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Evaluation of geothermal energy in desalination by vacuum membrane distillation

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HIGHLIGHTS

- Membrane porosity controls the flux through the polyvinylidene fluoride membranes.
- The highest flux at 9.28 kg/m^2 s consumes the lowest energy at 66.03 kW/kg h^{-1}.
- Geothermal energy can save approximately 95% of the total energy consumption.
- The cross-flow vacuum membrane distillation system can produce the drinking water.
- For a 20,000 m^3/d VDM plant, geothermal energy can save the cost at least \$0.72/m^3.

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ABSTRACT

This paper presents the energy evaluation of the cross-flow vacuum membrane distillation (VMD) for three types of lab-fabricated polyvinylidene fluoride (PVDF) membranes and the commercial Westran S PVDF membrane. Membranes with the effective area 23.5 cm^2 are tested with distilled water and geothermal water as the feed solutions. Results show that the membrane porosity controlled the flux through the fabricated membranes and the commercial membrane. The commercial membrane with porosity of approximately 76.5%, which was the most porous among the tested membranes, gave the highest flux at 9.28 kg/m^2 h under the optimum conditions of 33.2 L/h feed flow rate and 30 kPa downstream pressure. The corresponding specific energy consumption was 66.03 kW/kg h^{-1} when distilled water was examined. Heating energy of 87–89 kW/kg h^{-1}, which is approximately 95% of the total energy consumption, could be saved when the warm geothermal water is fed directly into the VMD system. The water produced meets the drinking water quality with the TDS varying between 102 and 119 ppm, thus the geothermal water desalination using the VMD system to produce the drinking water is satisfactory. An economic analysis for a 20,000 m^3/d VMD desalination plant finds that the water production costs are \$0.50/m^3 and \$1.22/m^3 respectively for the plant operated with and without geothermal energy (GE). Compare to the plant without GE utilisation, the water production costs of the plant operated with GE are less than \$0.50/m^3 that is at least \$0.72/m^3 or approximately 59% in cost saving when the water fluxes are larger than 6.6 kg/m^2 h. The specific membrane cost reduced from \$0.058/m^3 to \$0.035/m^3 when the membrane life extended from 3 to 5 years.

1. Introduction

Membrane distillation (MD) is a strategy of process intensification for sustainable development in desalination. The advantages of MD over traditional desalination techniques include lower cost, more energy saving, fewer mechanical part demands and safer; because the MD works at lower temperatures (<100 °C) and atmospheric pressure. By the MD process, water vapour is thermally driven through a porous hydrophobic membrane. Saline water is brought into direct contact with the upstream side of the membrane. A hydrostatic pressure of the saline water does not exceed the 'liquid entry pressure of water (LEP_w)' of the membrane and a liquid–vapour (*L–V*) interface is formed at the entrances of membrane pore. Warming the saline water permits the water evaporates at the *L–V* interface because of the heat of vaporisation while the salts remain in the saline water.

A driving force which results from an energy difference of water molecules between the upstream and the downstream sides of the membrane causes the water vapour transfers from the feed to permeate sides. The methods to lower the energy of water molecules

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Nomenclature

a	amortisation factor (–)
A	area (m^2); annual consumption per year (unit/y)
C	cost ($)
C_p	heat capacity (J/kg °C)
d	diametre (m)
E	heat exchanger efficiency (–)
E_c	electricity consumption (kW h)
f	plant availability (%)
i	interest rate (%)
J	mass flux (kg/m^2 s or kg/m^2 h)
K_m	membrane permeability ($mol^{1/2}$ s m^{-1} $kg^{-1/2}$)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular weight (kg/mol)
M_L	membrane life (year)
P	pressure (Pa)
q	flow rate (m^3/s)
Q	energy (W)
r	recovery
R	gas constant (J/mol K)
s	specific cost ($/unit)
t	time (s)
T	temperature (K)
ΔT_m	mean temperature (K)
U	global heat transfer coefficient (W/m^2 K)
$\dot{V}$	volumetric flow rate (m^3/s)
w	weight (kg); plant capacity (m^3/d)
W	specific work done (W/kg)

Greek letter

δ	thickness (m)
ε	pore size (m)
η	efficiency (–)
ρ	density (kg/m^3)
τ	tortuosity (–)

Subscript

BD	brine disposal
CH	chemical
CW	civil work
d	dry
E	electricity
f	feed; reference
h	heating
HE	heat exchanger
i	permeating component
I/P	intake and pretreatment
LB	labour
M	membrane
M/A	membrane per area
M, repl.	membrane replacement
OM	operating and maintenance
p	pore, pumping, permeate
PU	pump
r	membrane replacement factor
s	specific
SP	spares
ST	steam
T	total
TCC	total capital cost
v	vacuum
w	wet

Superscript

n	plant life

on the downstream side divide the MD into four different types of configurations: (1) direct contact membrane distillation (DCMD), with the downstream side of the membrane in contact with cold water; (2) air gap membrane distillation (AGMD), with the downstream side of the membrane in contact with stagnant air cooled by a cold plate; (3) sweeping gas membrane distillation (SGMD), with the downstream side of the membrane swept by an inert gas; and (4) vacuum membrane distillation (VMD), with the downstream side of the membrane maintained relatively low pressure (vacuum).

Within the MD unit itself, the main issue is the high energy consumption. In the case of VMD, the process requires pumping energy to circulate the saline water on the upstream side of the membrane; heating energy to warm the saline water and vacuum energy to lower the energy of water molecules on the downstream side of the membrane.

The specific energy consumption is defined as the ratio of the total energy consumption and the permeate flow rate. The high the permeate flux represents the performance of the MD for the desalination is relatively good because the specific energy consumption is low. The operating conditions and the physical properties of the membrane, basically, influence the permeate fluxes. For the VMD system, the flux increases with increasing the feed temperatures, feed flow rates and vacuum levels [1,2]. The design of the membrane properties i.e. pore size, porosity, thickness and pore length relies on the membrane formulations and fabrication techniques [3–6]. The flux increases with pore size and porosity but decreases with thickness and pore length. One or more of the membrane properties can control the fluxes significantly if the effect of the properties on the fluxes has outweighed the effect of the other properties on the fluxes. Apart from the fabricated membranes, the commercial membranes specially developed for microfiltration applications have also been adapted in VMD desalination [7,8].

The VMD system becomes expensive if operated at feed temperature of 75 °C or higher because of high energy consumption [9]. Utilisation of the renewable energy is worthy of further research in order to bring the technology closer to the process intensification. Until now, renewable energy such as solar energy is frequently studied in MD [10,11]. The cost of water production by the solar powered MD, however, is quite high because the solar collectors are too expensive [12]. Geothermal energy in desalination is expected can reduce the cost of water production because a converter of the energy is not necessary. But the geothermal energy has been rarely examined in MD. Geothermal water is groundwater which is heated by the Earth's interior energy. The geothermal energy is not suitable for the traditional desalination techniques because the enthalpy water energy is low [13].

The aim of this work is to evaluate the geothermal energy in water desalination using the cross-flow VMD system. Four types of polyvinylidene fluoride (PVDF) membranes were used; three membranes were fabricated from three different formulations using phase inversion technique under the same fabrication conditions, and one membrane which is commercially developed for protein sequencing. An optimum operating condition was found out based on the lowest specific energy consumption when distilled water was fed into the VMD system. The VMD system was tested for the geothermal water where the reservoir is located at Ranau, Sabah, Malaysia. The temperature of the geothermal water varied from 56 to 62 °C at corresponding reservoir depth of 0–