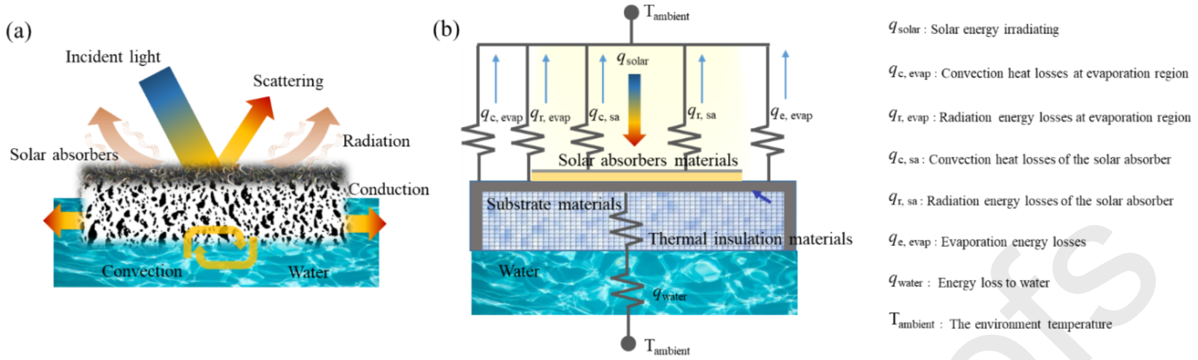

Fig. 6 (a) The heat transfer process of typical solar interfacial heating to generate steam, and (b) The thermal resistance analysis of solar-thermal conversion for quantitatively calculating heat loss and heat transfer efficiency [13,35]

3. Solar-thermal conversion materials, structures and devices

3.1. Solar absorption materials

Solar evaporation is widely used in wastewater treatment and desalination. Compared to traditional solar evaporation technology, the new solar evaporation system based on nano-materials, in particular the interface evaporation system, has the advantages of small heat loss and high evaporation efficiency [75]. So far, many materials can be classified into several types, as shown in Fig. 7. The photo-thermal film is the core element of the interface evaporation system [24]. The development of high efficiency and low cost solar absorbed materials is the key for promoting the development and application of interfacial evaporation systems [76].

It is not difficult to realise that solar energy absorbing materials include mostly plasmonic materials, polymer materials, carbon materials and hybrid materials. Carbon materials are normally used as solar energy absorbers as they possess natural high bandwidth light absorption characteristics. So far, carbon material has been found in the solar absorber of a SCSG system as it absorbs light with broadband wavelength [77]. Using solar absorbers based on carbon, such as graphite, carbon sponge, graphene oxide, carbon nanotubes, hollow carbon spheres or wood carbonisation can provide high evaporation efficiency. For example, the evaporator based on graphene oxide achieved 99.0% absorption at a wide band wavelength of 250-2500 nm [30]. Other carbon-based materials include cellulose membrane, air deposition paper, polyacrylonitrile/carbon black, porous filter paper and polyurethane sponge [78]. Furthermore, advanced manufacturing technologies are also used for

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producing structures with independent water transport channels, such as 3D printing, self-assembly, femtosecond laser processing and flame processing. However, we have not yet seen whether devices which use complex materials or manufacturing technologies deliver better system performance than devices which use simple fibre wicks or packages [79].

Considering that the individual component carbon absorber only has excellent optical characteristics, the material-combined absorber has thermal sensitivity and optical activity [80]. Plasmonic absorbers such as germanium, aluminium, palladium, silver, gold and gold/silver bimetallic are widely used in a SCSG system due to their strong light to heat conversion and light absorption abilities. These properties are due to the match between the natural frequency and the photon frequency of the electrons on the metal surface. It is worth noting that the absorption band of a single plasmonic nanoparticle is narrow. To enlarge the absorption spectra, the plasmonic nanoparticles must be fixed on the porous membrane, like cellulose fibre, nanoporous anodic aluminium oxide (AAO) template, graphene, wood or SiO_2. For example, Fu and his colleagues prepared and measured the UV-vis spectra of Au, GO and GO-Au nanofluids [81]. It was found that there was only one surface plasmon resonance bond at 533 nm wavelength. However, in GO-Au nanofluids, this became two absorption bonds, which can absorb more sunlight. Compared with independent cellulose filters, the deposition of gold nanoparticles on cellulose filters can increase optical absorption ability from 70% to 90%, particularly in the wavelength range of 300-2500 nm [81,82]. In recent years, a new type of photo-thermal absorption material has been developed, and it has the advantages of wide bandwidth, low cost and durability against high temperatures and sustained friction [82,83]. These are based on transition metal nitrides, cotton nano agarose aerogels, nano scale molybdenum oxide, molybdenum oxide quantum dots, monosilene, Ti_2O_3, and $W_{18}O_{49}$, [83]. Interestingly, the developed photothermal absorber has a high water evaporation rate.

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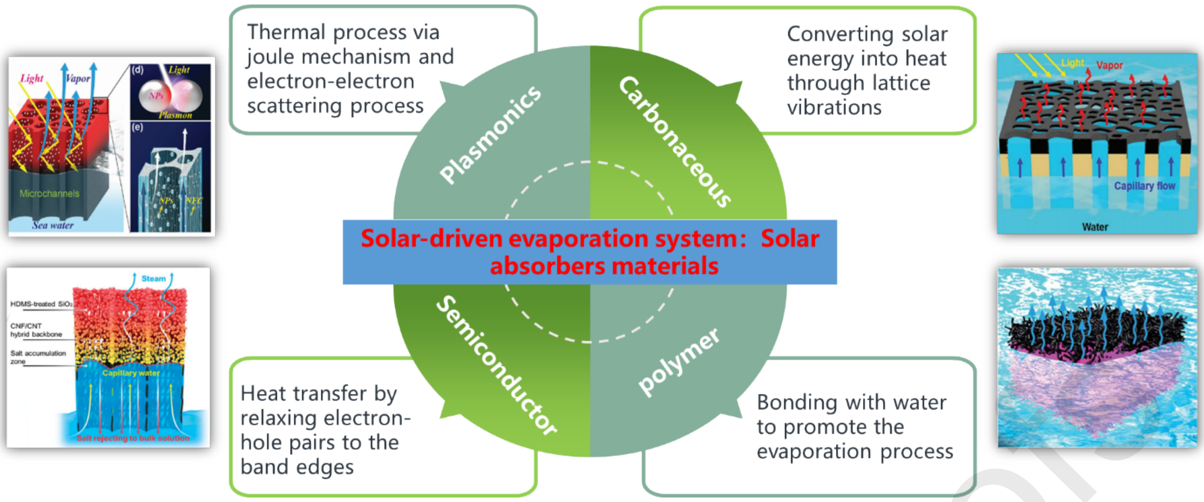

Fig. 7 Different types of solar absorption materials used in a solar-driven evaporation system: (a) Plasmonic materials enhance the solar absorption via Joule expansion and electron-electron scattering process [42]; (b) Carbon-based materials convert solar energy into heat with wide absorption spectrum [61], (c) Semiconductor materials accelerate heat transfer through relaxing electron-hole pairs and [70] (d) Polymers bond with water promote the evaporation process [51]

3.2. Structure for thermal insulation and water transport

The heat-receiving structure is generally composed of two parts with different functions. The upper layer is the solar absorption layer, and the rock-bottom is floating body, water conveyance and heat preservation base material [84]. In addition to absorbing solar energy, substrate material is also important for improving the evaporation efficiency of the SCSG system. The structure of the substrate is generally less dense than water, so it floats in a thin layer of water. Sometimes, the substrate itself is a solar absorber, but in other cases, it is placed under the solar absorber, as the material is normally porous and has a low thermal conductivity. The separated floating parts can provide additional insulation. For this reason, two main functions are usually considered in most research, including water transfer or evaporation, and heat preservation [85].

For the first critical function, effective water transfer and evaporation rates, good wetting properties and a continuous path are all essential [86]. It can be seen that the optimisation of the evaporation rate of water and liquid supply in the heating zone plays an important role in obtaining higher SEE. Therefore, in addition to the control and design of absorbents, the role of waterway design is essential for achieving high vapour generation. Some researchers did not use the whole floating material to suck up the water, which could actually damage the thermal positioning. Instead, they used independent suction water in a non-humid floating body in order to reduce the heat leakage through the water and provide sufficient water supply for the evaporator. This was verified in the

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design of Ni et al. [75]. The insulation foam limits heat transfer in the water below, and several fabric cores embedded in the foam are used to transport water through the foam to the evaporating surface [75,87].

The balance between effective water delivery and thermal insulation must be carefully studied in order to achieve greater evaporation efficiency. Fig. 8 shows several typical combinations between water transportation and thermal insulation based on solar steam generation [43,70,74,76]. Cellulosic foam, polyurethane and polystyrene foam, AAO, graphene oxide aerogels, carbon nanotube arrays, natural wood, cotton and other substrates have been developed. This is because they possess low thermal conductivity, good hydrophilicity, high porosity, low thermal conductivity and the water transport characteristics of nano channels. It is worth noting that the surface properties of the evaporation structure are important factors which affect the performance of SCSG. Therefore, hydrophilicity is helpful for the evaporation of water at the interface and the effect on suspension, while the hydrophobic surface enables the solar absorbed materials to float on water. The three-dimensional structure shows that the recovery of diffuse reflection can reduce heat loss due to the ability of the wall and the bottom of the cup. Therefore, almost 100% of the suspension is irradiated at $1\text{kW}\cdot\text{m}^2$ [9]. Due to its porosity, carbon foam has low thermal conductivity, which aims to provide heat insulation in order to minimise heat leakage from large quantities of water from the solar absorber to the container. At the same time, in order to ensure the supplementary evaporation of water supply, hydrophilic treatment is adopted for both layers.

However, low thermal conductivity and porous structure are ideal for improving adiabatic performance. It is important to note the relationship between these factors. In other words, the structure of the pore is a factor which controls water conveyance and heat preservation. Therefore, it should be noted that in the water channel design system, the absorber is suspended in the liquid phase due to the insulation structure. During operation, the thermal conductivity of hydrophilic carbon foam is similar to that of water, which is much higher than that of dry carbon. Many subsequent studies use a similar double-layer structure, with various solar energy absorbing materials and foams, paper and wood as a supporting layer for liquid conveyance and heat insulation [27,50]. In order to minimise heat losses, the pores in the thermal insulator should be closed, and the pores in the water conveyance structure should be open for water supply [27]. Therefore, it is necessary to verify the balance between the designed thermal insulator and the water delivery structure in order to

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obtain high SEE.

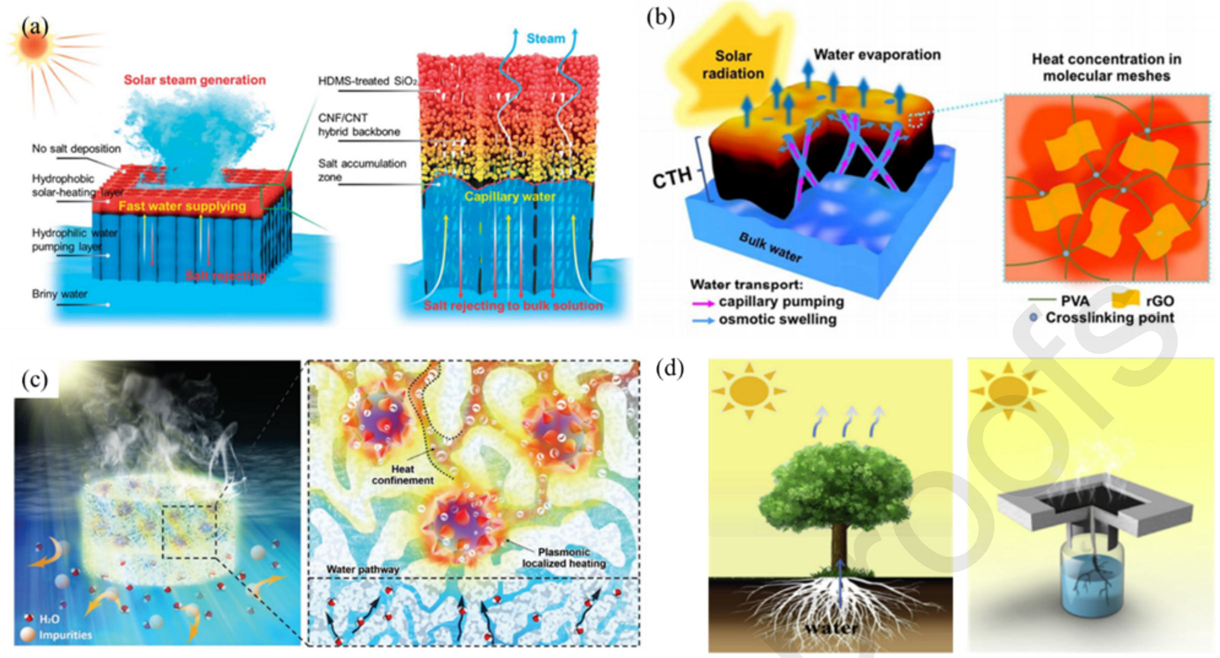

Fig. 8 Water pathway and transport based on solar steam generation: (a) The pore structure within low tortuosity design of the evaporator accelerates water transport [70]; (b) Solar vapour generation based on hybrid hydrogels with capillarity facilitates water transport [76]; (c) Controllable pore size absorber gel provides capillary water transport channels and steam pathways [43]; and (d) Water transport within confined evaporation, branched diffusion based on mimetic transpiration system [74]

3.3. Hybrid devices

Recently, several methods have been developed which can improve the SEE mentioned above. This provides an opportunity to expand desalination in a low-cost way [6,14,88]. In order to achieve large-scale desalination of salt water, many devices have been developed, which are based on a single basin and consist of monoclinic cover, cone-shaped, quasi semi spherical, house model and pyramid prototype [27,34,35,66,69]. It can be seen that there are many cavities with special internal structure, which can concentrate sunlight, improve urine and produce fresh water [27,32,55]. Generally, there are two methods of evaporated water collection: passive water transport and active water transport. The first method relies on gravity structure design and the second requires additional power consumption (Fig. 9). There have been many reports about desalination which uses different SCSG designs, including graphite film, graphene oxide coated wood graphene/polymer/metal composite film and other materials [24,27,50]. So far, the highest level of solar-thermal conversion efficiency has been reported, even more than 100% of the combined structural and material design

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[27,50].

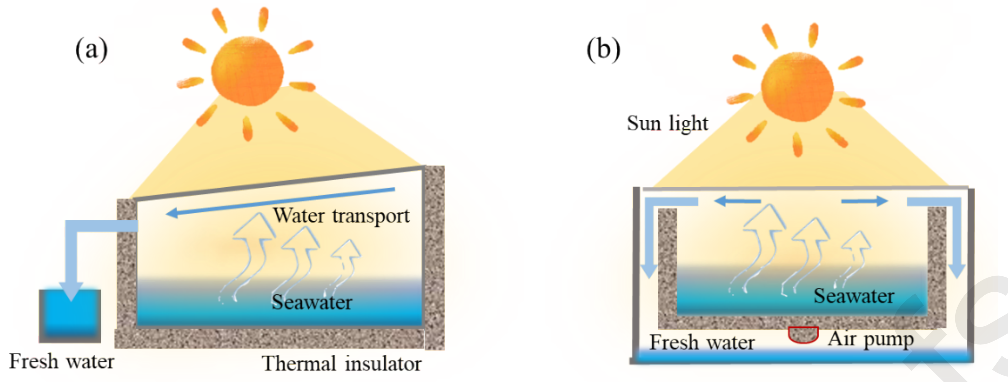

Fig. 9 Two different water production types of SCSG devices: (a) Passive water transport with gravity structure design and (b) Active water transport with additional power consumption

However, the specific performance evaluation and calculation formula are not clear, such as indoor temperature, body water temperature, humidity and other experimental conditions, including or excluding the impact of natural evaporation on the final water evaporation. With this in mind, a number of systems have been developed and manufactured and experimentally studied on a laboratory scale, and this is shown in Fig. 10. The combination has the advantages of low operating temperature, reduced convection, radiation and conduction losses, receiving a large range of incident light, and fast thermal response while simultaneously interpreting the effect of different heat transfer cones and different foams on photo-thermal cones [89,90]. The results show that the absorptivity of photo-thermal cone is greater than 99%, while that of planar photo-thermal film is 93%. By using synergism, oil pollution can be improved by dual function or simultaneous cleaning of crude-oil spills or water supplies. For example, the Wang's group [90] coated an absorber with a functional photo-thermal sponge, which was prepared via a facile method using silver nanoparticles and reduced graphene oxide. With the help of a foam frame, the system can float in large volumes of water. Note that water transport is in contact with bulk water through the tail, while the bottom is only in contact with bulk water. Also, many solar desalination experiments have been conducted in a stable and open environment, and the evaporation rate cannot be directly converted into the final aquatic products. In an actual solar desalination system, the absorber is usually placed in a sealed space. In this case, the total evaporation efficiency is much lower than that in the open environment, as the condensed water droplets on the cap increase solar reflection and humidity in the limited space is higher. At the same time, the rapid loss of latent heat during condensation also leads to a decrease

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of water production. Therefore, the design of a solar desalination system requires further innovation in order to improve final water production. For the first challenge, new materials and structural designs are required to reduce the reflection of incident light and to improve the use of solar energy in closed systems.

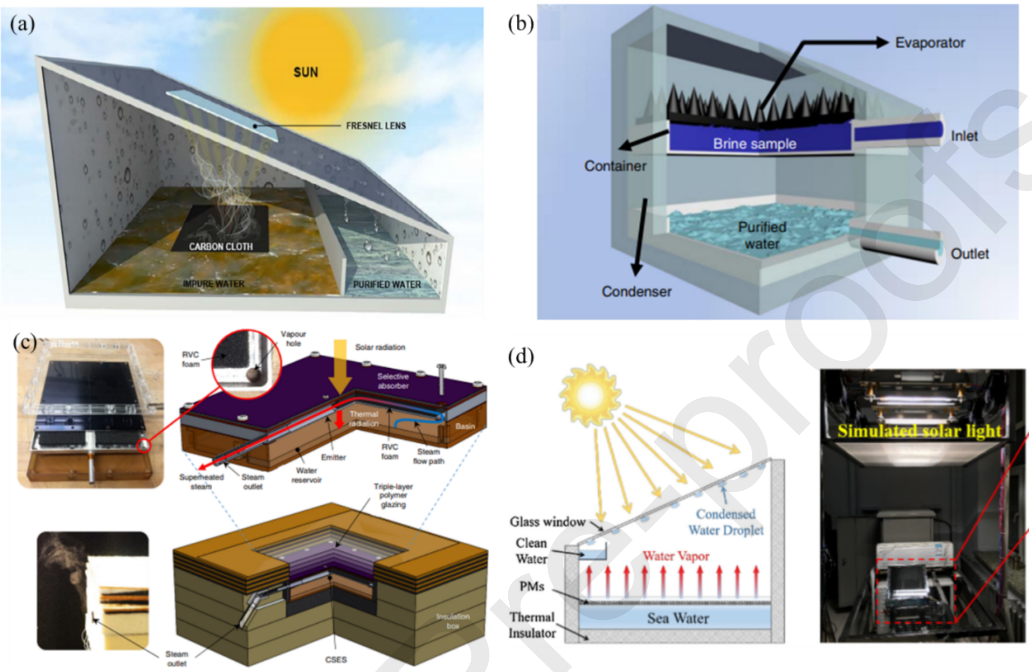

Fig. 10 Water pathway and transport based on solar steam generation: (a) The schematic diagram of the prototype used for water purification [57]; (b) Solar desalination and durability of the biomimetic 3D evaporator [91]; (c) The main components and steam flow path of the solar-assisted disassembled contactless evaporation device [66]; and (d) Passive water transport using a condensation chamber for steam generation [24]

4. Applications

In recent years, the interface evaporation system driven by solar energy has developed rapidly, and this has made the application of steam power generation more common. In this section, we will focus on the latest application of steam in desalination, wastewater purification, sterilisation and power generation. Fig. 11 shows these four steam applications and their advantages, based on solar-thermal conversion technology [15,52,55,81].

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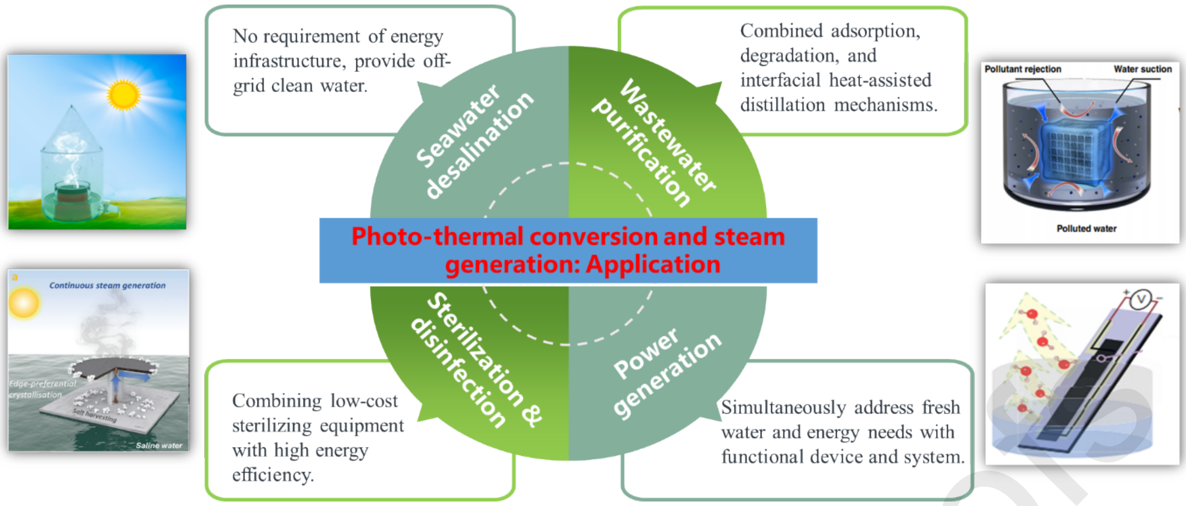

Fig. 11 Recent steam applications in water desalination without energy infrastructure, wastewater purification with heat-assisted distillation, sterilisation and simultaneously power generation [15,52,55,81]

4.1. Seawater desalination

There is no life without fresh water. At the same time, the supply of fresh water is an important and urgent matter for human beings. In real life, there may be many islands and remote ship emergencies [91]. SCSG is a unique technology which is attractive for desalination distillation, as the system uses low-grade waste solar energy. Rectification desalination has historically produced high-quality water, and the ion removal efficiency is even higher than with the more popular alternative, osmosis method. Due to the influence of solar energy, seawater will be affected by evaporation temperature, and one form of seawater evaporation is solar evaporation. It is worth noting that after desalination, the salinity coefficient of steam condensate is significantly reduced, which indicates that this technology is a great progress of desalination technology. Therefore, scalable solar energy is still the most economical way of providing fresh water.

A solar freshwater self-produced ecological membrane which floats on the sea was proposed by Chen's team [75,92]. Fresh water production yielded the highest return of 2.8 L/m^2 during the first day of roof testing and 2.5 L/m^2 during the first day of ocean testing. The rate at which fresh water is produced can meet an individual demand for drinking water. It is worth noting that the material cost of the system is only \$3. This is much lower than a traditional solar still. In addition, there is no requirement for energy infrastructure, so it can supply cheap, clean water for off-grid communities. As with this model, they used a salt resistant evaporation structure which constantly produces clean steam when the device is floating in a brine solution [93]. The structure of salt protection evaporation is composed of black cellulose fabric as the surface layer, expanded polystyrene foam as local

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heating, and excessive salt on the solar absorber's surface.

4.2. Wastewater purification

The purification of domestic and industrial sewage is also an important part of the SCSG device [94]. Desalination technology can be used to remove heavy metal ions, degrade dye molecules and disinfect equipment. The capture of renewable solar energy and its conversion to other forms of energy such as photoelectric, photochemistry and photo–thermal has attracted a great deal of attentions. It is worth noting that photo–catalysis, as a kind of photochemical conversion, has been recognised as an ideal and effective potential method for overcoming environmental pollution. For the re-use of polluted water, an rGO coated paper was made by Shang's team [95] for multi–functional solar clean water generation. It is worth noting that due to the physical adsorption mechanism, organic pollutants can be removed from the composite in the rGO chip. Therefore, the rGO composite can be used as a solar adsorbent in order to generate clean water under sunlight, while at the same time, improving the adsorption and removal performance through upward steam flow. The proposed method involves regenerating clean water from polluted water by photo–catalyst, adsorption, photo–degradation and interfacial thermal assisted distillation [96]. This photochemical conversion process is accompanied by the photo–thermal conversion process, which has an impact on photochemical conversion. The research of photo–thermal enhanced photochemical conversion is mainly to expand the absorption of light to the visible solar spectrum and generate more light carriers in order to improve conversion efficiency. Some researchers [77,97] have studied the influence of solar–thermal conversion on wastewater treatment and clarified the relationship between solar–thermal conversion and photochemical conversion. These advantages provide a means of recycling solar thermal conversion materials. Additionally, they provide potential opportunities for other applications such as the photo–catalytic treatment of organic pollutants. Fig. 12 shows the schematic of water treatment by the sunlight–powered purifier within a microstructure that a water suction channel chains via capillary force. It can switch freely between water generation and suction by changing the temperature, which solar energy provides.

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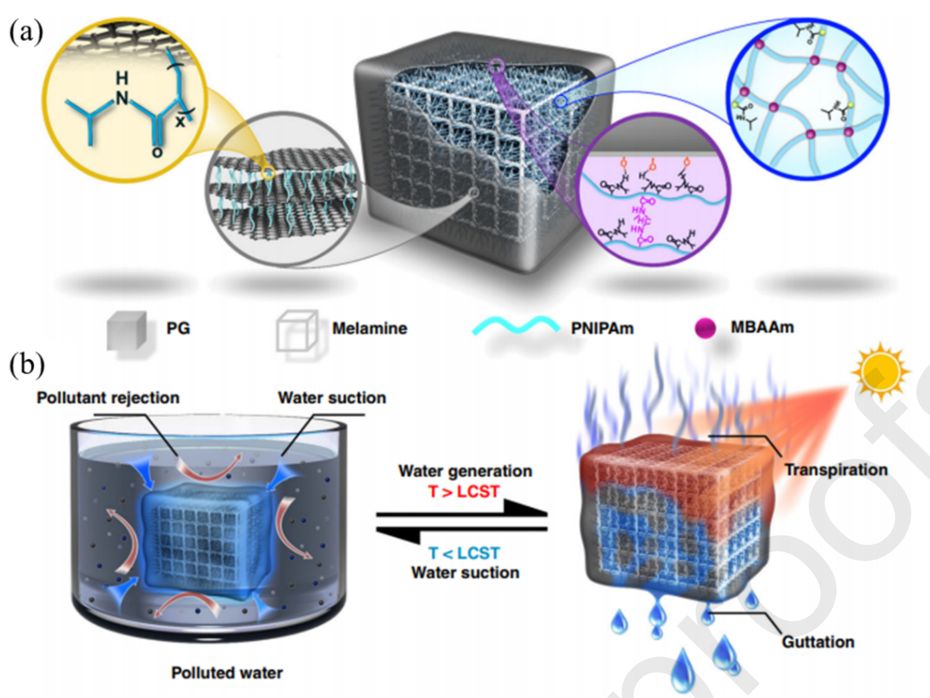

Fig. 12 Schematic of water treatment by the sunlight–powered purifier within a microstructure that a water suction channel chains via capillary force. Photo-thermal conversion and pollution rejection are controlled by the solar–assisted heating [52]

4.3. Sterilisation and disinfection

Steam sterilisation is among the most reliable and widely used medical sterilisation methods [98]. However, traditional steam sterilisation requires electricity, and about 1.5 billion people in developing countries and regions do not have access to electricity. In the field, due to disasters and other special circumstances, a stable power supply cannot be guaranteed. Due to the lack of effective and reliable disinfection technology, people in these areas face many dangerous epidemics which are caused by pathogen infection. Therefore, an urgent solution is required to provide reliable, low-cost and efficient sterilisation methods for areas without electricity and with special circumstances. The superheated steam produced by environmental pressure and low flux solar radiation can effectively kill E. coli and other microbial indicators. Solar steam sterilisation has three stages: heating stage (steam temperature rise), heat preservation stage (the higher the steam temperature, the shorter the time), and cooling stage (steam temperature drops to 100 ºC to open the steriliser safely) [99]. However, most previous solar sterilisation technologies generated high-temperature steam by massive heating (heating the whole water body). This heating strategy makes the heating and cooling process time-consuming and involves low energy utilisation, which greatly limits the practical

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promotion and application of this technology. Different to traditional bulk heating, only the water molecules in the water air interface are continuously activated into steam during the process of interface solar-thermal conversion, while most water bodies can still maintain a low temperature. As only the water molecules on the interface require heating, the thermal mass will be greatly reduced, which results in an order of magnitude increase in the production rate of high-temperature steam and the reaching of a stable state. Therefore, the corresponding SEE and energy efficiency of solar steam sterilisation technology have been significantly improved. The technology combines low-cost solar absorbers and disinfection equipment with a strong processing capacity and high energy efficiency is expected to provide important disinfection solutions for those who live in areas which are off-grid.

4.4. Power generation

As a process of energy conversion, solar evaporation is an effective way of obtaining energy by the conversion of solar energy into heat energy and storing it in the form of hot water or steam [100]. However, in human life and industrial production, the use of high-end power is more frequent. Reasonable utilisation of solar evaporation process capacity provides more possibilities for solving water and energy shortages. In recent years, the combination of solar power generation and evaporation technology has provided an encouraging method and potential for solving the global energy shortage and water pollution challenges and has attracted extensive attention and research. Recently, Zhou's team [12,15] proposed a power hybrid system based on SCSG, which can generate 1 W of power per square metre and achieve high evaporation efficiency. Another study showed that when steam is naturally generated and passes through the surface layer of amorphous carbon, it can generate a high-voltage current of 1V. The researchers used an integrated carbon sponge evaporator design combining solar power and distillation while collecting clean water. The thermal energy in the hot steam can also be converted into electrical energy by using a nano generator and thermoelectric module. It uses an integrated interface to absorb only the input energy of solar energy, while generating electricity and fresh water [12], compared to the traditional method of steam condensation into water which wastes a lot of latent heat. The designed integrated system uses the enthalpy of steam as heat energy for storage and recovery and converts the enthalpy of steam into electrical energy using the thermoelectric system. In the future, as it can meet the demands of fresh water and energy at the same time, this multi-functional device will gradually receive more attention. It is related to materials and structural design, as well as interdisciplinary system integration.

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However, continuous effort is still required to further improve energy conversion efficiency and reduce the commercial application value of materials and equipment.

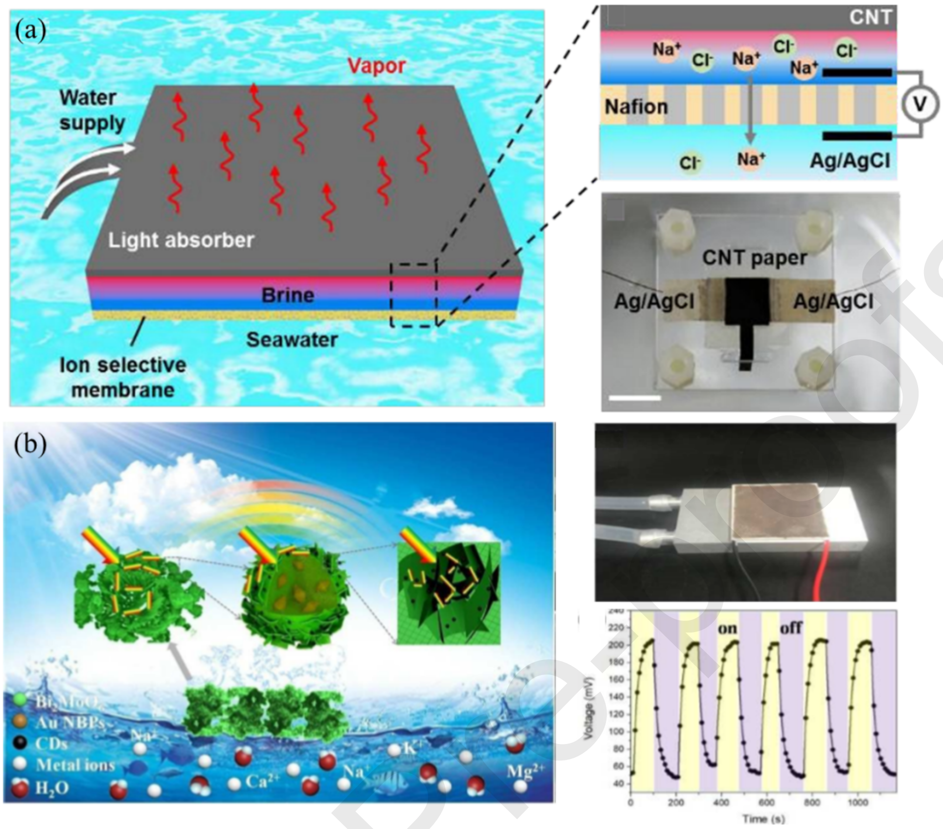

Fig. 13 (a) Schematic of salinity power extraction and desalination using ion selective membrane, which is based on the mechanism salinity gradient [12]; (b) Solar steam generation induced electricity based on innovative 3D nanocomposite solar steamer [3]

5. Challenges and prospects for a solar-driven evaporation system

However, despite some achievements in recent years, SCSG technology still faces some important challenges. Firstly, SEE has exceeded 100% previously, but two problems must be clarified, it was concluded in Fig. 14. The first problem is to clarify the specific calculation and how to determine any parameter in the formula. Natural evaporation occurs continuously under natural environmental conditions and is influenced by many factors, such as wind, humidity and temperature [24,27]. In addition, we believe that it is not easy to compare SCSG systems, as they are executed and operate under different conditions, and the most difficult part to understand is that these systems do not work particularly well. A way of solving these problems is to verify the experimental conditions of the standard. These experimental conditions include the settings of humidity, body water temperature, room temperature, performance evaluation and efficient calculation.

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Secondly, the current experimental conditions are not matched with the actual level of economic development. Many potential users are willing to accept development low cost, large scale manufacturing products. So far, one hurdle is that it cannot be accurately estimated how much it costs to manufacture scalable materials, structures and systems. Therefore, in addition to the strategy of developing low-cost materials and structures, cost estimation and large scalability research methods become a new way of presenting new research results. We should therefore actively adopt SCSG technology in order to improve the SEE of the system. It is necessary to make high light transmissivity of the lid or increase the light concentration of the device which is used to collect condensate water. The solution to these problems must adopt SCSG technology.

Thirdly, there is still a huge challenge facing the SCSG system, and that is how to make the device better and stronger during the development of the system's components. When these devices are in use, particularly when working in an environment with a water supply, they have a waterproof quality, thermal quality effect, salt effect, and most importantly, bacteria and bad weather protection [78,101]. This includes lakes, rivers, seawater, industrial polluted water and municipal sewage. If these devices can meet the quality requirements, it is of great significance to the development and use of the system. However, the current task is actually mainly focussed on the research and improvement of SEE, while the long-term stability of solar absorbing materials is not as important, and less attention was paid to this aspect [56,67]. In order to solve this problem, we must consider how to develop solar absorption materials with high chemical or thermal stability, recyclability and compatibility with a variety of environmental or structural engineering aspects, such as pore engineering and structural integration, to protect the SCSG device. However, we still face the significant challenge of clogging and fouling at the surface of evaporation devices. There was an additional problem when the SCSG was working on a real water source composed of volatile organic components, in which impure aquatic products were produced. Therefore, we must study the evaporation of organic components in water.

Fourthly, the generation of steam requires many conditions in order to be produced. The current system is an important technology for SCSG development and future applications. As it is the main force for the development of steam, it is necessary to develop and study the steam system. Currently, most of the steam is produced during the day [55,89]. However, the main challenge of SCSG application is bringing it to a factory. The steam power generated by nanostructured materials can be

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used for power generation at any time of the day, and can also be used for all-weather power generation and fresh water generation. Furthermore, it is difficult for us to understand the dynamics of the operating process of the system and the potential structure-performance relationship. We are quite limited and passive in this respect. Therefore, we must fully understand water transport, light transport, water evaporation and water transfer ratio, and understand that thermal diffusion behaviour and dynamics are the key to optimising the material, structural design and water evaporation rate of the system.

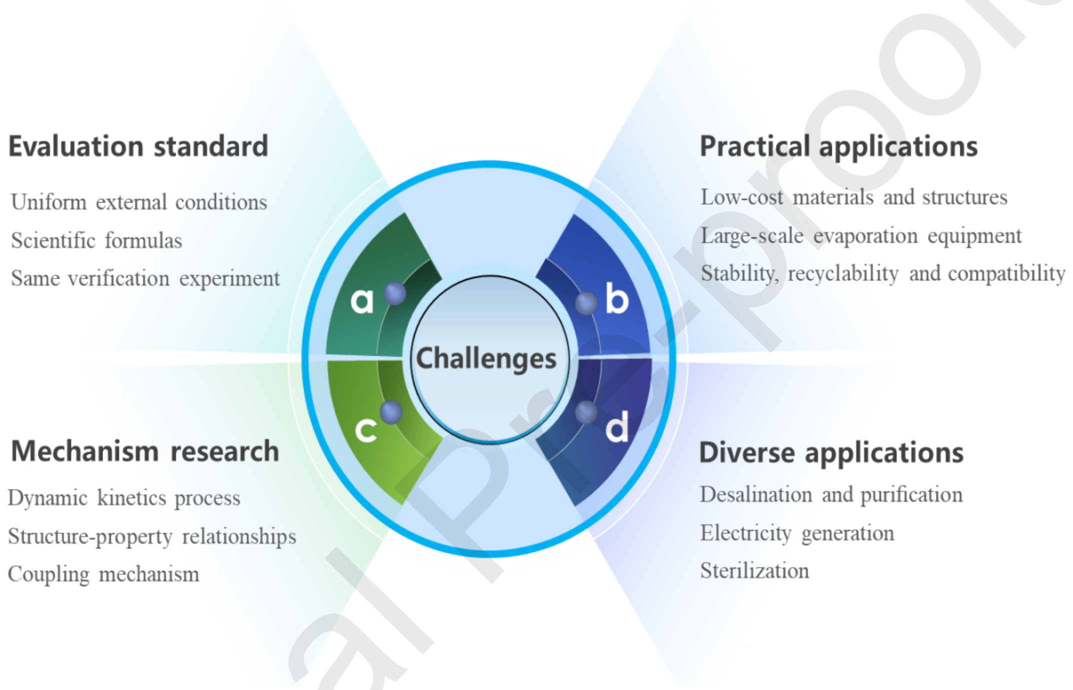

Fig. 14 Challenges for the solar-driven evaporation system: (a) Uniform evaluation standard for testing and calculation; (b) Practical applications for industrial production and commercial competition; (c) In-depth theoretical studies accelerate further breakthroughs in efficiency; and (d) Combination with other industrial applications and coproduction

6. Conclusion

SCSG technology has been greatly developed in recent years, particularly for the production of steam at the light-heat interface. In this progress report, we reviewed various solar-driven evaporation technologies, the physical processes of solar-thermal conversion of three solar absorption methods (bottom heating, bulk heating and interfacial heating), heat transfer principles (electron-hole generation, plasmonic heating and relaxation and molecule thermal vibration) and evaluation principles are summarised. The research status of solar light-to-heat conversion materials, such as noble metal materials, carbon-based materials, semiconductor materials, organic polymer

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materials and composite photo-thermal materials was introduced in detail. The main applications of solar-thermal conversion technology in wastewater purification, seawater desalination, sterilisation and power generation were discussed. This work also summarised the two collection methods of fresh water after SCSG steam production and highlighted their advantages and disadvantages. Finally, on the basis of the above analysis, the future research prospects and challenges of seawater desalination were discussed from engineering and science perspectives in order to promote further development of the research direction and accelerate the commercial application of seawater desalination.

Acknowledgements

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