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# Dynamic solar-powered multi-stage direct contact membrane distillation system: Concept design, modeling and simulation

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## ABSTRACT

This paper presents a theoretical analysis of the monthly average daily and hourly performances of a solar-powered multi-stage direct contact membrane distillation (SMDCMD) system with an energy recovery scheme and dynamic operating system. Mid-latitude meteorological data from Busan, Korea is employed, featuring large climate variation over the course of one year. The number of module stages used by the dynamic operating scheme changes dynamically based on the inlet feed temperature of the successive modules, which results in an improvement of the water production and thermal efficiency. The simulations of the SMDCMD system are carried out to investigate the spatial and temporal variations in the feed and permeate temperatures and permeate flux. The monthly average daily water production increases from 0.37 $m^3$/day to 0.4 $m^3$/day and thermal efficiency increases from 31% to 45% when comparing systems both without and with dynamic operation in December. The water production with respect to collector area ranged from 350 $m^2$ to 550 $m^2$ and the seawater storage tank volume ranged from 16 $m^3$ to 28.8 $m^3$, and the solar fraction at various desired feed temperatures from 50 °C to 80 °C have been investigated in October and December.

## 1. Introduction

The membrane distillation (MD) process is an emerging technology for seawater desalination. This is the thermal separation process based on membrane which transports water vapor across a microporous hydrophobic membrane. The partial vapor pressure difference, generated by the temperature gradient across the membrane, is the driving force of the MD process. The MD process can achieve nearly 100% rejection of non-volatile electrolytes and also has several advantages such as lower requirement of operating temperature and hydraulic pressure than conventional thermal processes, lower effect of salinity on the permeate flux, and lack of the corrosion thanks to the characteristics of polymer membrane materials [1–16]. There are four typical types of MD processes: direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD), and vacuum membrane distillation (VMD). Most studies have been conducted on the DCMD process due to its simple configuration in which the condensation of water vapor occurs at the permeate side, as well as its potentially high permeate flux [1,2,6,9,12,13]. Here, the main consideration of the DCMD process is to reduce the energy consumption resulting from a higher conductive heat loss; thus many researchers have attempted to reduce the specific thermal energy consumption. Firstly, heat recovery systems have been applied in MD processes to reuse the residual thermal energy from the brine and permeate streams [1,4,9,17,18]. The heat recovery scheme has a great effect on the reduction of the energy consumption of the MD system. The heat energy is recovered from the retentate via heat exchanger, thus the preheating energy for inlet feed seawater can be reduced. Secondly, the membrane has been developed to reduce conductive heat loss and to increase permeate flux. The composite configuration is one of several commercial membranes used to improve the permeate flux and reduce conductive heat loss [1,19–22]. Composite membranes consist of an active layer of hydrophobic polymer casted on a thicker supporting layer of a hydrophilic or hydrophobic polymer. The support layer is thicker than the active layer to prevent heat loss via conduction. In addition, the thinner active layer can reduce the mass transfer resistance. Thirdly, thermal energy supply, which has low or negligible cost, is required for economic operation of the MD process [1]. Alternative energy sources have been studied as free energy suppliers for MD processes [1,23–29]. Among them, solar

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**Nomenclature**

| | |
|---|---|
| $A_a$ | Aperture area per collector [$m^2$] |
| $A_c$ | Total collector area [$m^2$] |
| ASHRAE | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| $c_1$ | Global heat loss coefficient [$W/m^2$ K] |
| $c_2$ | Temperature dependence of global heat loss coefficient [$W/m^2$ $K^2$] |
| $c_3$ | Effective thermal efficiency [$kJ/m^2$ K] |
| $c_p$ | Specific heat capacity [kJ/kg K] |
| $D$ | Chevron angle [°] |
| $d_f$ | Filament diameter [m] |
| $h_s$ | Spacer thickness [m] |
| HTF | Heat transfer fluid |
| HX | Plate heat exchanger |
| $\Delta H$ | Enthalpy of vaporization [J/kg] |
| $J$ | Permeate flux [$kg/m^2$ h] |
| $J_m$ | Mean permeate flux [$kg/m^2$ h] |
| $l_m$ | Mesh size [m] |
| $L_h$ | Effective plate height [m] |
| $L_{loc}$ | Longitude [°East] |
| $L_w$ | Effective plate width [m] |
| $N_c$ | Number of collectors [−] |
| $N_{DM}$ | Number of DCMD modules [−] |
| $N_{OH}$ | Operating hours [−] |
| $N_{TM}$ | Total number of operating modules [−] |
| $p$ | Plate pitch [m] |
| $P$ | Pressure [Pa] |
| $Q$ | Heat flux [$W/m^2$] |
| $r$ | Mean pore size [m] |
| $R_f$ | Fouling factor [$m^2$ K/W] |
| $SF$ | Solar fraction |
| SMDCMD | Solar-powered multi-stage direct contact membrane distillation |
| $t$ | Plate thickness [m] |
| $T$ | Temperature [K] |
| $U$ | Overall heat transfer coefficient [$W/m^2$ K] |
| $v$ | Velocity [m/s] |
| $V$ | Volume flow rate [l/min] |
| $V_{st}$ | Seawater storage tank volume [$m^3$] |
| $W_p$ | Daily water production [$m^3$/day] |

*Greek letters*

| | |
|---|---|
| $\beta$ | Tilt angle [°] |
| $\gamma$ | Azimuth angle [°] |
| $\delta_m$ | Membrane thickness [m] |
| $\varepsilon$ | Membrane porosity [%] |
| $\varepsilon_s$ | Surface porosity [%] |
| $\eta$ | Local thermal efficiency or collector efficiency |
| $\eta_i$ | Thermal efficiency at each module |
| $\eta_{TM}$ | Average thermal efficiency of the total modules operated at each time |
| $\eta_m$ | Monthly average daily thermal efficiency |
| $\eta_0$ | Optical efficiency [%] |
| $\theta$ | Angle between filaments [°] |
| $\rho$ | Density [$kg/m^3$] |
| $\phi$ | Latitude [°North] |

*Subscripts*

| | |
|---|---|
| $a$ | Ambient |
| $al$ | Active layer |
| $b$ | Bulk |
| $D$ | Desired |
| $f$ | Feed |
| $m$ | Mean or membrane |
| $p$ | Permeate |
| $s$ | Salt |
| $sl$ | Support layer |
| $v$ | Vapor |
| $w$ | Water |
| $z$ | Axial coordinate |

energy, which is environmentally-friendly and sustainable, is harvested through the solar collector or photovoltaic cell, and can be utilized to preheat the feed seawater for MD process.

Numerous experimental and theoretical studies on solar-assisted or -powered MD desalination systems have been reported. Kim et al. [1] presented a theoretical analysis of DCMD desalination system using a solar energy and auxiliary heater, which consists of a temperature modulating scheme and a heat recovery scheme. A shell-and-tube-type PVDF hollow fiber membrane module was employed, and the results showed that the overall permeate production capacity is 31 $m^3$/day. Guillen-Burrieza et al. [24] presented an experimental analysis of a solar desalination system incorporating the AGMD process using a flat sheet type PTFE membrane module. Chen and Ho [25] presented experimental and theoretical studies of immediately assisted solar DCMD in saline water desalination using a lab-scale experimental equipment. Banat et al. [30] presented a performance evaluation in an experimental study of the solar-driven MD desalination plant in Aqaba, Jordan.

All of aforementioned experimental and theoretical studies have been conducted to investigate short- or long-term operation near the equator in areas such as Jeddah in Saudi Arabia or Aqaba in Jordan, which experience negligible changes in monthly meteorological conditions. However, the construction of solar-thermal systems outside of equatorial areas should be considered. In these areas the variance in monthly meteorological conditions must be accounted for based on the lines of longitudinal and latitude because the variation of the earth-sun distance does lead to large variations in aspects such as solar radiation, ambient temperature, and seawater temperature over the span of a year.

In addition, a number of modules in a multi-stage concept should be dynamically adjusted based on the monthly changes in local meteorological conditions, e.g. by implementing the suggested dynamic operating system in order to increase the thermal efficiency and water production. A dynamic operating system is a modulating system that adjusts the number of membrane modules used based on the inlet feed temperature of the successive module in a multi-stage MD system. The available inlet feed temperature at each month would be changed based on the monthly changes in local meteorological conditions; the available difference in partial water vapor pressure as a driving force should also be changed each month. As shown in Fig. 1, a higher thermal efficiency and partial water vapor pressure difference can be achieved at the higher temperature difference region between the feed and permeate sides in the MD process. This means that it would be better to not operate the MD process at the low inlet feed temperature of the successive module by using a dynamic operating system to improve the water production and thermal efficiency.