Applied Energy 184 (2016) 491–505

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Membrane distillation model based on heat exchanger theory and configuration comparison

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HIGHLIGHTS

- GOR increases linearly with thermal efficiency, but more rapidly with effectiveness.
- Module design should increase overall heat transfer coefficient for seawater desalination.
- At constant flux and condenser area, GOR varies as AGMD < DCMD < CGMD.
- DCMD GOR exceeds CGMD only when heat exchanger area 7× greater than membrane area.
- Simplified heat-exchanger-theory based model for CG, PG and DCMD deviates <11%.

ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form 19 August 2016
Accepted 26 September 2016

Keywords:
Membrane distillation desalination
Energy efficiency
Conductive gap
Thermal efficiency
Heat exchanger
Performance limits

ABSTRACT

Improving the energy efficiency of membrane distillation (MD) is essential for its widespread adoption for renewable energy driven desalination systems. Here, an energy efficiency framework for membrane distillation modules is developed based on heat exchanger theory, and with this an accurate but vastly simplified numerical model for MD efficiency and flux is derived. This heat exchanger analogy shows that membrane distillation systems may be characterized using non-dimensional parameters from counter-flow heat exchanger (HX) theory such as effectiveness (ε) and number of transfer units (NTU). Along with the commonly used MD thermal efficiency (η), "MD effectiveness" ε should be used to understand the energy efficiency (measured as gained output ratio, GOR) and water vapor flux of single stage membrane distillation systems. GOR increases linearly with η (due to decreasing conduction losses), but increases more rapidly with an increase in ε (better heat recovery). Using the proposed theoretical framework, the performance of different single stage MD configurations is compared for seawater desalination. The gap between the membrane and the condensing surface constitutes the major resistance in both air gap (AGMD) and permeate gap (PGMD) systems (75% of the total in AGMD and 50% in PGMD). Reducing the gap resistance by increasing gap conductance (conductive gap MD (CGMD)), leads to an increase in ε through an increase in NTU, and only a small decrease in η, resulting in about two times higher overall GOR. GOR of direct contact MD (DCMD) is limited by the size of the external heat exchanger, and can be as high as that of CGMD only if the heat exchanger area is about 7 times larger than the membrane. While MD membrane design should focus on increasing the membrane's permeability and reducing its conductance to achieve higher η, module design for seawater desalination should focus on increasing ε by reducing the major resistance to heat transfer. A simplified model to predict system GOR and water vapor flux of PGMD, CGMD and DCMD, without employing finite difference discretization, is presented. Computationally, the simplified HX model is several orders of magnitude faster than full numerical models and the results from the simplified model are within 11% of the results from more detailed simulations over a wide range of operating conditions.

1. Introduction

Increasing unmet demand for water, due to rising population and rising consumption rates, is leading to increasingly widespread use of desalination as an alternative source of water, with installed capacity now above 85 GL/day [1]. Desalination involves

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http://dx.doi.org/10.1016/j.apenergy.2016.09.090
0306-2619/

Nomenclature

Roman symbols

A	membrane area, m^2
$\bar{A}$	ratio of heat exchanger area to MD membrane area
AGMD	air gap membrane distillation
a_w	activity of water
B	membrane permeability, kg/m^2 s Pa
BPE	boiling point elevation, °C
CGMD	conductive gap membrane distillation
c_p	specific heat capacity, J/kg K
d	depth or thickness, m
DCMD	direct contact membrane distillation
dA	elemental area, m^2
g	Gibbs free energy, J/kg
GOR	gained output ratio
h	heat transfer coefficient, W/m^2 K
h_{fg}	enthalpy of vaporization, J/kg
HX	heat exchanger
J	permeate flux, kg/m^2 s
k	thermal conductivity, W/m K
L	length of module, m
MD	membrane distillation
MR	ratio of cold permeate inlet mass flow rate to hot feed inlet flow rate in DCMD
$\dot{m}$	mass flow rate, kg/s
NTU	number of transfer units
P	pressure, Pa
PGMD	permeate gap membrane distillation
p^{vap}	vapor pressure, Pa
$\dot{Q}$	heat transfer rate, W
$\dot{q}$	heat flux, W/m^2
Re	Reynolds number
RR	recovery ratio
s	salt concentration, g/kg
T	temperature,°C
T_0	ambient temperature,°C
TTD	terminal temperature difference, °C
U	overall heat transfer coefficient, W/m^2 K
v	velocity, m/s
w	width, m

Greek symbols

δ_m	membrane thickness, m
ε	module effectiveness
η	MD thermal efficiency
ϕ	membrane porosity
ρ	density

Subscripts/superscripts

b	stream bulk
br	brine stream
c	cold stream
ch	cold or hot flow channel
f	feed (hot) stream
g	gap
h	heater
in	inlet
m	membrane surface
out	outlet
p	product stream
s	solid
sat	saturation
v	vapor
wall	condensing surface

the separation of pure water from a saline stream, often the ocean, but frequently ground water. The separation of pure water is achieved either by the application of mechanical work, in the form of pressure in the case of reverse osmosis, or electricity in the case of electrodialysis, or by the use of thermal energy through phase change as in multi-effect distillation, multi-stage flash distillation, freeze desalination, etc. Even when carefully optimized, desalination is an energy-intensive process and hence many investigators have looked towards offsetting the energy requirement through renewable energy resources. Solar thermal energy or geothermal energy can be used for thermal desalination. Similarly, renewable electricity production has been used to reduce the carbon-footprint of reverse osmosis or electrodialysis systems.

Membrane distillation (MD) is a thermal desalination process that is particularly interesting for renewable energy applications because it can use low temperature, low grade heat sources. The process is very simple, requiring no high-pressure or vacuum pumps leading to a modular scalable system. Ghaffour et al. [2] recently investigated membrane distillation and adsorption desalination as innovative energy efficient desalination options for combining with renewable energy sources. Sarbatly and Chiam [3] evaluated MD powered by geothermal energy and found that while cost of water from a vacuum MD system powered from conventional sources is about US$1.29/$m^3$, with geothermal energy use, the cost drops to about US$0.5/$m^3$ making it competitive with other desalination technologies.

Suarez et al. [4] investigated low-temperature direct contact membrane distillation in combination with a solar thermal gradient salt pond. About 70% of the total energy collected was used within the MD module, but sensible heat conduction losses through the membrane made up 50% of this energy. The study's authors identified the need to reduce heat losses and improve the thermal efficiency of the process in order to make solar-powered renewable desalination viable.

Another relevant question associated with renewable MD systems is the choice of MD configuration. Zaragoza et al. [5] investigated this by experimentally comparing five commercial MD modules in air gap, permeate gap, and multi-effect vacuum configurations for desalination coupled with solar thermal energy. Although the recovery ratio, defined as pure water production divided by feed flow rate, of the multi-effect system can be an order of magnitude higher than for single stage configurations, the energy efficiency of single stage spiral wound permeate gap systems was the maximum. Electrical energy consumption for maintaining the vacuum was also significant in the case of the multi-effect vacuum configuration.

The recurring challenges in the above studies are the low energy efficiency of membrane distillation preventing MD's widespread use for renewable desalination and the various MD configurations being pursued without a clear hierarchy in terms of their energetic performance. In this article, multiple membrane distillation configurations are investigated under similar conditions to compare their energy efficiency and capital cost. In any given single stage MD configuration, there is a trade-off between energy efficiency and capital costs, with energy costs decreasing and capital expenditure increasing with larger module length. In the present work, a clear trend is established in terms of overall performance and cost among different MD configurations. The