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Structural integration of solar desalination system

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As population grow and climate change place significant water stress on numerous regions, the demand for efficient and environmentally friendly water resource solutions becomes increasingly urgent. To address this challenge, desalination technology has received much attention and is widely employed, with a recent emphasis on solar-powered solutions driven by the global push for carbon neutrality. Solar desalination presents a hopeful approach, particularly for underdeveloped, water-deficient regions abundant in solar resources, such as the Middle East, North Africa, and sub-Saharan Africa [1,2]. Concentrated solar desalination systems, utilizing methods like multi-effect and flash distillation, boast efficiencies exceeding 1000%. However, their complex designs result in significant energy losses and increased costs. Moreover, achieving high efficiency requires high optical concentration, elevated evaporation temperatures, and maintenance of high vacuum levels. Direct solar distillation offers a simplified system alternative but suffers from poor thermal conversion efficiency [3,4]. Emerging solar interfacial desalination (SID) technology provides a solution by localizing energy absorption and transfer, enabling real-time solar heat utilization with efficiency rates of up to 78% [5]. SID systems are adaptable, cost-effective, and operate off-grid (Fig. 1a). Recent advances in photothermal materials and evaporator structures have enhanced SID performance, yet industrial-scale implementation remains a challenge.

To develop a high-performance SID system and explore its potential applications, it is necessary to optimize each process and their integration. First, in order to improve the absorption of solar energy and heat conversion capabilities in seawater desalination using a SID system, it is crucial to use photothermal materials such as metal plasma and semiconductors. These materials facilitate light-to-heat conversion, which provides the energy basis in the SID system [6,7]. Various mechanisms, such as localized surface plasmon resonance and electron-hole pair relaxation, enable efficient light-to-heat conversion. Extensive research has focused on understanding the chemistry and architecture of photothermal materials, as well as systematically investigating their preparation and the fabrication of photothermal evaporation components (PECs) (Fig. 1b). Refining preparation processes is critical to ensure accessibility and long-term performance maintenance. Carbon-based PECs possess cost advantages, while polymer-based PECs show potential for large-scale production because of their facile preparation. PECs with hydrophilic surfaces and molecular-level microchannel structures can form hydrogen bonds with water molecules, altering the bonding state of seawater [8]. This effect induces water to evaporate in clusters, thereby enhancing the evaporation process (Fig. 1c) [6,9]. A highly feasible and industrialized approach, complemented by methods to bolster capability against salt and fouling, is the gravity-aided cleaning technique (Fig. 1d). This approach involves establishing a vertical gradient within a PEC system to control brine transfer, resulting in a salt-free process [10]. To improve steam collection and water output, it is desirable for the interior face of condenser cover materials to have superhydrophobic property and strong light permeability in the front systems (Fig. 1e) [11]. In contrast, in the back-side system, materials exhibiting excellent heat conductivity, like metal Cu, are generally employed to enhance condensation and expedite freshwater production (Fig. 1f) [4,12]. Besides material design, multistage systems present many structural parameters that significantly impact performance, and there are ample opportunities for future improvement.

In industrial seawater SID designs, multistage designs are commonly favored over single-stage ones, though thicker multistage systems have longer thermal response times, posing challenges for steady-state operation due to solar flux fluctuations. Hybrid-driven systems have been proposed to address these challenges. Representative studies have demonstrated advanced multi-tier systems enabling simultaneous water and electricity generation. Gravity-aided cleaning techniques have also been employed. It is noted that coastal regions can use wind and solar energy for continuous system operation, and these anti-interference, fast response, and all-weather capabilities will be important in the design of high-performance SIDs in the future (Fig. 1g).

Desalination equipment comprises front-side and back-side systems. Front-side systems are generally straightforward, cost-effective, and suitable for various applications such as individual homes, island areas, and industrial facilities. In contrast, back-side systems commonly show high solar-to-water efficiency but require higher manufacturing costs, mainly targeting regions with prolonged sunshine and limited electric energy access. Economic feasibility must be considered for the application of SID systems. Some previous SID systems have demonstrated production costs as low as US$0.4 per ton, highlighting their promising economic potential [13]. The freshwater production costs through SID systems are influenced by both equipment material costs and space occupation. Considering additional environmental and social benefits, such as CO_2 emissions reduction, is essential for comprehensive technical-economic evaluations in the future.

The recent work by Dang *et al.* has systematically discussed the tremendous potential of seawater SID technology in confronting worldwide water scarcity and cutting carbon emissions

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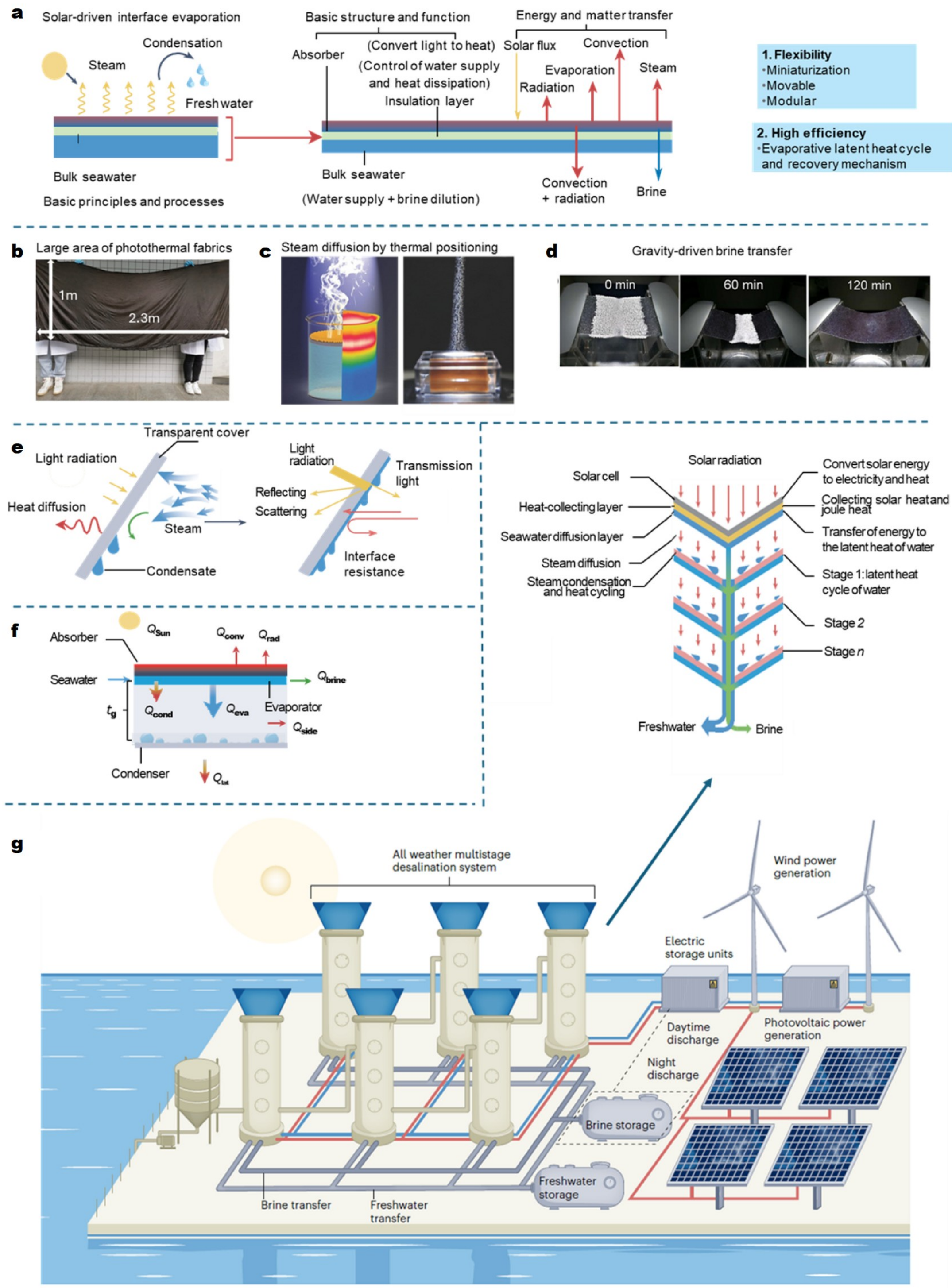

Figure 1 (a) Principle and configuration of seawater SID process. Reprinted with permission from Ref. [13], Copyright 2024, Nature Publishing Group. (b) An example of a sizeable PEC fabricated by incorporating photothermal materials onto fabric. Reprinted with permission from Ref. [7], Copyright 2022, American Chemical Society. (c) Permeation of seawater *via* capillary interaction and its evaporation using heat concentration. Left: Reprinted with permission from Ref. [9], Copyright 2015, Wiley. Right: Reprinted with permission from Ref. [6], Copyright 2018, Wiley. (d) Salt-free strategy achieved through gravity-assisted cleaning. Reprinted with permission from Ref. [10], Copyright 2019, Wiley. (e) Steam diffusion and condensation in the front-side of a SID system. (f) The thermal and mass transfer mechanisms within a single-stage SID device on the back side involve energy exchange from the lateral side walls (Q_{side}) and the heat exchange from the latent heat of steam (Q_{lat}). (g) Diagram illustrating the structure of a multi-stage SID unit designed for all-weather conditions, and a schematic representation of practical deployment of a climate-resistant SID system. Reprinted with permission from Ref. [14], Copyright 2024, Nature Publishing Group.

[14]. SID systems exhibit significant advantages such as strong adaptability, low cost, and ease of production, making them suitable for various applications. This work also suggests potential hybrid-driven solutions for designing desalination

systems in the future, ensuring the systems are resistant to external interference, possess rapid response capabilities, and can function in all weather conditions. The work offers valuable insights into the advancement and widespread industrial application of advanced solar-powered desalination systems. The study by Dang *et al*. has provided the following insights to the researchers in the field. (1) Steam condensation is crucial for enhancing water production and latent heat recovery, increasing the output of desalination equipment. (2) The application of efficient photothermal materials and thermal management can enhance solar absorption and conversion capabilities, thereby improving the performance of desalination systems. (3) Optimizing the structural design of the evaporator can improve the evaporation rate and water output of desalination systems. (4) Enhancing the design to withstand salt and fouling improves the stable performance and durability of desalination systems. (5) The development of miniaturized equipment provides a promising approach for household and personal use. (6) Through employing high-performance condenser materials and multi-stage latent heat recovery systems, SID systems can enhance distillation efficiency, increase water yield, and provide new opportunities for industrial applications.

Solar-driven desalination technology has demonstrated itself as a highly promising approach to addressing international water scarcity and lowering carbon emissions, particularly in regions with abundant sunlight. However, achieving commercial viability still remains a challenge, necessitating a delicate balance of water yield, equipment lifespan, and costs. To address these challenges, all-weather, high-efficiency seawater desalination systems can be developed through partial solar energy storage and the incorporation of other clean energy sources. SID technology also offers new possibilities for energy and resource development by using latent heat from steam and seawater concentration processes, such as converting latent heat into electricity and extracting valuable mineral salts from seawater. Further research and development of advanced SID technology, which include optimizing system design, reducing costs, increasing water yield, and improving energy utilization efficiency, will provide crucial support in addressing the global water crisis and promoting relevant economic development. Interdisciplinary cooperation will play a key role in driving the innovation and industrial applications of SID technology, which will facilitate its integration with other fields such as energy and materials science, facilitating significant technological breakthroughs and broader application development.

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