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CFD study of heat transfer enhanced membrane distillation using spacer-filled channels

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Abstract

Membrane distillation (MD) can utilize low level thermal energy and holds high potential to replace conventional energetically intensive separation technologies. Direct contact membrane distillation (DCMD) is suitable for the applications of desalination and concentration of aqueous solutions. Employing spacer-filled channels can enhance the mass flux of the DCMD modules, which can further result in the increase of energy utilization efficiency of the separation. The trans-membrane mass flux is controlled by the boundary layer heat transfer of both fluid channels. The estimation of heat transfer coefficients is critical to the analysis and design of MD modules. This paper presents the results of a comprehensive 3-D computational fluid dynamics (CFD) simulation which covers the entire length of the module and takes into account the trans-membrane heat and mass transfer. The model was verified with experimental data in the literature. The contour maps show that spacers create high velocity regions in the vicinity of the membrane. The trans-membrane heat and mass fluxes both show fluctuating patterns corresponding to the repetitive structure of the spaces and the fluxes are much higher than that of the modules using empty channels. The heat transfer coefficient enhancement factors obtained from CFD simulation are significantly higher than the predictions from literature correlations. The model can serve as an effective tool for developing correlations of heat transfer coefficients and optimal design of spacer-filled MD modules.

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Keywords: Computational fluid dynamics, Membrane distillation, Heat transfer, Spacers

1. Introduction

Membrane distillation is a process that utilizes differences in vapor pressure to permeate water through a porous membrane and reject other non-volatile constituents present in the influent. Direct contact membrane distillation (DCMD), in which the membrane is in direct contact with liquid phases, is the

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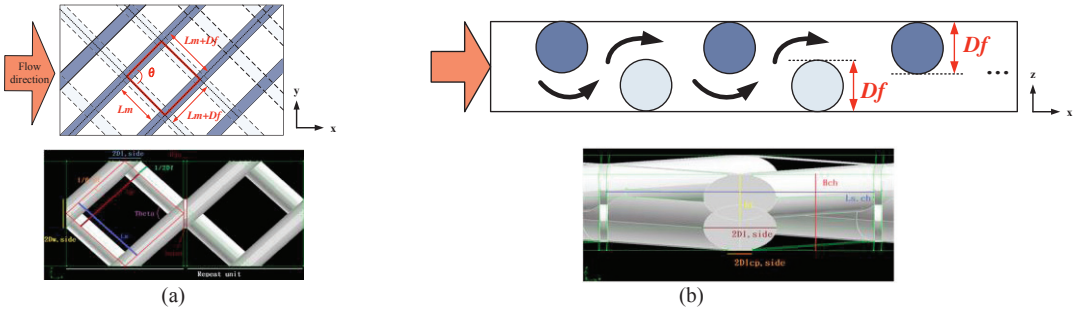
simplest MD configuration capable of producing reasonably high flux. It is best suited for applications such as desalination and concentration of aqueous solutions (e.g., juice concentrates) [1].

In MD processes, heat and mass transfers are coupled together in the same direction from the hot side to the cold side. Besides the permeation inside the membrane, the mass transfer is determined by the vapor pressure difference across the membrane, which is controlled by the boundary layer heat transfer of both liquid channels. Net-type spacers have been applied in heat exchangers and membrane modules, including ultrafiltration, reverse osmosis and membrane distillation, to enhance boundary layer heat and mass transfer. For DCMD with net-type spacers, heat transfer coefficients from experimental results were reported in [2,3]. 2-D and 3-D computational fluid dynamics (CFD) simulation of DCMD modules with spacers have been reported. However, only a short section of the module was simulated and the trans-membrane transfer considered was either only the heat transfer [4] or simulated with a uniform heat flux [5]. In this study, 3-D CFD simulation was employed to investigate the fluid flow friction, heat transfer and mass transfer of the DCMD modules with spacer-filled channels for desalination. The entire length of the DCMD module was simulated with the trans-membrane heat and mass transfer taken into account.

2. Modeling

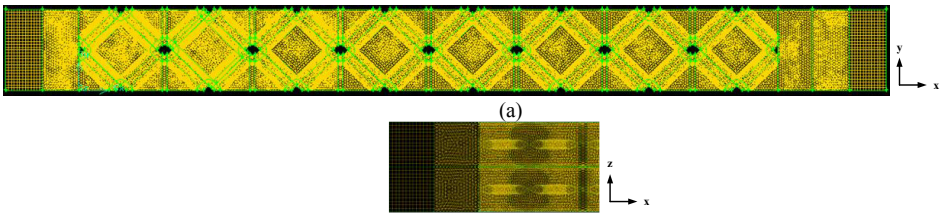
The spacer orientation is shown in Fig. 1. The CFD computational domain and grids of the DCMD module with spacers are shown in Fig. 2 and Fig. 3. The experimental modules of [2] were simulated. Both hot and cold channels of the module are filled with spacers made of two layers of filaments. The modules are characterized by the hydrodynamic angles (θ) and mesh size (l_m), which are 45°-11mm (L11T45) and 90°-8mm (L8T90), respectively. The diameter of the filament (D_f) is 3mm. The entire module length of 100mm was included in the computational domain, but in the lateral direction, only the width of one mesh unit was simulated, as shown in Fig. 2 and Fig. 3. An extra 10mm was added at both inlet and outlet for velocity development. The two sides in the lateral direction were defined as symmetric boundary condition. The boundary conditions of the two bulk fluid exits were defined as pressure outlet. The flow configuration of the hot and cold fluids are co-current. For comparison, the same computational domain with no spacer, i.e. empty channels, was simulated too.

The laminar flow model of the FLUENT software was employed for the CFD simulation. The trans-membrane heat and mass fluxes were include in the model using the information of the cells adjacent to the membrane. The mechanisms of heat transfer (heat conduction) and mass transfer (Knudsen diffusion, molecular diffusion and viscous flow) were taken into account to calculate the fluxes. Grid independent analysis was undertaken to determine the grid sizes by examining the pressure drop of the modules via a hydrodynamic simulation. For the simulations, in addition to the conservation of momentum, energy and mass, the trans-membrane mass flux was included in the convergence criteria.



(a) (b)

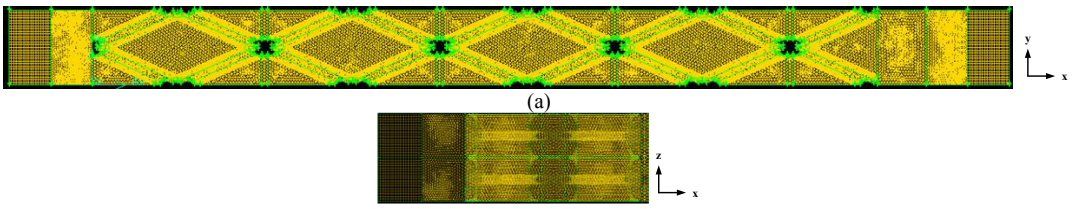
Fig. 1. Spacer orientation (a) top view; (b) side view



(a)

(b)

Fig. 2. Computational domain and grids of the L8T90 module (a) top view; (b) side view



(a)

(b)

Fig. 3. Computational domain and grids of the L11T45 module (a) top view; (b) side view

3. Results and discussion

The model was verified using the experimental data from [2]. The membrane material is PVDF (Polyvinylidene fluoride) and the spacer filament material is PP (Polypropylene). The membrane thickness, pore diameter and porosity are 126 μm, 0.22 μm and 0.62. Both hot and cold fluids are pure water. The cold fluid inlet conditions were fixed at 20°C and 0.1 m/s. The hot fluid inlet velocity was fixed at 0.1 m/s and inlet temperature was varied in the range of 40-70°C. The comparisons of simulation and experimental mass flux (N) for both modules are shown in Fig. 4. The average deviations of the simulation from the experimental mass flux for L8T90 and L11T45 channels are 6.8% and 16.5%, respectively. The higher mass flux from simulation might be due to several causes: (1) the uncertainty of membrane properties; (2) the uncertainty of the actual spacer porosity in the experimental modules; (3) the lateral direction (y-direction) boundary effect was not simulated in the model.

A representative sample of the contour maps on a vertical cross section plane at 0.25 location of simulated width are presented in Fig. 5 and Fig. 6. The hot fluid flows in the bottom channel. In Fig. 5, it shows that both modules give the desired feature of creating high velocity zones in the vicinity of the membrane surfaces. In the L11T45 module, the velocity is lower due to the higher porosity of the channel compared to L8T90 module. The contour maps of temperature for both modules are illustrated in Fig. 6. Note that the scale bars for hot and cold fluids are different. The contour maps of both modules are similar in pattern. However, comparing the hot fluid channel thermal boundary layer in the vicinity of the membrane, the layer of the L11T45 module is slightly thicker than the L8T90 module. It can be explained by the lower fluid velocity in the L11T45 module.

The trans-membrane mass and heat flux profiles of both modules as well as the empty channel module are shown in Fig. 7. For the empty channel module, the fluxes decrease along the module and a significant thermal entrance region results in very high mass and heat fluxes at the inlet end. However, in the two modules with spacer-filled channels, the fluxes maintain at higher levels than the average flux of the empty channel module but with a fluctuating pattern, which corresponds to the repetitive structure of the spacer. Because the effective membrane area of the two modules are different, although the local fluxes of the

L8T90 module are slightly lower than the L11T45 module, the averaged fluxes of the L8T90 module are higher than the L11T45 module.

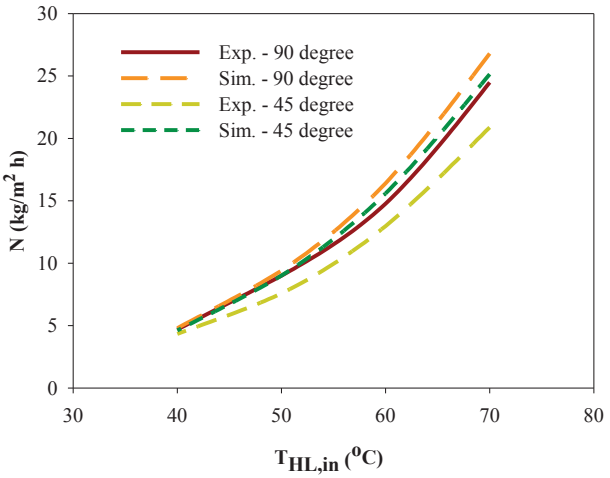


Fig. 4. Model verification

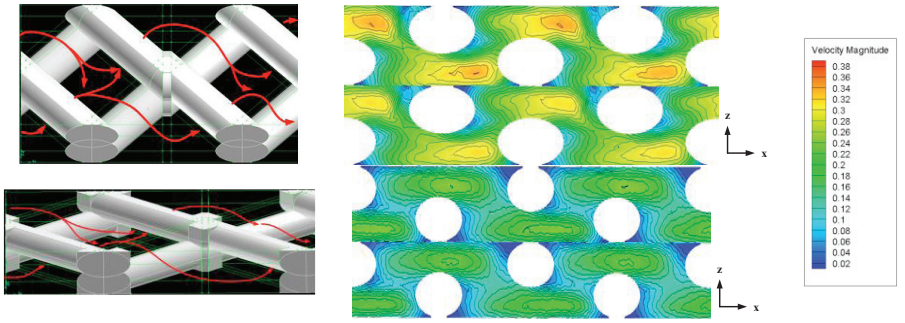


Fig. 5. Main flow paths and contour maps of velocity magnitude for both modules: top: L8T90; bottom: L11T45

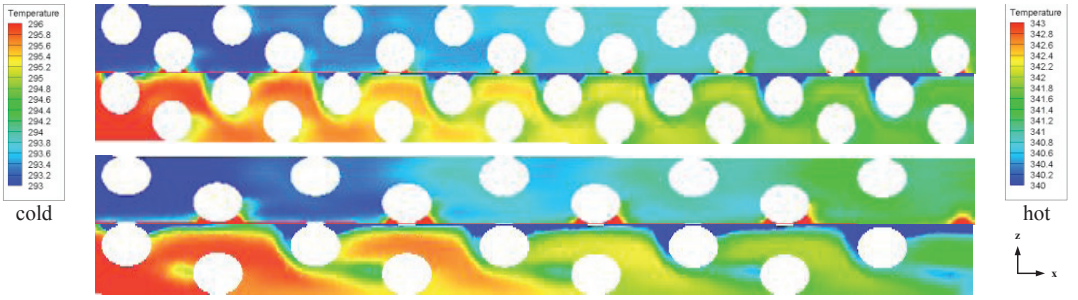


Fig. 6. Contour maps of temperature for both modules: top: L8T90; bottom: L11T45

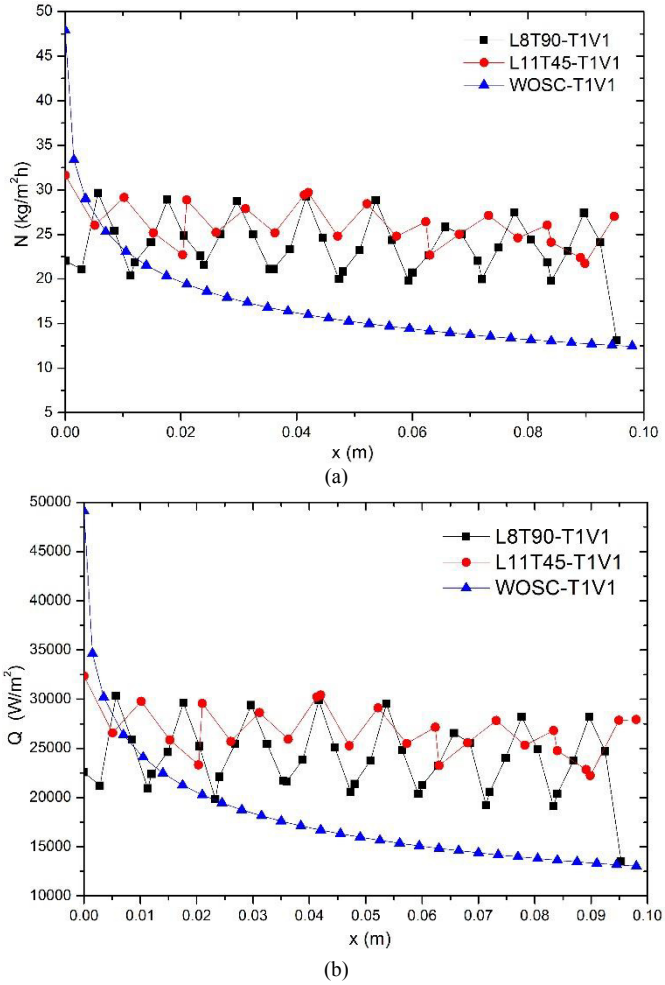


Fig. 7. Local profiles (a) mass flux; (b) heat flux

The Nusselt number of the module using spacer-filled channels (Nu_S) can be compared to that of the empty channel under laminar flow (Nu_{lam}) and an enhancement factor (α_S) can be defined as the following:

$$Nu_S = \alpha_S Nu_{lam} \quad (1)$$

The estimation of the enhancement factor in terms of the parameters of the spacer has been proposed for ultrafiltration (UF) membrane module [6] and DCMD [3], respectively, as:

$$\alpha_{S,cor1} = 1.654\left(\frac{D_f}{H}\right)^{-0.039}\varepsilon^{0.75}\sin\left(\frac{\theta}{2}\right)^{0.086} \quad (2)$$

$$\alpha_{S,cor2} = 1.88\left(\frac{D_f}{H}\right)^{-0.039}(\sin\theta)^{1.33}\, e^{\left(-4.05\left[\ln\left(\frac{\varepsilon}{\varepsilon_m}\right)\right]^2\right)} \quad (\varepsilon_m = 0.6) \quad (3)$$

Where H and ε are the height of the spacer and the porosity of the spacer module, respectively. The correlation for UF was obtained from mass transfer enhancement by the analogy between heat and mass transfer [3]. In [3], the Nu_S was determined by assuming a constant heat transfer coefficient for the entire module and solved from a 1-D mathematical model of the module using the experimental data. In [3], the Nu_{lam} was estimated using a conventional correlation developed for rigid heat exchangers:

$$\mathrm{Nu}_{lam} = 4.36 + \frac{0.036 Re_S \mathrm{Pr}(d_h^S/L)}{1+0.0011(Re_S \mathrm{Pr}(d_h^S/L))^{0.8}} \quad (4)$$

The results obtained from CFD simulation and the predictions from Eqs. (2) and (3) are listed in Table 1. Both $\mathrm{Nu}_{S,CFD}$ and $\mathrm{Nu}_{lam,CFD}$ are the average values of the local Nu in the module. For all the analyzed cases, the enhancement factors obtained from this CFD study are significantly higher than the predictions using the correlations from the other two studies. Two possible explanations for this difference are: (1) The model used in this study overpredicts the actual mass flux as has been discussed above for Fig. 4. (2) The correlation 1 was developed by the analogy between heat and mass transfer, which is not from the study of MD modules. (3) The correlation 2 was developed using 1-D mathematic model, while in this study, the rigorous 3-D CFD model was used.

Table 1. The heat transfer coefficient enhancement factor of spacer-filled channel

Cases	Re_S	$\mathrm{Nu}_{S,CFD}$	$\mathrm{Nu}_{lam,CFD}$	$\alpha_{S,CFD}$	$\alpha_{S,cor1}$	$\alpha_{S,cor2}$
L8T90-V1T1	582.83	71.19	31.10	2.29		
L8T90-V2T1	500.49	60.82	28.21	2.16	1.12	1.85
L8T90-V3T1	364.67	44.22	23.43	1.89		
L11T45-V1T1	584.29	74.15	31.10	2.38		
L11T45-V2T1	501.19	63.35	28.21	2.24	1.25	0.99
L11T45-V3T1	364.38	45.88	23.43	1.96		

4. Conclusions

The 3-D CFD simulation results of the internal transfer characteristics of spacer-filled DCMD modules for desalination have been presented. The comprehensive model includes the trans-membrane heat and mass transfer and the entire length of the module was simulated.

This simulation study has revealed the following points:

(1) The contour maps of the velocity magnitude show high fluid velocity in the vicinity of the membrane, which results in the enhancement of the trans-membrane heat and mass transfer.
(2) The trans-membrane heat and mass fluxes feature a fluctuating pattern corresponding to the repetitive structure of the spacer.
(3) The heat transfer coefficients of empty channel modules show significant variation in the entire module. However, the heat transfer coefficients of spacer-filled modules maintain some fluctuating pattern throughout the entire module. By combining conventional correlations of heat transfer coefficients for rigid heat exchangers with well-developed correlations of enhancement factors, the heat transfer coefficients of spacer-filled MD modules can be accurately estimated.
(4) The enhancement factors of the heat transfer coefficient obtained from this CFD study are significantly higher than the predictions from literature correlations.

The CFD model reported in this study can serve as an effective tool for developing correlations and optimal design of the spacer-filled MD modules.

Acknowledgements

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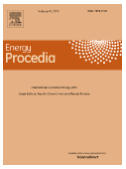

Biography

Hsuan Chang is a professor in the Department of Chemical and Materials Engineering, Tamkang University, Taiwan. She received her Ph.D. from the Department of Chemical Engineering of Ohio State University, USA. Her research interest is in the simulation and design of chemical and energy processes.