Desalination 417 (2017) 9–18

Contents lists available at ScienceDirect

Desalination

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

Spacer optimization strategy for direct contact membrane distillation: Shapes, configurations, diameters, and numbers of spacer filaments

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ARTICLE INFO

Keywords:
Spacer
Optimization
Direct contact membrane distillation
Computational fluid dynamics
Desalination

ABSTRACT

The decrease of vapor flux in a direct contact membrane distillation (DCMD) system is usually triggered by temperature polarization (TP) and concentration polarization (CP). Optimal spacer design is therefore essential to minimize vapor flux decrease. In this study, a numerical DCMD model was developed using computational fluid dynamics. Using a simultaneous evaluation of the effects of TP, CP, and spacer shape and configuration on vapor flux, shear stress and hydraulic pressure drop, the model seeks an optimal manufacturable spacer design. Fifty-one different spacer designs were comprehensively compared after model validation. Based on the simulation results, a symmetric circular-zigzag configuration of spacers gives the best performance for vapor flux, 26% higher than an empty channel. Spacer design optimization was conducted with reference to various sizes and number of spacer filaments. In conclusion, with relatively expensive heat sources, a symmetric circular-zigzag spacer design with a larger diameter and more filaments can be theoretically recommended to maximize vapor flux; in contrast, with cost-free heat sources, a smaller diameter size and fewer filaments can be theoretically recommended to minimize hydraulic pressure drop. In addition, the model outlined in this study could be used to evaluate the performance of other membrane processes associated with spacers.

1. Introduction

With increasing industrialization and urbanization, there has been a significant growth in the global demand for water over the past few decades [1,2]. Desalination technologies have been used as a solution to water stress in many countries to ensure an adequate water supply [3–6]. Large-scale thermal desalination plants were introduced in the 1950s. Middle Eastern countries contributed to the initial development and implementation of thermal seawater desalination processes, such as multi-effect distillation (MED) and multi-stage flash (MSF). Recently, in conjunction with significant technological advances, the reverse osmosis (RO) process has gained popularity in the seawater desalination market due to its low energy consumption [3,7]. Despite significant progress in the RO process, a number of other ways to increase the recovery rate of desalination and to reduce energy consumption have also been explored. One such potential solution is membrane distillation (MD). The MD process combines the advantages of thermal process and membrane processes: it can be driven with a lower temperature difference than traditional distillation processes, and with a lower operating hydraulic pressure than pressure-driven membrane desalination processes. It also provides high quality water, a low impact from feed water concentrations, and so on [8]. Therefore, MD can be considered as a promising new desalination process for producing high quality water from saline water. Where the major permeate component is water, as in desalination, direct contact membrane distillation (DCMD) has been highlighted from a range of other MD processes [8].

The driving force behind the DCMD process is the vapor pressure difference between feed and permeate solutions. The vapor pressure difference is caused by temperature differences. Therefore, temperature polarization (TP) should be given serious consideration. TP is a phenomenon where the temperature difference between membrane surfaces is lower than the bulk temperature difference due to heat conduction and evaporation [9]. TP reduces DCMD performance because it leads to lower vapor pressure difference. At the same time, concentration polarization (CP) occurs in the vicinity of the membrane. CP is induced by vapor transfer across the membrane, which concentrates the feed concentration in the membrane vicinity. As a result, CP decreases water vapor flux because of lower vapor pressure caused by

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http://dx.doi.org/10.1016/j.desal.2017.05.009
Received 2 December 2016; Received in revised form 28 April 2017; Accepted 8 May 2017

Nomenclature

A_A	Constant for Antoine equation
B_A	Constant for Antoine equation
c	Concentration (M, mol/m^3)
C_p	Specific heat at constant pressure (J/kg·K)
C_A	Constant for Antoine equation
C_{MD}	Membrane distillation coefficient (kg/m^{2}Pa·s)
d	Spacer filament diameter (m)
D	Diffusion coefficient (m^2/s)
$\mathbf{F}$	Volume force vector (N/m^3)
h	Channel height (m)
$\mathbf{I}$	Identity tensor
J	Vapor flux (kg/m^2 s)
k	Thermal conductivity (W/m·K)
L	Channel length (m)
M_w	Molecular weight of water (kg/mol)
p	Hydraulic pressure (Pa)
P	Vapor pressure of solution (Pa)
Q	Heat source (sink) (W/m^3)
Q_{flow}	Volumetric flow rate (ml/min)
Q_m	Heat flux across the membrane (W/m^2)
r	Membrane pore radius (m)
R	Gas constant (J/mol·K)
R_i	Reaction rate (mol/m^3 s)
T	Temperature (K)
$\mathbf{u}$	Velocity vector (m/s)
v	Velocity (m/s)
w	Channel width (m)

Greek symbols

α	Coefficient of Knudsen diffusion model
β	Coefficient of Poiseuille flow model
δ	Membrane thickness (m)
ε	Porosity
η_{gas}	Gas viscosity (N·s/m^2)
λ	Heat of vaporization (J/kg)
ξ	Auxiliary variable for integration
ρ	Density (kg/m^3)
τ	Tortuosity
$\boldsymbol{\tau}$	Viscous stress tensor (Pa)
x	Mole fraction

Subscripts

A	Antoine equation
fin	Feed channel inlet
$fout$	Feed channel outlet
fm	Feed solution–membrane interface
i	Ion species
m	Membrane
$mean$	Mean value
pin	Permeate channel inlet
pm	Permeate solution–membrane interface
s	Solid
v	Vapor

Mathematical operators

∇	Del
$\cdot$	Dot

higher solute concentrations.

To enhance performance by reducing TP and CP, many researchers have studied the effect of spacers on vapor flux in the DCMD process [10–26]. Previous studies have shown that a spacer can reduce TP and CP by mixing and changing the flow path of the solution [19,25,27,28]. To effectively reduce TP and CP, and to evaluate the performance of a spacer-filled DCMD process, the shape and configuration of the spacer should be taken into account simultaneously with mass, momentum, and heat transports.

In this study, various shapes and configurations are explored in order to determine optimal spacer design with regards to TP and CP. Spacer-filled DCMD models simultaneously simulate mass, momentum, and heat transports under various conditions with experimental studies. In addition, various diameter size and the number of spacer filaments in a channel are considered with respect to two different heat source scenarios. Based on the results, this study can be applied to the selection

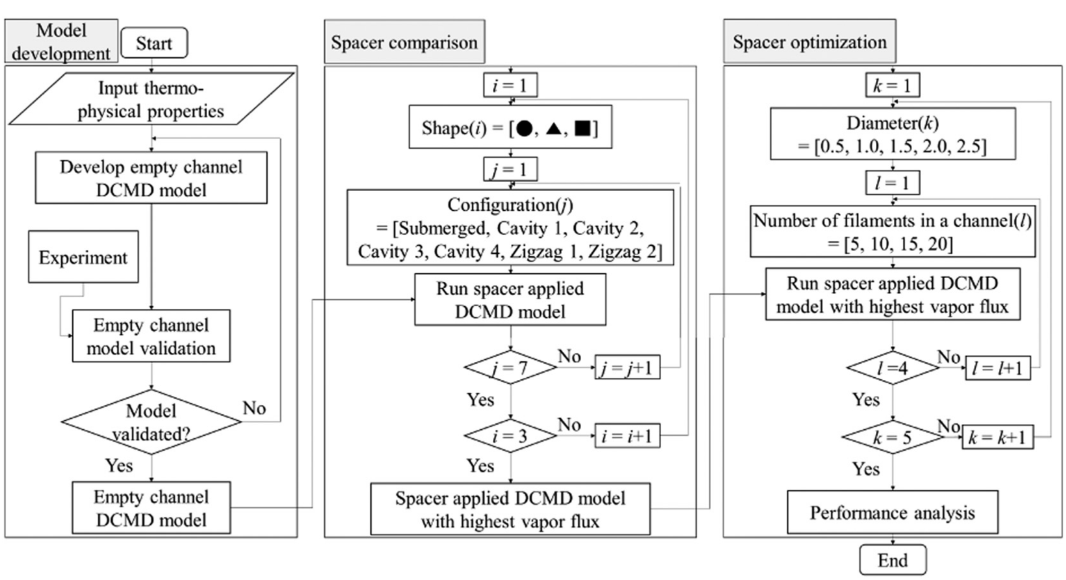

Fig. 1. Flow chart of the spacer design optimization strategy for the DCMD system.