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Experimental Performance Evaluation of Vacuum Membrane Distillation Seawater Desalination System Combined With LCPV/T Module

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ABSTRACT

In this paper, a stable and efficient thermal-electric seawater desalination system based on vacuum membrane distillation (VMD) technology and utilizing the energy of solar low concentrated photovoltaic/thermal (LCPV/T) module is established. The new membrane distillation unit has a smaller and more convenient size and higher fresh water yield. The total surface area of the membrane component was 0.22m^2. The experiment was carried out under the condition of all-day variable irradiation. The detailed temperature variation was recorded and analyzed. Results show that the system can achieve a maximum temperature difference of 7°C in the membrane distillation without electric heating and other heat source, and the water yield of membrane distillation is 2.73 L/(m^2▪h), besides it can realize 99.9% desalting rate of simulated seawater.

Keywords: desalination; water yield; vacuum membrane distillation; PV/T; cogeneration system; heat utilization

NONMENCLATURE

Abbreviations	
AGMD	air gap membrane distillation
CPVC	chlorinated polyvinyl chloride
DCMD	direct contact membrane distillation
LCPV/T	low concentrated photovoltaic/thermal
MD	membrane distillation
PTFE	polytetrafluoroethylene
SGMD	sweeping gas membrane distillation
VMD	vacuum membrane distillation
Symbols	
A	effective membrane area
c_f	feed side concentration
c_c	permeate side concentration
h_m	heat transfer coefficient
J	water yield rate
k_s	membrane mass transfer coefficient
Δm	water yield
P_f	pressure on feed liquid side
P_p	pressure on permeable side
q_m	heat transfer in membrane distillation
T_f	temperature of feed liquid side
T_p	temperature of permeable side
η	distillate rate
ρ_f	feed liquid conductivity
ρ_c	permeate water conductivity

1. INTRODUCTION

Membrane distillation (MD) is a new seawater desalination technology with high industrial potential. It is a heat membrane separation method that uses a microporous hydrophobic membrane to extract water vapor from its hot feed liquid. There are four forms of MD: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), sweeping gas membrane distillation (SGMD). Although MD has the advantages, there are still drawbacks like large energy consumption in MD process.

Solar energy has a good application prospect as the driving heat source of MD. The typical desalination ways by using solar energy include solar pond [1], solar still [2], solar thermal collector, and membrane technology such as reverse osmosis, nanofiltration and MD [3, 4]. As separate membrane or thermal technology has disadvantages, the combination of the two technology become gradually favored [5].

Kawtar et al. [6] developed a sustainable desalination system using a combination of DCMD and solar pond. Asaad et al. [7] built an experimental facility

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to examine and observe the performance of saline-gradient solar ponds before and after paraffin-covered ponds. Some scholars designed photovoltaic panel and MD (PV-MD) combined technology, which uses solar energy as a driving heat source and solar radiation energy to drive MD to purify seawater to obtain fresh water. Achmad et al.[8] developed portable and hybrid solar MD systems that utilize PV and solar collectors. The results showed that the average and the maximum of distillate output rate respectively are 11.53 L/h and 15.94 L/h. Rihab et al. [9] used the thermodynamics properties of seawater model to executing a detailed exergy analysis of the solar VMD unit. The research proves that the combination of MD and solar energy can realize the effective supply of low temperature heat source. Miladi et al. [10] also selected four typical days to analyze the energy of the solar VMD system, the results presented that the maximum freshwater production obtained by the system is 17.68 (kg/h·m^2) at the maximum feed temperature of 75°C. Omar [11] proposed a tubular solar collector auxiliary solar still for seawater desalination and analyzed its exergy performance, environmental and economy.

However, the above technology has limited temperature increase, which cannot fully meet the requirements of inlet water temperature of MD. Hence, scholars proposed to use solar photovoltaic/thermal (PV/T) technology to rise water temperature and electric energy. Zarzoum et al. [12] set up a PV/T solar MD system, in which the membrane area is 10m^2 and the collector area is 2 m^2. After the experiment, the maximum yield productivity is 15.2 L/h and the all-day yield productivity is 86L. Muhsen et al. [13] studied the performance of concentrated PV/T system (CPV/T) coupled with DCMD. The results show that DCMD can produce 3 kg/(m^2·h) of fresh water. Andrew et al. [14] proposed a seawater desalination system based on CPV system and DCMD. The experimental studies showed that the average mass flux could reach 7.1 kg/(m^2·h) even at a low membrane temperature difference of 18.82°C.

Nevertheless, the above work did not study the dynamic change of the outlet water temperature of the solar collectors under variable irradiation conditions, nor did it explain the correlation between the water yield rate and solar irradiation. In this work, we established a reliable LCPV/T dual-axis tracking heat-power cogeneration system, explored the change of water production rate with irradiation and outlet water temperature of LCPV/T collectors, explored the desalination performance of the VMD module used in the experiment.

2. PROPOSED SYSTEM DESCRIPTION

2.1 Overall system setup

A schematic of the proposed portable LCPV/T-VMD system for desalination is depicted in Fig. 1. The system consists of four PV panels arranged in series (each rated power is 40W), four composite parabolic condensers, saline water tank, hot water tank and important components of VMD. In order to simplify the processing, this schematic diagram only shows the structure of one LCPV/T unit and the solar thermal concentrator (STC) part. The detailed structural parameters and pictures of LCPVT unit are shown in the paper [15, 16] published earlier by our research. Besides, the system also includes a vacuum pump and two feed pumps. The MD unit is composed of hollow fiber membrane. A large number of polytetrafluoroethylene (PTFE) hollow fiber membranes are installed in a 50cm long tubular container made of chlorinated polyvinyl chloride (CPVC). Membrane filaments are characterized as 400-μm thickness, 48% porosity, 0.08μm pore size. In order to prevent the excessive cooling water temperature from affecting PV power generation, as shown in Fig. 1, the flow channel under STC without PV panels is adopted at the end of the module. Studies show that the inlet water temperature of MD should reach about 60-80°C [17], which can have better water production performance. If the heating temperature of the concentrating module cannot meet this condition. The electric energy generated by the PV panel can be used for electric heating. Temperature data is collected by T-type thermocouples at different points in the system.

The instruments and equipment used in the LCPV/T-VMD experimental system are listed in Table 1.

Table 1 Instruments and Equipment list

Instruments	Range	Accuracy
Vacuum pump	0~98kPa	±2.5 %
IV Curve tester	10-1000 V 0.1-30 A	±1 %
Flowmeter	10-100L/h	±2.5 %
Thermocouple	−100–400°C	±0.4%
Conductivity meter	0.055μS/cm-199.9mS/cm	±0.5%

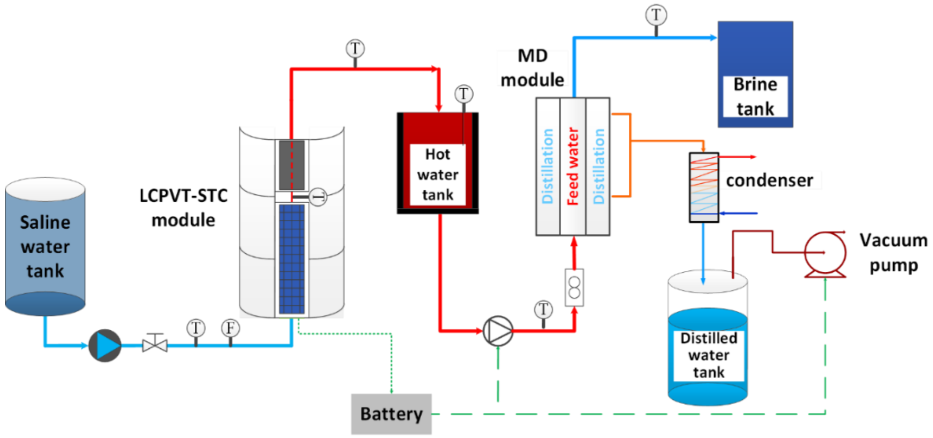

Fig. 1 schematic of LCPV/T-MD system

2.2 MD process

VMD is a membrane separation process using latent heat of evaporation to realize phase transformation. The driving force is the vapor pressure difference between the two sides of the hydrophobic membrane. VMD operation vacuum is generally between 0.07Mpa-0.095Mpa, so as to ensure that it is lower than the saturation pressure of volatile molecules (water molecules) in the feed solution.

2.2.1 Mass transfer flux

VMD seawater desalination is a synchronous process of heat and mass transfer. In the mass transfer process, one of the key quantities is the vapor mass transfer flux in the membrane pore and the membrane flux calculation model is given as follows.

$$J = k_s(P_f - P_p) \qquad (1)$$

J is water yield rate, kg·m^{-2}·h^{-1}, P_f is the pressure on the membrane of feed liquid side, Pa; P_p is the pressure on the membrane of permeable side, Pa; k_s is the membrane mass transfer coefficient, J/mol. k_s is related to the temperature of the material liquid and the porosity of the membrane, etc.

2.2.2 The heat transfer model

The MD heat transfer process can be simplified as one-dimensional steady heat transfer process, and the following calculation model is given

$$q_m = h_m(T_f - T_p) \qquad (2)$$

h_m is the heat transfer coefficient, W/(m^2·K), In the process of MD seawater desalination. h_m is determined by membrane thickness, thermal conductivity, porosity, membrane material and other factors.

2.2.3 Water yield rate and desalination rate

The calculation model of water yield in MD process is as follows：

$$J = \frac{\Delta m}{A\Delta t} \qquad (3)$$

Δm is water yield, kg , A is effective membrane area,m^2, Δt is system uptime, h.

As there is a linear relationship between concentration and conductivity within a certain range of NaCl concentration, the ratio between them of saline water (seawater) can be considered constant within a certain range of salinity. Therefore, in the calculation of desalination rate, the difference of conductivity can be directly replaced by the difference of concentration.

$$\eta = \frac{c_f - c_c}{c_f} \times 100\% = \frac{\rho_f - \rho_c}{\rho_f} \times 100\% \qquad (4)$$

η is desalination rate in MD process, %. c_h is feed side concentration, g/L; c_c is permeate side concentration, g/L; ρ_h is feed liquid conductivity, µS/cm; ρ_c is permeate water conductivity, µS/cm.

In addition, the calculation models of electrical efficiency and thermal efficiency have been shown in previous research papers[21].

3. RESULTS AND DISCUSSION

3.1 All-day irradiation

The experiment was conducted in Beijing, China, on July 31st. Seven groups of experiments were carried out throughout the day, as shown in Table2.

Table 2 Basic data of experiment

No.	Start time	Duration (mins)	Electric power (W)	Thermal power (W)
1	10:30	10	282.8	2795
2	11:07	10	288.0	2357
3	12:54	10	268.4	2698
4	13:34	10	252.9	2354
5	16:06	10	240.8	2677
6	16:50	10	217.3	2536
7	17:30	10	166.5	1952

Fig. 2 shows the variation trend of daily tracking irradiation and horizon irradiation. During 10:00 - 13:00 in the morning and noon, the solar radiation value is high, and the tracking radiation is stable at more than 950W/m^2. After that, the radiation value fluctuates greatly. It can be seen that the irradiation drops sharply for the shield by thick clouds. The lowest tracking irradiation reached 420W/m^2(13:45), then gradually recovered to more than 900W/m^2. After 16:00, with the increase of solar tilt angle, the irradiation began to decrease greatly.

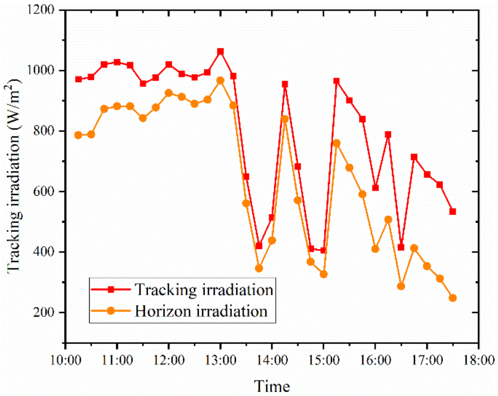

Fig. 2 Variation of irradiation value on experiment day

3.2 *Feed liquid temperature*

The MD experiment was carried out in an appropriate period, with each experiment lasting 10 minutes. Fig. 3 shows the average irradiation, ambient temperature, inlet and outlet temperature of LCPV/T during the experimental period. The average outlet temperature were above 60°C under experimental conditions. The highest outlet water temperature in the experiment reached 70.8°C (16:15). It can be noted that the average outlet temperature of LCPV/T is strongly correlated with the irradiation. When the irradiation reaches more than 900W/m^2, the outlet water temperature can generally reach more than 68°C. Although the irradiation at 16:00 decreased to 775W/m^2, it increased the temperature of photovoltaic panels and affected the outlet temperature reach to 67.71°C.

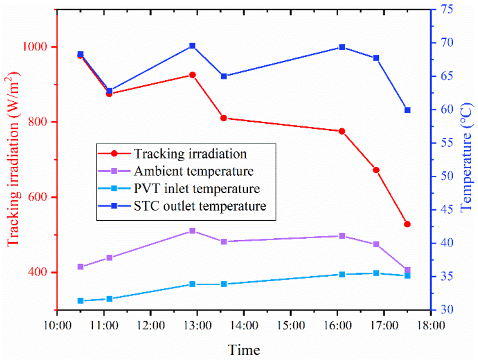

Fig. 3 Temperature trend of the inlet and outlet of LCPV/T

3.3 *VMD process*

Fig. 4 showed the changes of inlet and outlet temperature of membrane filament during the VMD experiment. It can be seen that at about 12:54, the inlet and outlet side of membrane began have an obvious temperature difference, indicating that the latent heat of vaporization of feed solution was released, resulting in the decrease of the feed solution temperature. The increase of feed solution temperature before. In the VMD process, the inlet water temperature of LCPV/T is stable at around 70°C, and the highest outlet water temperature reaches 70.5°C. The average temperature difference at the inlet and outlet of VMD reaches 6.0°C.

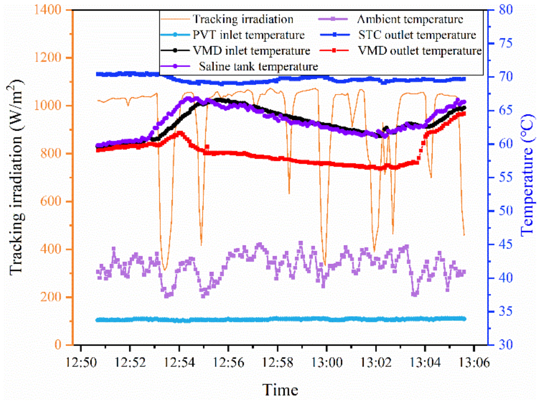

Fig. 4 Inlet and outlet water temperature of MD process

3.4 *Distillate yield and distillation rate*

Fig. 5 described the distillate yield and rate. The maximum water yield is 100.09 mL with the highest water yield of 2.73 L/(m^2·h) while the minimum water yield is 1.20 L/(m^2·h) in the 7$_{th}$ experiment. It can be seen that distillate yield is positively related to irradiation and outlet water temperature of LCPV/T. The higher the irradiation is, the higher the outlet water temperature is, and the higher the distillate yield is. Compared with the rapid response of irradiation, the change of water yield rate is relatively slow. In the previous experiment of VMD driven by electric heating, the highest water yield of the component was 3.682L/(m^2·h).

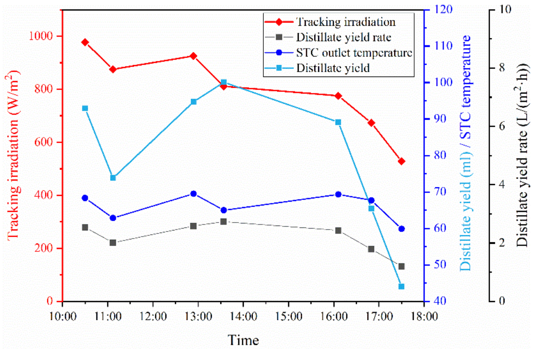

Fig. 5 distillate yield and rate of MD process

The power generation effect of LCPV/T and the heat recovery performance of MD system were tested. As shown in Table 2, the maximum electrical thermal power are 288W and 2795W respectively. The corresponding electrical efficiency and thermal efficiency are shown in Fig. 6. The highest electrical efficiency can reach 20.9%, while the highest thermal one reach 73.3%.

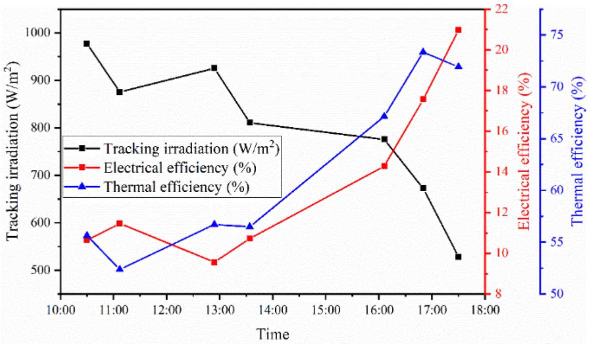

Fig. 6 Electrical and thermal efficiency of LCPV/T system

In addition, in order to verify the conductivity of water yield, brine water (salinity of 25g/L) was used for experimental analysis on August 21st. The conductivity and water yield of feed solution were measured by conductivity meter. The calculated results show that the desalination rate of hollow fiber membrane used for VMD is above 99.9%, which has an excellent desalination performance.

4. RESULTS AND DISCUSSION

This paper constructs an operational combined seawater desalination system based on VMD technology. The conclusions are as follows.

1) Through detailed data recording and analysis, the highest outlet water temperature of LCPV/T collector reached 70.4°C, and the average outlet water temperature is 66.1°C, which meets the requirements of inlet water temperature of VMD.

2) The water yield of the combined seawater desalination system can reach 2.73L/(m^2·h) under stable working conditions (ie. feed side 64°C, permeate side 59°C) in summer sunny day

3) The desalination rate of 99.9% of simulated seawater can be achieved.

4) In terms of power generation, the maximum electric power of the whole test stage is 288W, and the maximum electric efficiency reaches 20.9%, which can be well used for power consumption of the experimental system and has good application value.

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