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Thermal efficiency enhancement of the direct contact membrane distillation: Conductive layer integration and geometrical undulation☆

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HIGHLIGHTS

- Presented validated high fidelity simulation of Direct Contact Membrane Distillation.
- Assessed the DCMD performance at different flow velocities and temperatures.
- Evaluated DCMD metrics: Mass-flux, thermal-efficiency and polarization coefficients.
- Improved DCMD efficiency using undulated channel with integrated conductive layer.

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ABSTRACT

The roles of high conductive layer integration and geometry undulation are investigated in order to improve the performance of the direct contact membrane distillation processes. In particular, the temperature polarization coefficient, mass flux and thermal efficiency are evaluated for the baseline and undulated flow under integrated superconductive layer membrane. This work caters for experimental and numerical model development. Experimentally, a countercurrent flow module for the desalination of sea water was developed using a flat-sheet electro-spun Polyvinylidene fluoride membrane generated and characterized by the author's group for model validation. A steady state, conjugated heat, Navier-Stokes flow model computational fluid dynamics model was developed and subjected to the exact thermal and velocity flow conditions. The setup comprises two adjacent channel flows representing the hot saline feed and the cold fresh permeate channels. The two channels are thermally coupled through the hydrophobic membrane that is equipped with superconductive feathering layers. The results show agreement between the numerical model and experimental model measurements for the surface temperature distribution and the inferred temperature polarization co-efficient. In view of these plausible results and in line with numerous works on direct contact membrane distillation, a combined Knudsen and Poiseuille flow model is integrated to estimate the permeated mass and heat flux and explore improving the Membrane Distillation system in terms of thermal efficiency. While the role of superconductive feathering showed insignificant improvement in the temperature polarization coefficient, mass flux and thermal efficiency, the effect of combined undulated channels geometry was more pronounced. The gain obtained in the mass flux reaches 5.8% at lower feed temperature (50 °C), which is associated with a 5.8% gain in thermal efficiency and a 9.5% gain in temperature polarization co-efficient. It reaches a 6.1% gain in mass flux and thermal efficiency and a 9.5% gain for temperature polarization co-efficient at a higher feed inlet temperature.

1. Introduction

In countries that are highly dependent on sea water, inefficient desalination is a major concern. In the Gulf region, where up to 98% of water is based on desalination, further optimization of the techniques is required to meet the ever increasing demand for clean water and to reduce its production cost. Currently, desalination is being heavily carried out using membrane technologies. Some examples of these technologies are Micro-Filtration (MF), Ultra-Filtration (UF), Reverse Osmosis (RO) and Membrane Distillation (MD) [1]. Among these options, there are several reasons as to why MD is proving to be a more effective choice.

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Nomenclature

x, y	Spatial independent variable (m)
ρ	density (kg/m^3)
u, v	axial and perpendicular velocity components (m/s)
P	thermodynamic pressure (Pa)
g	gravitational acceleration
K	thermal conductivity (W/m·K)
C_p	specific heat capacity (W/kg·K)
T	temperature (T)
J″	mass flux Kg/m^2·h
c_m	mass transfer coefficient
P_f^{sat}	saturation pressure of the water at the feed side (Pa)
P_p^{sat}	saturation pressure of the water at the permeate side (Pa)
c_k	Knudson mass transfer coefficient (dimensionless)
c_p	Poiseuille mass transfer coefficient (dimensionless)
S_h	the source heat term associated with the energy equation
k, k_g, k_b	thermal conductivity and g and b signifies the vapor and bulk (W/m ·K)
$\alpha(T)$	Knudson temperature dependency factor (dimensionless)
$\beta(T)$	Poiseuille temperature dependency factor (dimensionless)
ϵ	porosity (dimensionless)
r_p	average pour radius (nm)
τ	tortuosity (dimensionless)
δ_m	membrane thickness (μm)
R	Universal gas constant (J/mol·K)
M_w	water molecular weight
P_m	average thermodynamic pressure across the membrane (Pa)
T_m	average temperature across the membrane (T)
μ	molecular viscosity (pa·s)
Δ_H	change in the enthalpy (J/kg·K)
$H_{m,f}$	enthalpy of the feed water side of the membrane (J/kg·K)
$H_{m,p}$	enthalpy of the permeate water side of the membrane (J/kg·K)
Q_v, Q_c	latent heat of vaporization and conductive Heat flux (J/kg·K)
$T_{m,p}$, $T_{m,f}$	permeate membrane surface temperature and feed membrane surface temperature (T)

Although MD is thermally driven, it is characterized as a low energy process in comparison to the pressure driven processes [2]. MD is beneficial due to its ability to use low grade energy, which can either be sourced as co-generation from power plants or from other industrial processes sensible heat [3]. This renders the MD process less expensive. Renewable energy, i.e. solar, geothermal, wind or wave energy can also provide the MD process energy needed [4–6]. In two MD streams of water, the feed and permeate are made to flow either parallel or countercurrent to each other while being separated by a membrane. The feed is the elevated temperature stream, while the permeate is colder stream. The membrane that plays the most important role in this technical process is a hydrophobic porous sheet, with its pores hypothetically filled with air [7]. The vapor pressure difference between the streams drives the vapor from the feed to permeate [8,9]. The hydrophobicity of the membrane causes surface tension which restricts the aqueous feed from entering the membrane's pores. This is a non-isothermal process. As the feed is heated the vapor pressure increases, leading to better transport through the porous membrane and ultimately higher flux [10].

MD has been carried out in various pieces of work with some process variations. Four types of MD have been reported: Air Gap Membrane Distillation (AGMD), Vacuum Membrane Distillation (VMD), Sweep Gas Membrane Distillation (SGMD) and Direct Contact Membrane Distillation (DCMD) [2,11]. DCMD is the only process in which the feed and permeate are in direct contact with the membrane. This makes the evaporation and condensation closer to each other and reduces the setup size and rendering compactness of the DCMD. Nearly 100% rejection of dissolved solids has been reported with DCMD [12,13]. There have been many experimental works to analyze and optimize the DCMD process, however a faster and simpler option is a validated numerical simulation.

Bui et al. [14] worked on developing a mathematical model of the heat and mass transport processes in DCMD, with a hollow fiber membrane. The model was used to study the effect of the length and tortuosity of the fibers. Their results showed a linear relationship between the heat and mass transfer. Chen et al. [15] developed a 2D mathematical model to predict the temperature polarization in DCMD process. Their model was based on Knudsen flow and Poiseuille for membrane coefficient estimation. They designed a flat plate type DCMD setup for validation of their model, achieving theoretical and experimental agreement. Their model was used to study the effect of saline water temperature and volumetric flow rate on pure water production and hydraulic energy dissipation. An increase in saline water temperature and volumetric flow rate showed an increase in pure water flux due to the lowering of the thermal boundary layer and trans-membrane pressure incremental difference. They assumed a laminar flow model in their simulation. Amir et al. [16] studied the effect of feed temperature, feed circulation rate and feed inlet concentration on permeate flux in DCMD using a numerical heat and mass transfer model developed in MATLAB. The effect of these parameters on the temperature and concentration polarizations has been studied. The physical and flow property variations with temperature and heat transfer coefficients were also considered. The influence of mass transfer on heat transfer coefficients and heat transfer rates was also studied. They found that the feed temperature showed significant effects on temperature polarization coefficient (TPC) as compared to feed inlet concentration. Apart from mathematical modelling, Computational Fluid Dynamics (CFD) is also being used to analyze the performance of DCMD. Yu et al. [17] carried out a comprehensive analysis of heat and mass transfer in DCMD with hollow fiber modules using CFD. They studied the effect of intrinsic mass transfer coefficient of the membrane on the temperature polarization coefficient. The effect of operating temperature on heat and mass transfer was also considered. They found that the TPC decreased significantly with increase in intrinsic mass transfer coefficient of the membrane. They also found that higher operating temperatures lead to increased heat and mass transfer and thermal efficiency, even with a small temperature difference of 10 K.

Turbulence plays a major role in increasing mass flux and efficiency, and thus extensive research on turbulence enhancers is critical. With the enhanced convenience provided by CFD modelling, it has become easy to design turbulence of flow in the channels and this option must be exploited. Work by Yang et al. [18] has used CFD to model a 2D heat transfer system in a hollow fiber DCMD setup to analyze effect of heat transfer on module performance. They also studied the effect of turbulence promoters, achieving a 6-fold increase in heat transfer coefficient with optimal turbulence promoters. They also found a 57% and 74% respective increase in TPC and mass flux with the addition of turbulence parameters. Zhang et al. [19] have also worked on a conjugate heat flow model for DCMD. In very recent work by Chang et al. [20], the effect of spacers as turbulence promoter was analyzed through CFD modelling. They tested three different DCMD modules, where one was normal and two others had cylindrical spacers in different orientations. The concluded that spacers enhance heat transfer in the DCMD module and the extent of which depends on the spacer geometry and Reynold's number of the fluid. The importance of creating turbulence was also emphasized by the work of Aikaterini Katsandri [21],