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Study of advancement to higher temperature membrane distillation

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ABSTRACT

It is well known that the mass flux (J) and the membrane thermal efficiency (η) of membrane distillation increase with the feed flow temperature. A comprehensive laminar and turbulent flow model for simulating and evaluating the performance of direct contact membrane distillation (DCMD) when operated at inlet feed temperature ($T_{f,i}$) from 80 °C to 180 °C, higher than the customary maximum of ~80 °C, was developed and used to explain and assess the performance of such high temperature DCMD, as well as the potential associated problems of the needed higher operating pressure, and provide knowledge useful for their future design and optimization. Some of the key results are that raising $T_{f,i}$ from 80 °C to 180 °C, increases J 9.4-fold, and η 2.1-fold, and decreases the specific energy consumption (*SEC*) 2.9-fold. Raising the flow Reynolds number from 1200 to 7000 increases J 2.6-fold and η by 15%, but *SEC* increases 2.3-fold. The needed system pressurization does not affect the process performance significantly. The higher operating temperatures also provide more practical opportunities for heat recovery, which could significantly further raise overall system efficiency.

1. Introduction and objectives

Membrane distillation (MD) is recognized as a thermally driven membrane separation process with many advantages [1–7], including the high purity of its product [2,6], as well as lower sensitivity to concentration polarization and fouling when compared to pressure driven membrane separation processes [1], its compact volume [3], and its capability to use low-temperature waste heat and/or renewable energy sources such as solar and geothermal energy. Typical feed solution temperatures for MD are below about 80 °C, which was mostly dictated by the tolerance of the separation membrane polymers. Notwithstanding the above mentioned advantages of using low temperature heat sources, it is widely published and known that the mass flux and the thermal efficiency of MD increase with the feed solution temperature [3,4]. Higher operating temperatures also provide more practical opportunities for heat recovery, which could significantly further raise overall system efficiency. The main objective and novel contribution of this study is therefore to explore the conditions, potential and consequences of raising the temperature above 80 °C for what is (arguably) the most used MD configuration called 'direct contact membrane distillation' (DCMD) in desalination MD, where, as shown in Fig. 1, the warm saline feedwater flows along one side of the separation membrane, while the colder fresh water product flows along its other (permeate) side.

It is noteworthy that while conventional MD, including DCMD, operates below the boiling temperature of the feedwater solution, which for saline water is associated with saturation pressures somewhat higher than atmospheric, increasing with salinity. Since boiling with the associated generation and motion of bubbles will disrupt the MD process (with yet-unknown consequences), operation at temperatures above the boiling temperature are conducted by raising the operating pressure to values above those of saturation corresponding the desired operating temperature. This study therefore also includes examination of pressure effects on the membrane transport.

There is much evidence, from both numerical simulations and experiments, of the above-mention flux and efficiency improvement trend with increasing of the feedwater temperature within the currently used low temperature range. For example, numerical analysis of DCMD has shown that increasing the feed temperature from 40 °C to 80 °C increases the permeate mass flux 4.6-fold and the below-defined membrane thermal efficiency (η) by 16% (from 77.1% to 89.5%) [4].

Furthermore, several experimental studies have been made of the mass flux of MD up to 128 °C at pressures up to 3 atm (~300 kPa), and thus verified the basic feasibility of successful operation at temperatures above the conventional 80 °C and well above atmospheric pressure. Reference [8] is a study of DCMD of a 1% NaCl solution using flat polytetrafluoroethylene (PTFE) membranes, and measured that raising the feed temperature from 80 °C to 95 °C elevated the vapor mass flux 4.6-fold, and that raising it from 110 °C to 128 °C elevated the vapor mass flux 1.9-fold. In [9] they used PTFE hollow-fiber DCMD and measured that raising the feed temperature

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Nomenclature

A	membrane area [m^2]
B	geometric factor [dimensionless]
C	membrane permeability [kg/(m^2·s·Pa)]
C_v	specific heat capacity at constant volume [J/(K·kg)]
C_p	specific heat capacity at constant pressure [J/(K·kg)]
d_p	membrane pore size [μm]
D	diffusion coefficient [m^2/s]
DCMD	direct contact membrane distillation
Eu	Euler number [dimensionless]
$\dot{E}_{des}$	exergy destruction rate [W]
$\dot{E}_{flow}$	rate of the overall flow exergy transfer [W]
$\dot{E}_{heat}$	thermal energy input rate needed to heat the fluid [W]
$\dot{E}_{input}$	exergy input rate [W]
$\dot{E}_{input}$	energy input rate [W]
$\dot{E}_{output}$	exergy output rate [W]
h_{ch}	channel height [m]
h_f	convective heat transfer coefficient of the feed stream [W/(m^2·K)]
h_m	conduction heat transfer coefficient of the membrane [W/(m^2·K)]
$h_{p.}$	convective heat transfer coefficient of the permeate stream [W/(m^2·K)]
H_m	total heat transfer coefficient of the membrane [W/(m^2·K)].
J	mass flux [kg/(m^2·s)]
k	thermal conductivity [W/(m·K)]
k_g	thermal conductivity of the gas present in the pores [W/(m·K)]
k_{me}	effective membrane thermal conductivity [W/(m^2·K)]
k_s	membrane material thermal conductivity [W/(m^2·K)]
LEP	liquid entry pressure [Pa]
l_{ch}	module length [m]
M	molecular weight of vapor [kg/mol]
MD	membrane distillation
$\dot{m}_d$	mass flow rate of the distillate [kg/s]
P	total pressure [Pa]
PP	polypropylene
Pr	Prandtl number [dimensionless]
PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride
$p_{f,m}$	vapor pressure at the membrane feed-side surface [Pa]
$p_{p.,m}$	vapor pressure at the membrane permeate-side surface [Pa]
p_{air}	average partial pressure of the non-condensable gas in the membrane [Pa]
$p_{v,w}$	vapor pressure of pure water [Pa]
$p_{v,sw}$	vapor pressure of sea water [Pa]
p_{sat}	saturation pressure at the feed inlet [Pa]
q_c''	heat flux across the membrane by conduction [W/m^2].
q_v''	heat flux across the membrane by evaporation [W/m^2].
q_{mem}''	heat flux across the membrane [W/m^2].
q_t''	total heat flux across the membrane [W/m^2].
r	average pore radius [m]
R	ideal gas constant [J/(mol·K)]
Re	Reynolds number [dimensionless]
S	salinity [g/kg]
SEC	specific energy consumption [J/kg]
Sc	Schmidt number [dimensionless]
SXC	specific exergy consumption [J/kg]
T	temperature [K]
T_g	glass transition temperature [K]
u	velocity [m/s]
$\dot{V}$	volumetric flow rate [m^3/s].
w	mass fraction [%]
$\dot{W}_{pump}$	pump work needed to pressurized the fluid [W].

Greek

γ_L	liquid surface tension [N/m]
δ	membrane thickness [m]
ΔH_{fg}	specific enthalpy of vaporization [J/kg]
ΔJ	difference between J corresponds to the highest $T_{f,i}$ and J corresponds to the lowest $T_{f,i}$ [kg/(m^2·s)]
ΔP_{inter}	pressure difference at liquid/gas interface [Pa].
$\Delta T_{f,i}$	difference between the highest $T_{f,i}$ and the lowest $T_{f,i}$ [K]
ε	membrane porosity [dimensionless]
θ	membrane/liquid contact angle [° or rad]
η	membrane thermal efficiency [dimensionless]
μ	viscosity [Pa·s]
ρ	density of the fluid [kg/m^3]
ψ	exergy efficiency [dimensionless]
γ	pump efficiency [dimensionless]
χ	membrane tortuosity [dimensionless]
Ω	relative heat transfer resistance [dimensionless]

Subscript

f,i	feed inlet
f,m	feed/membrane interface
i	inlet
mem	membrane
p,i	permeate inlet
p,m	permeate/membrane interface
pro	product
0	dead state

Superscript

*	dimensionless value

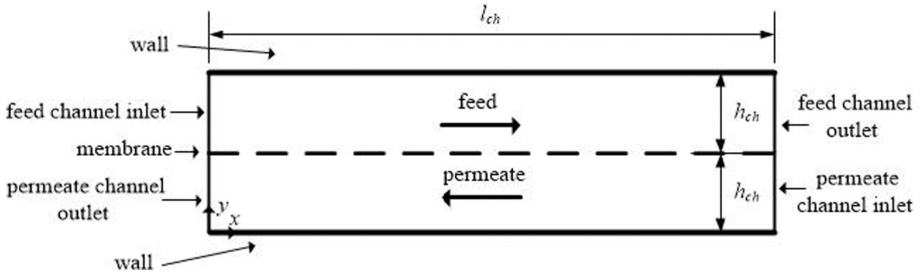

Fig. 1. Schematic of the studied DCMD module.