Journal of Membrane Science 524 (2017) 151–162

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Membrane distillation against a pressure difference

L. Keulen[a,1], L.V. van der Ham[b], N.J.M. Kuipers[c], J.H. Hanemaaijer[c], T.J.H. Vlugt[a], S. Kjelstrup[a,d,*]

[a] Department of Process and Energy, Delft University of Technology, Leeghwaterstraat 39, 2628CB Delft, The Netherlands
[b] Department of Process and Instrument Development, Netherlands Organisation for Applied Scientific Research, TNO, 2628CA Delft, The Netherlands
[c] Department of Water Treatment, Netherlands Organisation for Applied Scientific Research, TNO, 3704HE Zeist, The Netherlands
[d] Department of Chemistry, Norwegian University of Science and Technology, NTNU, NO-7491 Trondheim, Norway

ARTICLE INFO

Keywords:
Membrane distillation
Water desalination
Heat and mass transfer
MemPower
Irreversible thermodynamics

ABSTRACT

Membrane distillation is an attractive technology for production of fresh water from seawater. The MemPower® concept, studied in this work, uses available heat (86 °C) to produce pressurized water (2.2 bar and 46 °C) by membrane distillation, which again can be used to power a turbine for co-production of electricity. We develop a non-equilibrium thermodynamic model to accurately describe the transfer at the liquid-membrane interfaces, as well as through the hydrophobic membrane. The model can explain the observed mass flux, and shows that 85% of the energy is dissipated at the membrane-permeate interface. It appears that the system's performance will benefit from a lower interface resistance to heat transfer, in particular at the permeate side of the membrane. The nature of the membrane polymer and the pore diameter may play a role in this context.

1. Introduction

Fresh drinking water is essential for life on earth. We need water to survive, not only as drinking water, but also in food production, washing, industry, etc. According to the United Nations, the increase in potable water use was more than twice the rate of the population increase in the last century [1]. By 2025, an estimated 1.8 billion people will live in areas with water scarcity, and two-thirds of the world's population will be living in water-stressed regions as a result of water use, growth and climate change [1]. New solutions are therefore needed to decrease the scarcity of clean water in the world. Nearly 70% of the earth is covered by water, but only 2.5% of that water is fresh and usable for consumption, and only 1% of the fresh water is easily accessible [2]. The rest is trapped in glaciers or snowfields.

Consequently, fresh water produced from seawater and brackish water becomes increasingly important. Between 1% and 2% of the fresh water used as drinking or process water, is extracted from brackish and saline water [3]. In 2006, the desalination capacity worldwide was 40 million m^3/day [3]. In 2011 it had increased to almost 70 million m^3/day [3]. Many desalination processes exist, for example multi-stage flashing, multi-effect distillation, reverse osmosis, electro-dialysis or membrane distillation. The driving forces for these processes are either thermal, osmotic or electrical. The challenge in all cases is to obtain reasonable energy input and equipment costs per amount of fresh water produced.

Membrane distillation (MD) is attractive in this context, because of its possibility to use low grade waste heat as energy source in the production of drinking water. The first publication on MD dates back to the sixties of the last century [4]. Water vapor is transported through a membrane, driven by a temperature difference. The membrane pores are filled with water vapor, in contrast to other techniques, where water is transported in the liquid phase. Presently, MD is nearly commercial. The technology is competitive with reverse osmosis for low heat costs and feedstock with high osmotic pressures. The possibility to fully understand and possibly improve the attractive MD process has motivated the present study of a new invention, namely the MemPower® process concept [3,5–8]. Fig. 1 provides a schematic illustration of the MemPower concept [8], when used for seawater desalination. It produces fresh water against a hydrostatic pressure difference with the help of a thermal driving force. An aqueous feedstock with hydrostatic pressure $P_{\mathrm{total},2}$ (e.g. seawater) is first heated to temperature T_2, e.g. by utilizing low grade heat. During normal operation, water is transported against a pressure difference, $P_{\mathrm{total},3}$ - $P_{\mathrm{total},2}$, due to the transport of the latent heat of water down the temperature gradient. The positive temperature difference, $T_2 - T_3$, can be said to drive the desalination process, producing distilled water on the permeate side. The figure to the right shows the pressure of the distillate, $P_{\mathrm{total},3}$, maintained by throttling of the effluent valve on this

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[*] Corresponding author at: Department of Chemistry, Norwegian University of Science and Technology, NTN, NO-7491 Trondheim, Norway
E-mail addresses: luuc.keulen@polimi.it (L. Keulen), signe.kjelstrup@ntnu.no (S. Kjelstrup).
[1] Current affiliation: Department of Aerospace Science and Technology, Politecnico di Milano, 20156 Milano, Italy.

http://dx.doi.org/10.1016/j.memsci.2016.10.054
Received 5 July 2016; Received in revised form 28 October 2016; Accepted 31 October 2016

Nomenclature

B	membrane permeability, m^2K J/K mol s
c_w	concentration of water, mol/m^3
D_w	Fick's diffusion coefficient for water vapor, m^2/s
d	thickness, m
H_j	molar enthalpy of component j, J/mol
$H_{j,T}$	molar enthalpy of component j at temperature T, J/mol
$\Delta H_{vap,j}$	enthalpy of evaporation of component j, J/mol
J	general symbol for flux
J_j	flux of component j, mol/s m^2
J_q	thermal energy flux, J/s m^2
J'_q	measurable heat flux, J/s m^2
k_B	Boltzmann constant, $1.3807 \cdot 10^{-23}$ kg m^2/s^2 K
L	mean free path, m
$\dot{m}$	mass flow, kg/s
M_j	molar mass of component j, kg/mol
n	number of borders between control volumes, dimensionless
N	number of control volumes, dimensionless
P	total pressure, N/m^2
p_w^*	vapor pressure of water at saturation, N/m^2
q^*	heat of transfer, J/mol
r_{mn}	local resistivity coefficient, coupling force m to flux n
R	universal gas constant, 8.3145 J/K mol
R^{tot}	resistivity matrix for global description of system
T	absolute temperature, K
x	coordinate axis for transport, m
X_i	general symbol for driving force no i

Greek symbols

$\Delta_{ab} Y$	difference in property Y: $Y_b - Y_a$
λ	thermal conductivity, J/s K m^2
μ_j	chemical potential of component j, J/mol
$\mu_{j,T}$	chemical potential of component j at temperature T, J/mol
σ	local entropy production, J/K m^3 or J/K m^2
ε	membrane porosity, dimensionless
Ω	membrane cross-sectional area, m^2

Sub- and superscripts

0	reference point or ideal gas state
a,b,c,d	points on the x-axis
CV	control volume
i,j	component indices
h	homogeneous face
k	control volume index
l	liquid
mem	membrane
per	permeate
q	thermal energy or measurable heat
ret	retentate
s	interface
T	temperature
tot	total
vap	vapor
w	water

side. The pressure $P_{total,3}$ is larger than the hydrostatic pressure on the feed side $P_{total,2}$, meaning that water transport takes place against a pressure difference. It is indicated in the concept, Fig. 1 on the left, that the pressurized distillate can be used to drive a turbine to generate hydroelectric power. The power density is the turbine efficiency times the pressure difference and the volumetric flow of distillate. The net effect of this, is that (waste) heat can be used to produce drinking water as well as hydroelectric power. The process will continue until an upper pressure, the so-called break-through pressure of the membrane, is reached. At this pressure, the pores become wetted, causing liquid water to flow back via the membrane from the distillate to the feed.

Typical temperature and pressure variations under operation are

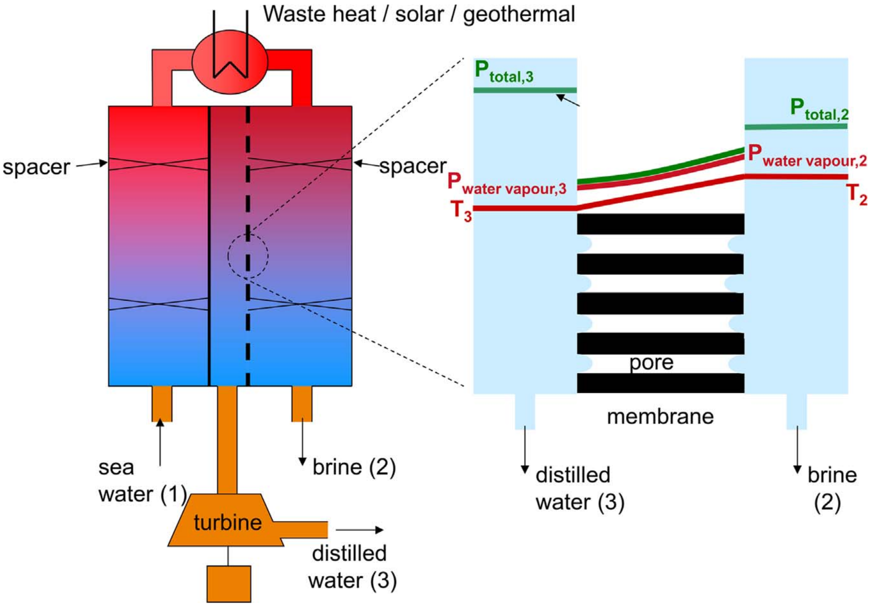

Fig. 1. Schematic representation of the MemPower concept [8] as applied to seawater desalination. Cold seawater enters the feed side, at (1) to the left in the figure, and flows through a compartment with non-permeable walls, where it is preheated by a counter-currently flowing stream at the permeate side. The preheated seawater is further heated by an external heat source, which can be waste heat from the industry, solar or geothermal energy. The heated seawater enters the retentate side of the system (2) with pressure $P_{total,2}$, where the water will partially evaporate and pass through membrane pores to the permeate side, at (3) in the figure, due to the temperature difference $T_3 - T_2$. The permeate compartment is shown in the center of the figure to the left, as well as in the enlargement to the right hand side figure. The water vapor condenses to yield distilled water at the permeate side at the hydrostatic pressure $P_{total,3}$. The distilled water is heated by the latent heat freed by condensation and heat conducted via the membrane material.