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Recent Developments in Solar-Powered Membrane Distillation

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Abstract

Freshwater scarcity remains one of the most crucial issues facing our world. Although the traditional membrane distillation (MD) technique can efficiently produce clean water irrespective of climate conditions, the process wastes a lot of energy. Thanks to the development of photo-thermal materials, the solar-powered membrane distillation (SPMD) process has received intensive attention in the last decade. SPMD is a highly promising substitute for traditional MD, which is based on fossil fuels, as it can stop the harmful emissions impact on the environment. Combining solar energy with MD has the potential to lower the expenses associated with water purification and ensure the generation of clean water remotely. Reviewing the most current advancements of the SPMD system is essential at this point, in addition to highlighting the challenges and prospective of this technology. Based on that, the background, recent progress, and principles of SPMD, their configurations and mechanisms, fabrication methods, and various applications, along with their advantages and current limitations, are reviewed.

Keywords: *Freshwater, solar-powered membrane distillation, desalination, energy consumption, photothermal membranes.*

1. Introduction

The world's population growth and declining water sources are contributing to an increase in global water consumption. Surface water and groundwater pollution caused by municipal, industrial, and agricultural contaminants are major factors in the deterioration of water quality. This can lead to a serious reduction in the availability of freshwater for human use. Despite water covering approximately 70% of the earth's surface, over 97% of it is saltwater in oceans and seas, leaving only a small fraction of freshwater available for human needs [1]. As a result of increasing population, agricultural development, and industrial expansion, many arid regions and countries are resorting to desalination as a means to supplement their water supply and meet the growing demand for water [2]. The United Nations World Water Development Report of 2020 reports that 4.2 billion people do not have adequate sanitation facilities, and 2.2 billion people lack access to safe drinking water [3].

A very promising desalination technology is SPMD, which could be used in conjunction with cheap and renewable energy sources (like solar energy). Due to the temperature difference between the permeate and feed sides, this thermally driven membrane process causes water to evaporate at the feed side of the membrane surface, pass through hydrophobic membrane pores, and eventually condense as freshwater on the cold permeation side. as shown in **Fig1(a)**.

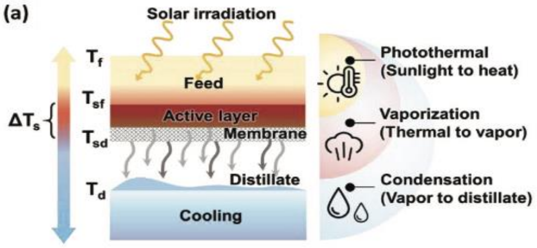

Figure 1(a): *Schematic illustration showing mechanism of SPMD.*[4]

In this work, we will highlight the recent developments in SPMD, mechanism, configuration, potential and application. Also, we have thoroughly examined the basic concepts behind creating an effective SPMD system, considering both the development of Photothermal materials and the design of the system itself. Additionally, the energy efficiency constraints of STD systems are examined by drawing a comparison between STD and the energy efficiency of solar desalination, which relies on photovoltaic (PV)-powered reverse osmosis (RO).

2. SPMD Configuration and its Performance

Solar energy, which remains in use to this day, is among the oldest sources of energy. In comparison to other energy sources, it has various benefits such as being environmentally friendly, widely accessible, highly secure, and sustainable. Hence, solar technology could prove to be a viable solution for areas with low population densities or minimal development where access to potable water remains a challenge. Solar-powered desalination systems can be utilized both ***directly and indirectly***, with the former category including both options as shown in **Fig 2**. Direct desalination systems are those that employ heat-gathering techniques. Desalination and heating processes will inevitably occur in the same location, and saline water can evaporate due to solar radiation. Fresh water is produced by condensing the evaporating water whereas, in the indirect method, the desalination procedure can include a second step for solar energy. This component might be thought of as a heating source or a power-producing component. These systems are commonly known as Solar Collectors because they may harness the potential of solar thermal energy [5].

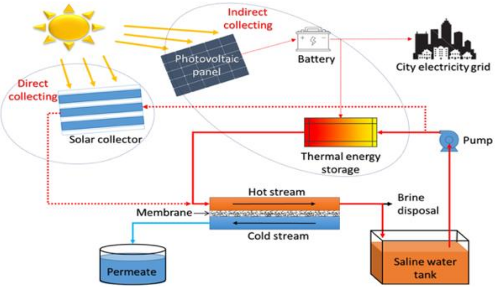

Figure 2: *Solar-Powered Membrane Distillation system employing direct and indirect collection methods for water purification* [6].

2.1 Performance of SPMD: The main criterion used to assess the efficiency of SPMD (solar-powered membrane distillation) systems in desalination is the specific water productivity (SWP). The SWP measures the amount of water produced per unit area of solar radiation over a given period of time. This parameter is an indicator of how efficiently solar energy is utilized to purify a specific water source.

The mathematical formula for calculating SWP as represented by **Eq.1** involves several factors, including solar irradiance, solar absorptivity, thermal efficiency, and gain-output ratio. The efficiency of thermal distillation is measured by GOR, which should be greater than one for a well-designed system. It is the ratio of the energy output (purified water) to the energy input (heat).

The governing equation for SWP is given below as:

$$SWP=\frac{E}{L}*\alpha*\eta_t*GOR \text{ ---------------------------}(1)$$

where, symbols have their respective meaning.

The first equation (Eq. 1) that governs STD systems is universally applicable, regardless of their specific design. It serves as a useful tool for quantitatively and theoretically understanding how to enhance the SWP by improving the efficiency of the three primary conversion processes involved: solar radiation to thermal energy conversion, heat-based vapor generation, and vapor-to-water conversion. These three processes' efficiencies can be measured by their solar absorptivity, thermal efficiency, and GOR, respectively. In the following section, we will delve into recent or upcoming research that examines how each conversion process's performance can be improved, guided by the structure of the governing equation illustrated in **Fig 3**.

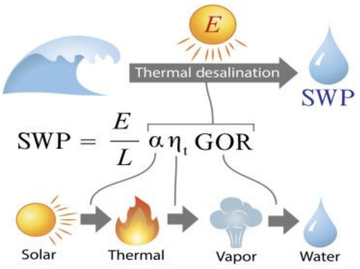

Figure 3: *Key factors in efficient SPMD systems.*[7]

3. Current advances and challenges associated with effective utilization of SPMD

As stated earlier, the SPMD system's overall energy efficiency relies on three sequential conversion stages, and every stage is essential for the system's optimal functioning. Therefore, each process must be given due attention for enhancing the overall efficiency of the SPMD system. In the upcoming discussion, we will organize our analysis according to the governing equation and explore how recent or forthcoming research efforts can ameliorate the performance of each conversion process.

Materials for efficient solar thermal energy conversion: To maximize solar-to-heat conversion, it is crucial to utilize a solar absorber with high absorptivity (α), which denotes the proportion of the total absorbed irradiance to the total solar irradiance received. Such materials should efficiently absorb light across the solar spectrum and possess blackbody-like properties, which allow for minimal reflection and transmission of incoming radiation. While carbonaceous materials and plasmonic nanoparticles are well-known for their exceptional solar absorption abilities, research has also explored other materials such as polydopamine-coated surfaces, black TiO_2 nanoparticles, and metal oxide nanoparticles. These studies have shown that certain solar absorbers surpass natural surfaces in terms of absorptivity. Nevertheless, the development of new materials for photothermal conversion should not solely prioritize enhancing absorptivity but should also consider their cost and sustainability [8].

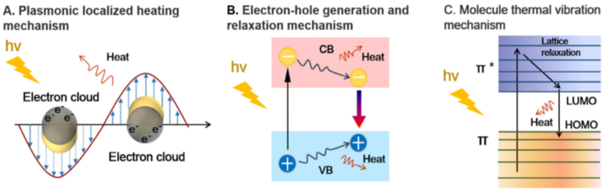

Figure 4: *Working Principles of Photothermal Materials: (A) Plasmonic Particles, (B) Semiconductors, and (C) Carbonaceous/Polymeric Materials* [9]

Thermal management strategies to efficiently generate vapour from heat: When using solar energy to create water vapor for desalination, there are thermal losses from radiation, convection, and conduction that prevent all absorbed energy from being effectively used. To enhance the efficiency of the process, methods of thermal management must be employed to reduce these losses. The thermal efficiency ($\boldsymbol{\eta_t}$) of the process measures the effectiveness of the heat produced from photothermal conversion for water evaporation. To achieve a high SWP (specific water production), as per **Eq 1**, a high $\boldsymbol{\eta_t}$ is essential.

To reduce conductive heat loss to the saline feed water during solar-based water vapor generation for desalination, a useful thermal management strategy is to minimize direct contact between the solar absorber and the feed solution. This can be achieved using hydrophilic wicks or thermal insulation with capillary channels [10]. A selective absorber can also be used to minimize thermal radiation heat loss to the air by applying optical coatings to non-selective absorbers. However, this method may not be effective when submerged in water or even with a thin water film on its surface, as thermal radiation depends on the emissivity of water. To overcome this, a hydrophobic top layer or non-porous solar absorbers can be used.

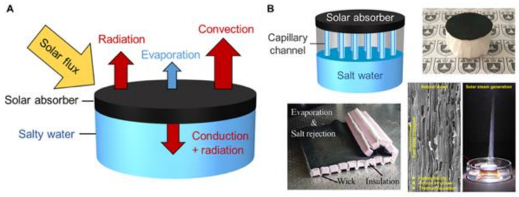

Figure 5: *Thermal management strategies in SPMD system.*[7]

Maximizing Efficiency: The Importance of Recovering Latent Heat

Solar-thermal energy-based water vapor generation is limited by parasitic heat losses, leading to a cap on the specific water production (SWP) efficiency. However, the generation of steam can be improved by enhancing the GOR, which quantifies the number of times latent heat is reused. Membrane distillation (MD) is a promising technology for small-scale solar-thermal desalination systems, particularly air gap membrane distillation (AGMD). Recent research has suggested the integration of photothermal materials onto the surface of MD membranes to increase the efficiency of direct contact membrane distillation (DCMD) systems. The use of a multistage AGMD configuration is also a potential improvement, where the latent heat of condensation from one stage drives the evaporation in the next stage.

4. Application of SPMD

Over the past two decades, various industries such as food, pharmaceuticals, and power generation have increasingly adopted solar-powered membrane-based separation technologies for water desalination, treatment, and concentration. The aim of employing these technologies is to generate superior quality water in regions characterized by low precipitation and scarce freshwater resources, where naturally occurring seawater or saline groundwater is prevalent. Membrane materials and technology have made solar-assisted membrane saltwater desalination procedures technically and economically feasible, and these technologies have been used for water purification, treatment, energy generation, biofuel production, and more as shown in **Fig 6**. The previous experimental studies suggest that a small-scale distillation plant paired with a solar heater is the most viable method for developing regions. Further research is needed to make these technologies more affordable, energy-efficient, and eco-friendly in the coming years. Desalination and water treatment with solar energy will advance with the development of membrane-based separation technology.

Figure 6: *Various applications of membrane distillation/SPMD technology.*

5. The SPMD's inherent limitations

The utilization of low-cost and simple low-temperature solar thermal collection equipment holds potential for benefiting MD. Solar energy, owing to its scalability, absence of emissions, and widespread availability, presents a promising alternative heat energy source for MD. Nonetheless, despite the capacity of an MD system with heat recovery to produce greater distillate, the requirement of a considerably large solar collector area is apparent for achieving a practical desalination capacity. This may lead to capital costs that are unaffordable or limit the use of solar MD to places with a lot of open ground [11]. Furthermore, the intermittent nature of solar energy presents another difficulty because a steady heat source is required for the system to function at its most effective level.

Although optimization of latent heat recovery can significantly improve the gain output ratio (GOR), it is important to recognize that solar-thermal distillation (STD) may not be the most energy-efficient method for utilizing solar energy in desalination. This is due to the fact that the most advanced desalination technique, reverse osmosis, is inherently much more energy-efficient than thermal desalination processes [12].

According to the previous research work comparing the performance of solar-powered desalination reverse osmosis (SPRO) and membrane distillation (SPMD) technologies, it was determined that the daily RO productivity per square meter of photovoltaic (PV) ranges from 47.9 to 90 l/day/m^2 when using seawater [13], and from 154 to 325.7 l/day/m^2 when using brackish water[14]. Banat et.al [15] onducted an investigation of the air gap spiral wound MD system heated by a flat plate solar collector (FPSC) and found that the maximum daily productivity of MD per square meter of the solar field was 19 l/day/m^2, which is relatively low. Nonetheless, MD remains a promising technology due to its capability to treat highly saline water.

6. Conclusion and future perspective

The present article offers a comprehensive assessment of the solar-powered membrane distillation (SPMD) technology. It delves into the underlying principles of photothermal conversion and solar-powered membrane distillation, as well as diverse approaches for developing efficient SPMD systems. The applications of SPMD technology in desalination, water treatment, and energy generation are also scrutinized. The review emphasizes the benefits of

SPMD technology, including its energy efficiency, capability to function under low pressure, and effectiveness in treating water with high salinity levels.

In conclusion, as a recommendation for advancing the solar-powered membrane distillation (SPMD) for desalination process/wastewater treatment, or oil-water separation, there is a need to merge the systems with evacuated tube collectors, creating resilient photo-thermal materials for membrane systems, investigating scalability and affordability, researching novel SPMD process configurations, and exploring applications for shale oil and unconventional gas extraction. The study also emphasizes the need for more research to be done on self-cleaning membranes and understanding the underlying molecular mechanisms of SPMD using Molecular simulation techniques which gives an underlying idea at an atomic level which helps in complimenting the experimental findings. Overall, the study highlights the significance of SPMD for various industrial application procedures and calls for further research to advance the technology for practical applications.

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