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Direct contact membrane water distillation assisted with solar energy

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ABSTRACT

An experimental and theoretical investigation for salt water desalination using tubular direct contact membrane distillation is introduced. The effect of operating and geometric parameters on the unit performance was studied. These parameters include feed water inlet temperature, feed water flow rate, salt concentration, cooling water temperature and membrane inner diameter and length. System thermal efficiency and gain output ratio (GOR) are also evaluated. The investigated parameters were set as follows: 70 °C for inlet feed water temperature, 15–20 L/min for feed water flow rate, 0–40 g Nacl/L water for feed water salt concentration, 20–56 °C for the inlet cooling water temperature, and 15–20 L/min for cooling water flow rate. Maximum productivity, daily efficiency, and Gain output ratio (GOR) of the system reached 40.587 kg/day, 60.06% and 0.624 respectively. Finally, a good agreement has been found between the present numerical data and experimental results.

1. Introduction

There are different methods for water desalination by using solar stills and reverse osmosis (RO). However, the solar stills had low productivity and low water quality. Also, the RO process had some problems due to the formation of polarization films because of high pressure operation and by-products which may generate bacteria and fouling. Also, high energy consumption and brine disposal problem is faced in RO process due to the limited recovery of water. These problems may be overcome by other membrane thermal process such as a membrane distillation (MD) [1–4].

Membrane distillation (MD) is a hybrid process which joins a thermally driven distillation process with a membrane separation process. The pure water is evaporated from saline water by thermal energy and transported through the pores of hydrophobic membrane. The driving force for DCMD is the vapor pressure difference across membrane. It results from the temperature difference between feed and permeate water. Then pure water vapor condensate at the downstream side of the membrane. The most common configuration of membrane distillation (MD) is direct contact membrane distillation in which hot feed saline water and cold permeate water are in direct contact with the membrane.

In addition, the temperature difference between feed and permeate sides causes the simultaneous heat and mass transfer through the porous membrane. In DCMD, the operation is simple and it requires the least equipment. So, it is considered the most appropriate configuration for desalination. Therefore a DCMD unit is designed, built and operated.

Desalination is the removal of excess salt and minerals from water and it is used to provide pure water from seawater or brackish water. Desalination of seawater by DCMD was investigated by Hote et al. [5]. The salt concentration has a little effect on the permeate flux up to 5% by weight salt. However, increasing both the feed flow rate in laminar region and temperature difference between feed side and permeate side have an important effect on the permeate flux.

Janajreh and Suwwan [6,7] used ANSYS Fluent to study the steady state performance of low energy direct contact membrane distillation. They found that, the increase in the inlet flow resulted in a higher values of mass flux. This was due to the higher convective heat flux as illustrated by the higher values of the Nusselt number. Temperature polarization was in the range of 0.2 and 0.6 and the highest mass flux achieved was above 4 kg/m^2 h. Salah et al. [8], Selvi and Baskaran [9] and Palanisami et al. [10] introduced a solar driven DCMD plants. An experimental study of using solar energy in direct contact membrane distillation process for desalination of real seawater has been performed in [8–10].

Madhubanti et al. [11] introduced a two dimensional mathematical model to explore the effects of operating parameters on the performance of DCMD module. The predicted results exhibited good agreement with the experimental results. Achmad et al. [12] developed an integrated solar-driven desalination system using

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Nomenclature

A	projected area of solar collector, m^2
C_P	specific heat, J/kg K
C	membrane distillation coefficient, kg/s m^2 Pa
C_{ms}	salt concentration at the surface of the membrane, Kg_{sal}/kg_{sol}
D	tube diameter, m
h	average heat transfer coefficient, W/m^2 K
h_v	latent heat of vaporization, kJ/kg_v
J	permeate flux per unit area of membrane, kg/s m^2
k	thermal conductivity of fluid, W/m K
L	length of membrane, m
M	molecular mass (kg mol^{-1})
$\dot{m}$	mass flow rate, kg/s
Nu	average Nusselt number, –
p	pressure, Pa
Pr	Prandtl number, –
Q	heat transfer rate, W
$Q_{E.H}$	power of electric heater, W
I	solar isolation, W/m^2
Re	Reynolds number, –
t	time, s
T	temperature, K
X_{ms}	mole fraction of salt, mole
W_{fpump}	power of feed water pump, W
W_{cwpump}	power of cooling water pump, W

Greek letters

ρ	density
η	efficiency
ε	porosity of the membrane
δ	thickness of the membrane, m
μ	fluid dynamic viscosity, kg/m s

Subscripts

f	feed water
$c.w$	cooling water
fm	membrane surface at feed side
pm	membrane surface at permeate side
m	membrane surface
b	Buk
i	inlet
cr	critical

Abbreviations

MD	Membrane Distillation
DCMD	Direct Contact Membrane Distillation
PTFE	Poly tetrafluoroethylene
RO	Reverse Osmosis
TM	Tubular Membrane Module
HFM	Hollow Fiber Membrane Module
Wt	by weight

membrane distillation process. This system is an integrated (self-contained) system that uses solar energy for its operation by combining solar photovoltaic (PV) and solar thermal collectors. Based on their results, the largest amount of water was produced by test E (99.6 L) under the following conditions: heat pump utilization, a higher thermal-tank temperature, a low feed flow rate, and high solar radiation. The average conductivity of the distilled water produced by the system was 6.2 µs/cm. The optimum feed flow rate was 69 L/h. Hung et al. [13] introduced a technique to optimize thermal efficiency of seawater desalination by DCMD system using brine recycling. The system water recovery was increased and the sensible heat of the hot brine was recovered to improve thermal efficiency. Chii-Dong et al. [14] introduced a new design of direct contact membrane distillation unit. They used a roughened-surface flow channel for enhancement of heat transfer to increase the pure water productivity in saline water desalination. A 37% of performance enhancement was obtained for their modified experimental system. Kezia et al. [15] used direct contact membrane distillation to concentrate saline dairy effluent. Flat Sheet PTFE membranes of nominal pore sizes 0.05, 0.22 and 0.45 mm were utilized. Salty whey waste streams have been successfully concentrated from less than 10 wt% solids to 30 wt% solids using membrane distillation. Young et al. [16] presented a solar-assisted DCMD system with novel energy recovery concepts for a continuous 24 h a day operation. This system contained evacuated-tube solar collectors of 3360 m^2 with 160 m^3 seawater storage tanks and 50 DCMD modules, the annual solar fraction and the collector efficiency were found to be 77% and 53%, respectively, while the overall permeate productivity was 31 m^3/day. Yehia et al. [17] developed a model for estimating the temperature polarization coefficient across the membrane. They taking into consideration the simultaneous heat and mass transfer phenomena. Higher temperature polarization effect was occurred due to higher feed temperatures and therefore a lower temperature polarization coefficient. Shim et al. [18] investigated a solar assisted DCMD system for seawater desalination and an improved mathematical model to predict the permeate flux for unsteady state conditions. The experimental heat energy consumption ranged from 896 kW h/m^3 to 1433 kW h/m^3, and the gained output ratio (GOR) ranged from 0.44 to 0.70. The solar-DCMD system was run continually for more than 150 days for seawater desalination in Korea. During day time, more than 77.3% of the heating energy was supplied by solar energy. In particular, in the month of September, 95.3% of the heating energy was supplied by solar energy.

Wang [19] presented a study examined the heat transfer coefficients applicable for membrane distillation. He proposed that, to exploit a modified Wilson plot technique to increase the accuracy of the measured feed side heat transfer coefficient. Through this approach, one can eliminate the uncertainty from permeate side and reduce the uncertainty in membrane to obtain a more reliable heat transfer coefficient at feed side from the experimentation. Suárez et al. [20] presented a promising system for renewable energy desalination which utilized low-temperature direct contact membrane distillation (DCMD) driven by a thermal solar energy system, such as a salt-gradient solar pond (SGSP). They obtained an average fresh water flux of nearly 1.0 L h^{-1} per m^2 of membrane.

Dong et al. [21] investigated theoretically and experimentally the laminar flow hollow-fiber direct contact membrane distillation module for desalination to produce pure water, under both concurrent-flow and countercurrent-flow operations. The y found that, the experimental results of pure water productivity were fairly close to the theoretical predictions with relative error of 2–6.1%. The local temperature distributions revealed a thick thermal boundary layer next to the membrane surface. Some useful comparisons between researchers are presented in Table 1.

In the present work, an experimental and theoretical investigation for salt water desalination using tubular direct contact membrane distillation is introduced. Heat and mass transfer equations that relates different relevant parameters are also analyzed in details. The effect of operating and geometric parameters on the unit performance was studied. These parameters include feed