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Energy efficiency of membrane distillation up to high salinity: Evaluating critical system size and optimal membrane thickness

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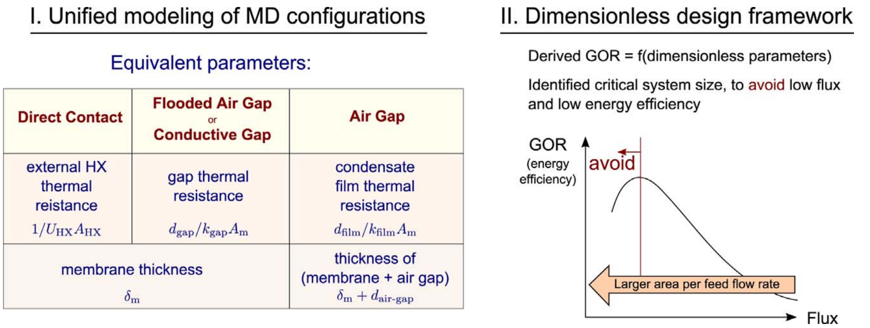
HIGHLIGHTS

- Heat transfer resistances of HX and gap fix relative performance of DCMD and PGMD.
- DCMD/CGMD with a thick membrane is resistant to high salinity, similar to AGMD.
- Method to simultaneously determine cost-optimal membrane thickness and area.
- Dimensionless framework gives generalizable results across all MD designs.
- Derived maximum allowable membrane area per feed flow rate for high salinity MD.

GRAPHICAL ABSTRACT



I. Unified modeling of MD configurations

Equivalent parameters:

Direct Contact	Flooded Air Gap or Conductive Gap	Air Gap
external HX thermal reistance $1/U_{\mathrm{HX}}A_{\mathrm{HX}}$	gap thermal resistance $d_{\mathrm{gap}}/k_{\mathrm{gap}}A_{\mathrm{m}}$	condensate film thermal resistance $d_{\mathrm{film}}/k_{\mathrm{film}}A_{\mathrm{m}}$
membrane thickness δ_{m}		thickness of (membrane + air gap) $\delta_{\mathrm{m}} + d_{\text{air-gap}}$

II. Dimensionless design framework

Derived GOR = f(dimensionless parameters)

Identified critical system size, to avoid low flux and low energy efficiency

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ABSTRACT

This study presents a comprehensive analytical framework to design efficient single-stage membrane distillation (MD) systems for the desalination of feed streams up to high salinity. MD performance is quantified in terms of energy efficiency (represented as a gained output ratio, or GOR) and vapor flux, both of which together affect the specific cost of pure water production. Irrespective of the feed salinity, permeate or conductive gap MD (P/CGMD) perform better than direct contact MD (DCMD) when the heat transfer resistance of the gap (in P/CGMD) is lower than that of the external heat exchanger in DCMD. Air gap MD's (AGMD) better performance relative to the other configurations at high salinity and large system area can be explained in terms of its thicker 'effective membrane', which includes the air-gap region. CGMD and DCMD employing a thick membrane are also resilient to high salinity, similar to AGMD, while not being susceptible to the gap flooding that can harm AGMD's performance. A method is described to simultaneously determine the cost-optimal membrane thickness and system size as a function of the ratio of specific costs of heat energy and module area. At low salinity and small system size, GOR rises and flux declines with an increase in membrane area. For salty feed solutions, there exists a critical system size beyond which GOR also begins to decline. Since both GOR and flux are lower, no economic rationale favors operation above this critical size, irrespective of the costs of thermal energy and system area. A closed-form analytical expression for this critical system area is derived as a function of the feed salinity and two dimensionless ratios of heat transfer resistances within the MD module.

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Nomenclature

Acronyms

AGMD	air gap membrane distillation
CGMD	conductive gap membrane distillation
DCMD	direct contact membrane distillation
GOR	gained output ratio
HX	heat exchanger
LMH	$L/m^2 \cdot hr$
MD	membrane distillation
NTU	number of transfer units
PGMD	permeate gap membrane distillation
P/CGMD	permeate or conductive gap membrane distillation
TTD	terminal temperature difference, °C

Roman symbols

A	area, m^2
a_w	activity of water
B	membrane permeability, $kg/m^2 \cdot s \cdot Pa$
B_0	membrane permeability coefficient, $kg/m \cdot s \cdot Pa$
c	specific cost, $\$/m^3$, $\$/kWh$ or $\$/m^2$
C	cost factor
c_p	specific heat capacity, $J/kg \cdot K$
d	depth or thickness, m
ΔT_{VPD}	measure of vapor pressure depression due to dissolved salts, °C
ΔT_{BPE}	boiling point elevation, °C
h	heat transfer coefficient, $W/m^2 \cdot K$
h_{fg}	enthalpy of vaporization, J/kg
J	permeate flux, $L/m^2 \cdot hr$
k	thermal conductivity, $W/m \cdot K$
L	length of module, m
m	molality, mol/kg-solvent
$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	heat transfer rate, W
$\dot{q}$	heat flux, W/m^2
p^{vap}	vapor pressure, Pa
R	thermal resistance, K/W
s	salinity, g/kg
T	temperature,°C
U	overall heat transfer coefficient, $W/m^2 \cdot K$
v	velocity, m/s
w	width, m
Y	non-dimensional resistance ratio

Greek symbols

δ_m	membrane thickness, m
ε	exchanger effectiveness
η	thermal efficiency
ϕ	porosity
$\phi_{ch:m}$	non-dimensional resistance ratio
$\phi_{c:v}$	non-dimensional resistance ratio

Subscripts, superscripts

b	bulk stream
c	cold channel
ch	channel – feed, cold or gap
cond	conduction
crit	critical size
eff,m	effective property of membrane
f	feed channel
gap	gap between membrane and condensing surface
HX	heat exchanger
in	inlet
m	membrane
max	maximum
MD	membrane distillation module
min	minimum
out	outlet
p	permeate
ph	preheating stream
sat	saturated state
vap	vapor
VPD	vapor pressure depression
w	wall

1. Introduction

Membrane distillation (MD) is a thermal desalination technology that is especially promising for high-salinity streams of $s_f \approx 70$–300 g-salt/kg-solution, where conventional reverse osmosis is not currently applied. This study develops a unified analytical description of single-stage MD configurations based on the heat transfer resistances in various portions of the MD module. The configurations evaluated are direct contact, permeate or conductive gap, and air gap MD. Using this framework, two important aspects of designing efficient MD systems for desalination up to high salinity are analyzed:

1. the choice of the best MD configuration for a given desalination application; and
2. system design and operation that avoids conditions of low flux and low energy efficiency.

As a related exercise, a method to identify the cost-optimal membrane thickness is developed. The novelty of this work lies in developing a unified description of several single-stage MD configurations by replacing a large number of design and operation variables with a few dimensionless parameters, and deriving an expression for maximum allowable system area as a function of these parameters.

1.1. Context: desalination up to high salinity

Seawater, brackish groundwater, and municipal wastewater streams are commonly desalinated to produce potable grade water. In these cases, the maximum salinity of the brine is often restricted, by the available technology, to be less than 70 g/kg. In other applications (e.g., industrial zero-liquid-discharge, inland brine management, and concentration of produced water from hydraulic fracturing), brines with salinities between 50 g/kg and saturation concentration may have to be further desalinated. Conventional spiral wound reverse osmosis (RO), the workhorse of the desalination industry today, is typically operated below 70 bar of applied pressure [1]. As a result, RO is not directly applicable to desalination of these saltier streams for which the osmotic pressure can be as high as 300 bar [2].

Thermal separation processes such as mechanical vapor compression (MVC) are often used for such applications [3,4], since desalination up to saturation concentration is possible in these systems at low pressures and temperatures (<100 °C). More recently, humidification dehumidification desalination (HDH) [5–8] has been developed as simple, low capital-cost thermal technology for treating ultra-saline produced waters [9,10].

Membrane distillation (MD) is a thermally driven, scalable desalination process [11,12] that has been identified as a candidate