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Effect of feed flow pattern on the distribution of permeate fluxes in desalination by direct contact membrane distillation

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ABSTRACT

The current study aims to highlight the effect of flow pattern on the variations of permeate fluxes over the membrane surface during desalination in a direct contact membrane distillation (DCMD) flat module. To do so, a three dimensional (3D) Computational Fluid Dynamics (CFD) model with embedded pore scale calculations is implemented to predict flow, heat and mass transfer in the DCMD module. Model validation is carried out in terms of average permeate fluxes with experimental data of seawater desalination using two commercially available PTFE membranes. Average permeate fluxes agree within 6% and less with experimental values without fitting parameters. Simulation results show that the distribution of permeate fluxes and seawater salinity over the membrane surface are strongly dependent on momentum and heat transport and that temperature and concentration polarization follow closely the flow distribution. The analysis reveals a drastic effect of recirculation loops and dead zones on module performance and recommendations to improve MD flat module design are drawn consequently.

1. Introduction

Membrane distillation (MD), among the most promising separation techniques for its low cost operation, has achieved the prototyping stage. There is now a need for proper MD module design for efficient process integration and scale-up [1–5]. MD is a thermal process and it is now well established that flow rate and inlet temperatures have a major impact on resulting permeate fluxes, thus performance. However, as in any chemical process equipment, flow distribution in MD remains driven by module design, such as its length, feed/permeate channel height, fluid inlet and outlet location, as well as operating conditions including inlet temperatures and fluid flow rate. Computational Fluid Dynamics (CFD) codes, which are available in commercial or open source versions, are now used in MD to assess process and equipment performance [6–16]. These codes, when associated with powerful mesh generators and post-processors, solve coupled momentum, heat and species transport to provide critical information, including, fluid velocity, pressure, temperature and chemical species distribution in complex computational domains. This information can then be used judiciously to improve process design and efficiency while reducing costly experimental trials. Generally, the flow approach for full size equipment is similar in all research efforts with an imposed velocity at the inlet and no slip boundary condition at the domain walls. However, the difficulty in CFD modeling of MD often lies in the choice of the boundary condition for the heat transfer problem. The nonlinear heat transfer mechanism across the membrane represents the major hurdle in DCMD analysis with contribution from both conduction and mass transfer. The difficulty in the calculation of the surface temperature at both sides of the membrane pushed researchers to tackle the task as a conjugate heat transfer problem by including the permeate side in the computational domain. However, commercial codes do not always offer easy implementation options to account for mass transfer contribution to heat transfer across the membrane. Early use of commercial CFD codes for DCMD was demonstrated by Katsandri and Vahdati [17], who performed 3D simulations of flat membrane module with spacers using ANSYS CFX. Yu et al. [18] used fluent 6.3 to investigate hollow fiber DCMD module by considering a constant mass transfer coefficient. Cipollina et al. [11] used the commercial software ANSYS CFX11.0 to simulate flow and heat transfer and assigned a constant heat flux at the domain boundaries. Similarly, *Al*-Sharif et al. [6] adopted a 3D approach in which they used OpenFOAM, an open source CFD code, and assigned a constant heat flux as a boundary condition for heat

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Nomenclature

a	coefficient in Antoine's equation
b	coefficient in Antoine's equation
c	coefficient in Antoine's equation
c_p	specific heat at constant pressure
c_{pv}	vapor specific heat
d_h	hydraulic diameter
h	convective heat transfer coefficient
h_{ext}	external heat transfer coefficient
k	turbulent kinetic energy
l	characteristic length
m_w	weight of collected permeate
p	fluid pressure
r	pore radius
s	salinity
t	time interval
u	fluid velocity
$\bar{u}$	mean fluid velocity
u'	fluid fluctuating velocity
v_i	fluid inlet velocity
w	species mass fraction
z	charge of salt ion
A	effective membrane area
A_{c_p}	coefficient in specific heat equation
A_μ	coefficient in water viscosity equation
B_{c_p}	coefficient in specific heat equation
B_μ	coefficient in water viscosity equation
C	membrane mass transfer coefficient
$C_{1\varepsilon}$	constant in k-ε turbulence model
$C_{2\varepsilon}$	constant in k-ε turbulence model
C_{c_p}	coefficient in specific heat equation
C_μ	constant in k-ε turbulence model
D	species diffusion coefficient in the feed
D_{c_p}	coefficient in specific heat equation
D_s	species diffusion coefficient in pores
G_k	generation of turbulent kinetic energy
H	fluid enthalpy
H_L	enthalpy of the permeate solution
H_v	vapor enthalpy
J	mass permeate flux
J_v	experimental water vapor flux
M	molecular weight
Nu	Nusselt number
P	vapor pressure
P_a	air pressure inside pores
P_{mf}	vapor pressure at the feed side of the membrane
P_{mp}	vapor pressure at the permeate side of the membrane
P_{sw}	seawater vapor pressure
Pr	Prandtl number
$\mathrm{Pr_t}$	turbulent Prandtl number
Q_c	heat transferred by conduction across the membrane
Q_f	convective heat transferred from the feed to the membrane
$Q_f{}^m$	heat due to mass transfer from the feed to the membrane
Q_p	heat transferred from the membrane surface to the permeate side
$Q_p{}^m$	heat due to mass transfer from the membrane to the permeate side
Q_v	heat due to vapor transport across the membrane
R	ideal gas constant
Re	Reynolds number
R_m	membrane total resistance to heat transfer
R_p	permeate side resistance to heat transfer
S	modulus of mean rate of stress tensor
$\mathrm{Sc_t}$	turbulent Schmidt number
S_{ij}	mean strain rate
T	temperature
T_{av}	average temperature inside the pore
T_{ext}	permeate bulk temperature
T_f	feed temperature
T_{face}	temperature of mesh boundary face
T_i	fluid inlet temperature
T_{mf}	temperature at the membrane surface on the feed side
T_{mp}	temperature at the membrane surface on the permeate side
T_p	permeate temperature
T_w	boundary temperature

Greek letters

δ_m	membrane thickness
δ_{ij}	Kronecker delta
ε	turbulent kinetic energy dissipation
ε_m	membrane porosity
ξ	pore tortuosity
λ_g	thermal conductivity of the membrane fluid phase
λ_m	membrane composite thermal conductivity
λ_s	thermal conductivity of the membrane solid phase
λ_{sw}	thermal viscosity of seawater
ρ	feed density
μ	fluid viscosity
μ_r	correction for seawater viscosity
μ_{sw}	seawater viscosity
μ_t	fluid turbulent viscosity
μ_w	water viscosity
σ_ε	constant in k-ε turbulence model
σ_k	constant in k-ε turbulence model
τ_C	concentration polarization coefficient
τ_T	temperature polarization coefficient

transfer. Shakaib et al. [8] used the commercial code FLUENT 6.3 and assigned a constant heat flux at the boundaries. Yu et al. [9] used FLUENT 6.3 assuming a constant membrane coefficient, which sets the rate of species transferred through the membrane thus the vaporization rate. Janajreh and Suwwan [19] presented a coupled approach taking into account both feed and permeate sides of the module. The authors update the temperature profiles after accounting for the latent heat of vaporization and re-run the flow model. However, the frequency of the temperature profile update is not mentioned and the authors present only two-dimensional simulations. Later, the authors validated a conjugate approach on a flat DCMD module [20]. More recently, Katsandri [21] circumvented ANSYS CFX restriction by applying appropriate heat and mass transfer fluxes at the interface between feed and permeate domains. Chang et al. [22,23] used fluent 6.3 to analyze flow in DCMD channels with and without spacers. The contribution of mass transport to heat transfer across the membrane was considered as source terms at both membrane sides. In a more recent contribution the authors investigated heat transfer coefficients in flat DCMD modules [24]. Hasanizadeh et al. [25] used COMSOL v3.4 to model a 2D representation of a flat DCMD module. However, their model does not include the contribution of vapor transport to overall heat transfer across the membrane. Further contributions can be found in a detailed review by Shirazi et al. [26] which reports the current state of the art of CFD modeling in MD. Interestingly, the authors state that although only temperature polarization is known to significantly affect the MD process, mass transfer should be included for an in-depth understanding