Design and Performance Optimization of a Solar-Driven Multi-Effect Membrane Distillation System

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Introduction

Solar desalination is a promising approach for alleviating the growing global freshwater shortage [1]. Among various desalination technologies, membrane distillation (MD) has attracted increasing attention because it can be directly driven by low-grade thermal energy [2]. In MD, a hydrophobic microporous membrane separates the saline feed from the permeate, and the vapor-pressure difference induced by the temperature gradient across the membrane drives water vapor transport. Owing to its operation at near-atmospheric pressure, high product purity, ability to treat highly concentrated solutions, and compatibility with latent heat recovery, MD shows considerable potential for solar-driven seawater desalination.

Early studies mainly focused on single-effect MD systems, with significant progress achieved in membrane material modification, structural optimization, and coupling with low-grade heat sources [3]. However, in single-effect systems, the latent heat released during condensation cannot be effectively reused, resulting in relatively low thermal efficiency. To overcome this limitation, multi-effect membrane distillation (MEMD) systems were developed, in which latent heat is recovered and reused in a cascade manner, thereby improving both thermal efficiency and water production performance [4]. Despite these advantages, challenges such as inter-effect temperature attenuation, heat loss management, and structural complexity still limit further performance improvement.

Therefore, this study investigates the thermal management and performance optimization of a solar-driven four-effect membrane distillation system. A transmembrane heat and mass transfer model was established to analyze the effects of inter-effect temperature distribution, heat injection strategy, and stage temperature boosting. An experimental system was also constructed to verify the feasibility of the proposed design.

Optimization Of Multi-Effect Membrane Distillation System

1. Equal Temperature-Difference Driving Force at Different Temperature Levels.

As shown in Fig. 1, calculations based on the modified Antoine equation indicate that the saturated vapor pressure difference of water is 1.902 kPa between 20 and 30 °C, 7.563 kPa between 50 and 60 °C, and 22.763 kPa between 80 and 90 °C. Compared with that in the 20–30 °C range, the vapor pressure difference in the 50–60 °C range increases by 297.6%, while the value in the 80–90 °C range is a further 200.9% higher than that in the 50–60 °C range. These results demonstrate that, under an identical temperature difference, the transmembrane driving force for vapor transport is significantly greater at higher temperature levels than at lower ones. Therefore, in the low-temperature range, the driving force for transmembrane water vapor transport is relatively weak, which is unfavorable for efficient mass transfer.

According to the Antoine equation, the driving force for transmembrane vapor transport, namely the vapor pressure difference, increases exponentially with temperature. In other words, a higher temperature corresponds to a larger vapor pressure and, consequently, a stronger driving force for mass transfer. Therefore, in a multi-effect distillation module, the rational allocation of temperature among different effects is essential for enhancing overall system performance. In this study, water production rate and energy utilization efficiency were adopted as the dual objective functions for system optimization.

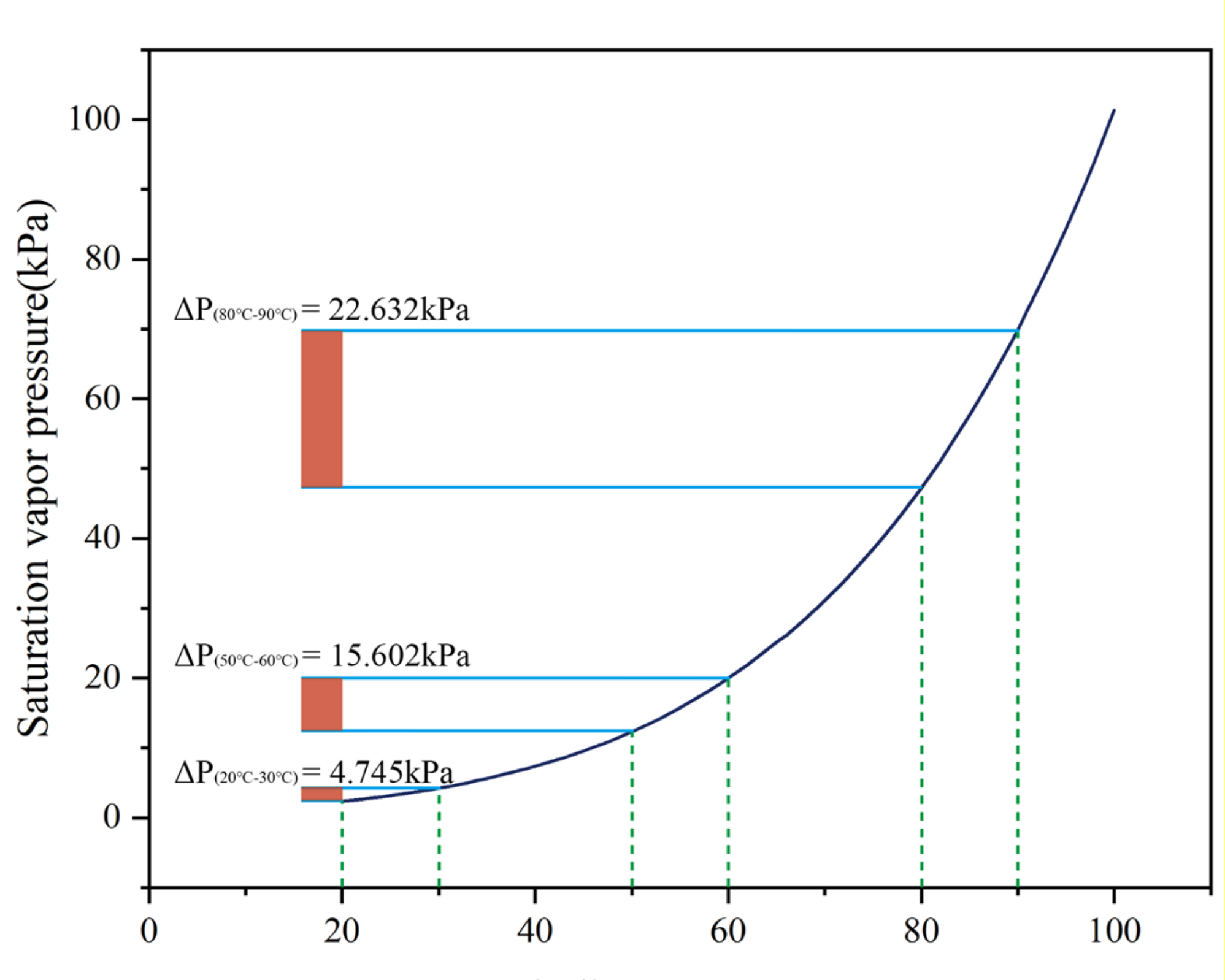

Fig. 1. Relation between saturation vapor pressure and temperature

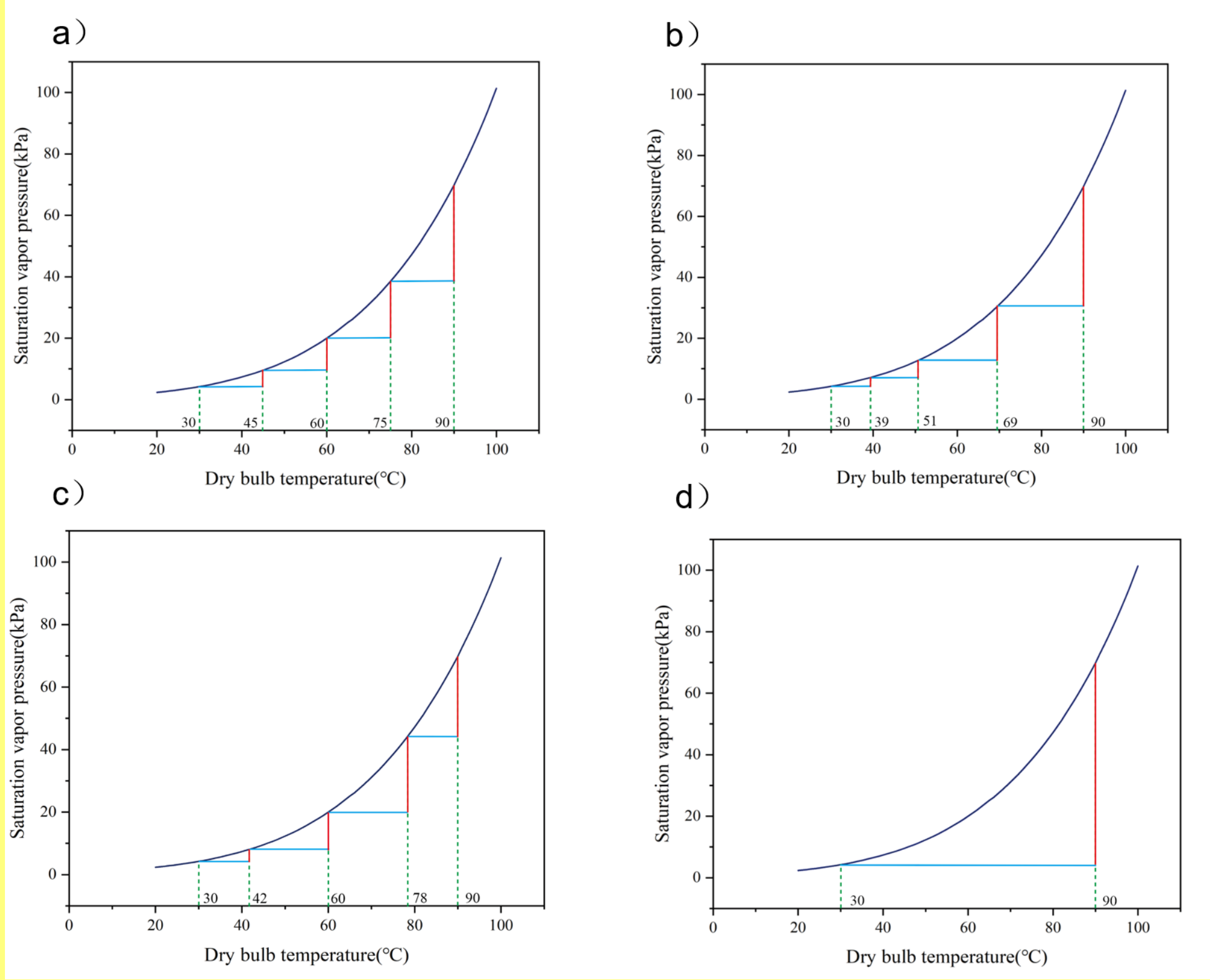

Fig. 2. **a)** Transmembrane vapor pressure difference of each effect under equal temperature-difference regulation; **b)** Transmembrane vapor pressure difference of each effect under high-temperature-end-biased regulation; **c)** Transmembrane vapor pressure difference of each effect under mid-range-biased regulation; **d)** Overall transmembrane vapor pressure difference between the low-temperature end and the high-temperature end.

2. Effect of Stage Temperature Distribution Strategy on Water Production

When optimizing the thermal performance of a multi-effect membrane distillation system, it is necessary to consider not only the effectiveness of heat recovery, but also the overall water production of the system. To this end, this study investigates the influence of different inter-stage temperature distribution patterns on the water production performance of a four-effect air-gap membrane distillation system.

Under steady-state conditions, with the hot-side boundary of the first effect, the cold-side boundary of the last effect, and the structural parameters specified, an inter-effect temperature-difference allocation coefficient was introduced to describe the temperature distribution among the effects. Combined with the single-effect flux equation and system performance indicators, a steady-state evaluation model for the multi-effect membrane distillation system was established.

3. Effect of Heat Injection into the Hot Sides of All Effects Except the First on Overall Water Production.

For the four-effect membrane distillation system under the equal temperature-difference distribution (φi = 0.25, 0.25, 0.25, 0.25; 90℃, 75℃, 60℃, 45℃, 30℃) additional heat was supplied to the hot sides of the second, third, and fourth effects. When the temperatures of these effects were each increased by 5°C (90℃, 80℃, 65℃, 50℃, 30℃), the calculated water production was 9.90 $kg\cdot m^{-2}\cdot h^{-1}$. When the temperatures were each increased by 10°C (90℃, 85℃, 70℃, 55℃, 30℃), the calculated water production was 9.55 $kg\cdot m^{-2}\cdot h^{-1}$. These results indicate that the water production of the four-effect membrane distillation system does not increase monotonically with increasing supplemental heat input to the later effects.

Under the equal temperature-difference distribution (φi = 0.25, 0.25, 0.25, 0.25; 90℃, 75℃, 60℃, 45℃, 30℃), the total water production of the four-effect membrane distillation system was 9.411 kg·m-2·h-1. Under the high-temperature-end-biased distribution (φi = 0.35, 0.30, 0.20, 0.15; 90℃, 69℃, 51℃, 39℃, 30℃), the total water production increased to 9.649 kg·m-2·h-1. In contrast, under the mid-range-biased distribution (φi=0.20, 0.30, 0.30, 0.20; 90℃, 78℃, 60℃, 42℃, 30℃), the total water production decreased to 9.169 $kg\cdot m^{-2}\cdot h^{-1}$. These results indicate that, among the three temperature distribution strategies considered, the high-temperature-end-biased distribution achieves the highest water production, further confirming that distillation flux in the high-temperature range is superior to that in the low-temperature range.

4. Effect of the Stage Temperature Boosting (STB) Strategy on Overall Water Production.

Without STB regulation, the temperature distribution of the four-effect membrane distillation system was assumed to follow a “front-end-high and rear-end-low pattern” pattern (φi = 0.35, 0.30, 0.20, 0.15; 90℃, 69℃, 51℃, 39℃, 30℃). After introducing an additional heat source to the hot side of the third effect, the temperature-difference allocation became more uniform, with a noticeable temperature increase in the later stages. Accordingly, the temperature distribution under STB regulation was assumed to be (φi = 0.30, 0.27, 0.23, 0.20; 90℃, 72℃, 55.8℃, 42℃, 30℃).

The calculated water production was 9.649 $kg\cdot m^{-2}\cdot h^{-1}$ without STB regulation and 9.549 $kg\cdot m^{-2}\cdot h^{-1}$ with STB regulation. This result further indicates that supplemental heating applied to the later effects does not necessarily enhance the overall water production performance of the system.

System Structure Design

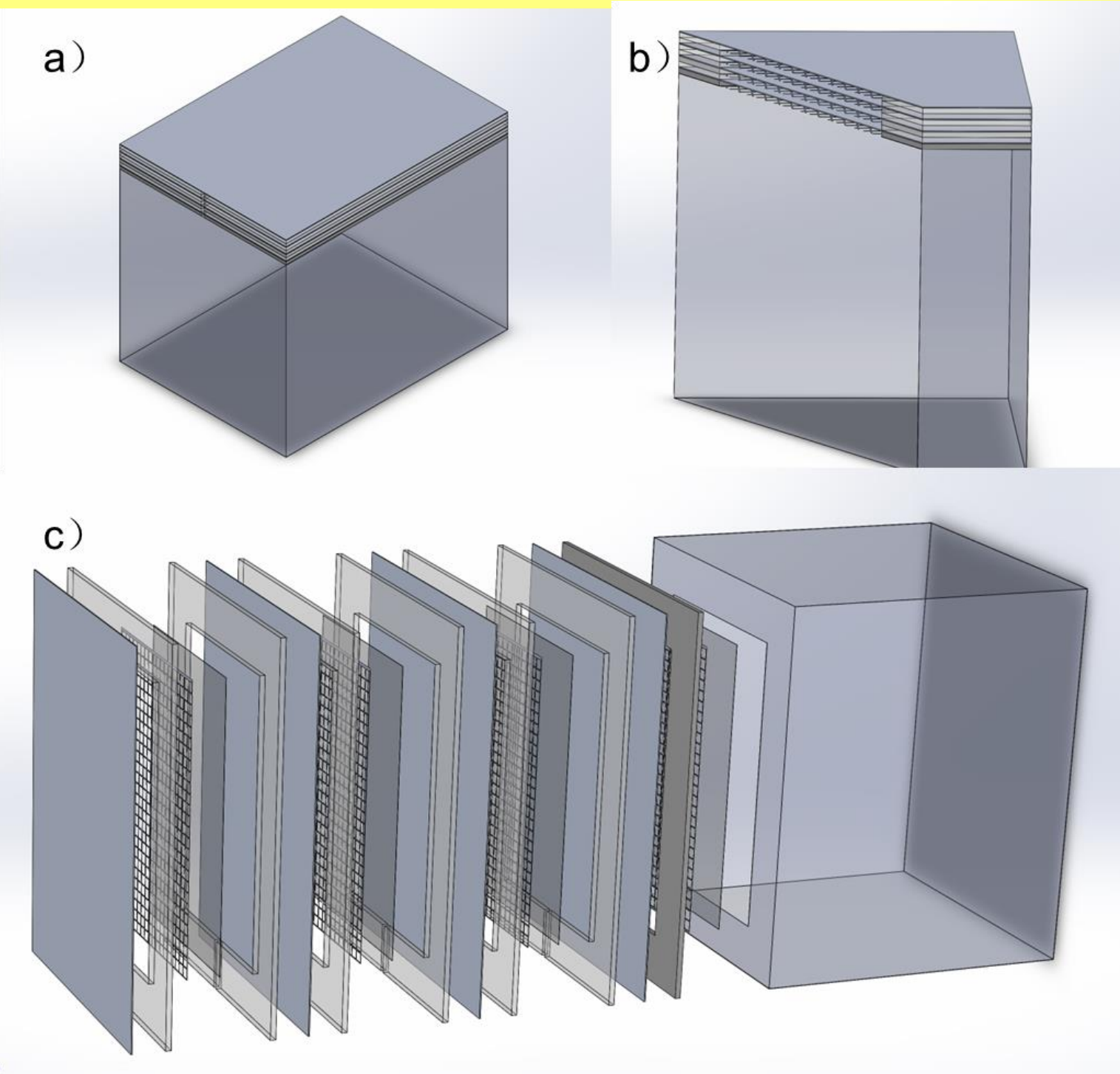

Fig. 3. Structural diagram of the four-effect membrane distillation system

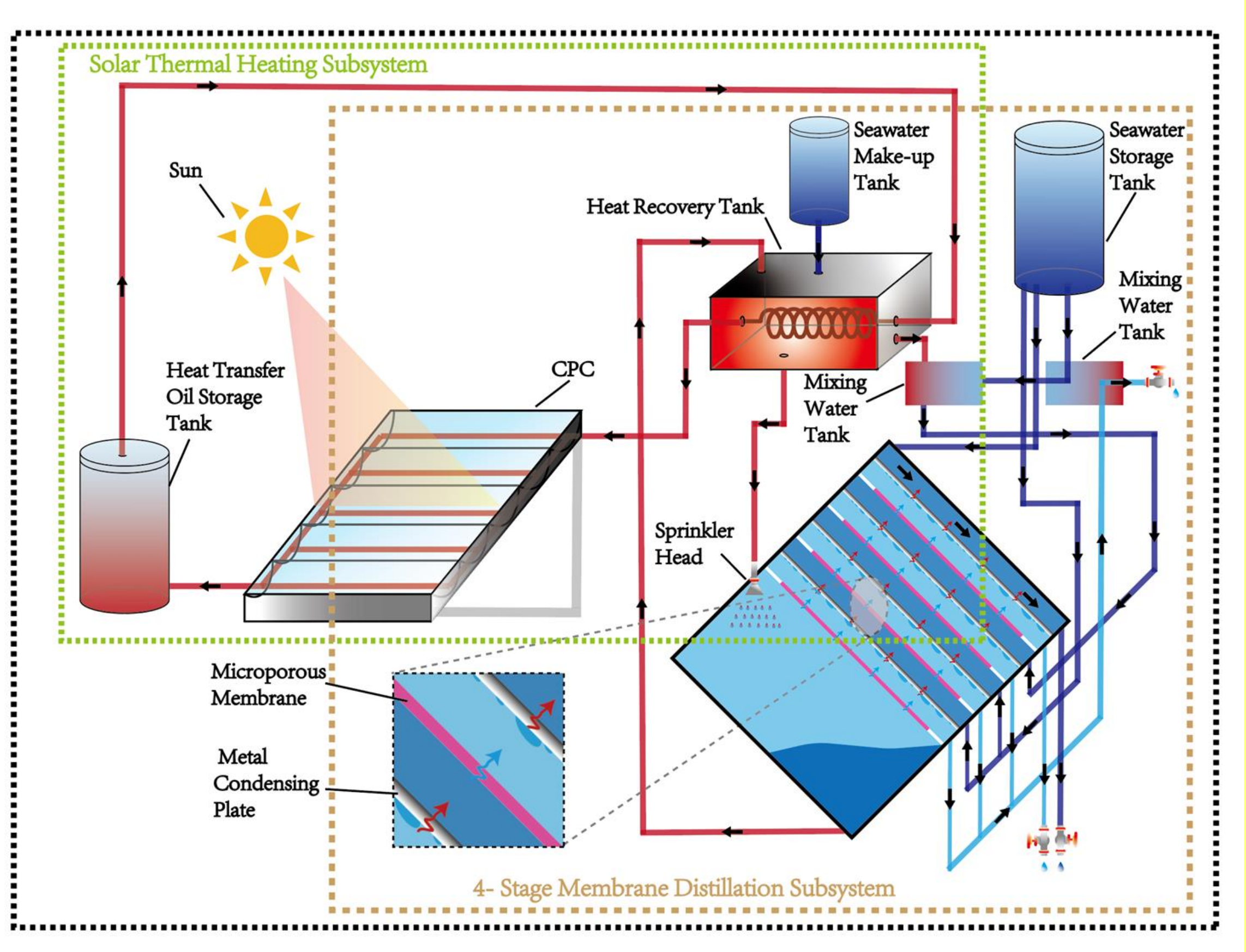

Fig. 4. Solar-Driven Multi-Effect Membrane Distillation System

As shown in Fig. 4, the proposed system couples a solar photothermal unit with a four-effect membrane distillation module. Solar-heated heat-transfer oil warms the feed, which is sprayed into the first effect. The generated vapor passes through the hydrophobic membrane and condenses on the aluminum plate, releasing latent heat to drive the next effect. Condensate from each cold side is discharged through the lower outlet.

To enhance the last two effects, residual heat from the condensate of the first three effects is recovered to preheat the raw feed. Part of the high-temperature feed is then mixed with the preheated feed, further increasing the inlet temperature of the third effect and improving vapor flux in the third and fourth effects.

Finally, the conventional four-effect system and the modified system with feed preheating and thermal mixing are compared in terms of water production rate and energy-to-water efficiency..

Conclusions

A heat and mass transfer model was established for a solar-driven four-effect membrane distillation system. The results indicate that, under a fixed total temperature difference, allocating a larger proportion of the temperature drop to the high-temperature effects can improve the overall freshwater productivity of the system. In contrast, simply supplying additional heat to the later effects does not necessarily enhance total water production, owing to the redistribution of the transmembrane driving force among the stages. A four-effect experimental system was further constructed, and the proposed thermal management strategy based on feed preheating and temperature boosting was demonstrated to be feasible. These findings provide useful guidanzce for the structural design and thermal optimization of solar-driven multi-effect membrane distillation systems.

References

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