

CFD modeling for fluid flow and heat transfer in membrane distillation

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Abstract—The CFD study shows that temperature profile, turbulent viscosity and heat transfer coefficient depend on spacing between the filaments and Reynolds number. The turbulence is noticed to be higher in the region in-between of the filaments and is least near the membrane surface. The spacer with a spacing of 6 mm is found to be of superior characteristics.

Keywords- spacers, heat transfer coefficient, membrane distillation

I. INTRODUCTION

Membrane distillation is a separation process used to treat water and other fluids. It involves a hydrophobic membrane that separates the feed and permeate streams at different temperatures. A fraction of hot fluid evaporates, flows through the porous membrane due to temperature (or vapor pressure) difference and then condenses on low temperature side. A phenomenon that limits the process effectiveness is temperature polarization [1, 2] which reduces the driving force for vapor permeation. In many membrane distillation modules net-type spacers are used which separate the membrane layers. In addition spacers also disrupt the thermal boundary layer thereby increasing the heat transfer rates and in-turn enhance the permeate flux.

Various studies have been done to investigate the effect of spacers on the membrane performance. Martinez et al. [3 - 5] studied the influence of three configurations; open separator, coarse screen separator and fine screen separator. It was found that screen separator results in turbulence due to formation of eddies and wakes which reduces temperature polarization and enhances permeate flux. The study also showed that coarse separator was best among three configurations. Phattaranawik et al. [6, 7] carried out experiments for direct contact membrane distillation. Product flux enhancement was noticed when spacers were used in the membrane channels. Alklaibi and Lior [8] performed simulations for three different spacer arrangements: zigzag spacer, non-central suspended and central suspended. The three arrangements were compared on the basis of spacer effectiveness defined as ratio of permeate fluxes with and without spacer. The central suspended spacer resulted in highest spacer effectiveness. Cipollina et al. [9] conducted 3D simulation for spacer-filled membrane distillation channel. The paper showed that spacers considerably improve the temperature gradients for

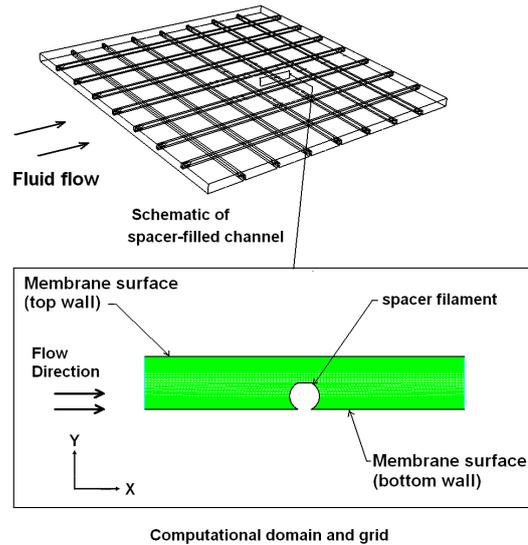


Figure 1. Schematic and computational domain.

this process. In the present work we discuss the turbulent flow and temperature patterns in membrane channel.

II. MODELING PROCEDURE

The spacer-filled channel contains number of cells and flow becomes repeating after first few cells. It is thus suitable to restrict the computational domain to single cell composed of a single filament for two dimensional simulations as shown in Fig. 1. This procedure allows modeling fully developed flow region in the membrane channel and also reduces the computational time and space. The fluid is water assumed to be of constant density and thermal conductivity and viscosity varying with temperature. The spacers are compared in terms of heat transfer coefficient and pressure drop. Reynolds number (Re_{ch}), Nusselt number (Nu) (based on hydraulic diameter d_h) and Prandtl number (Pr) are determined and compared with correlation given in Eq. 1

$$Nu = 0.664Re_{ch}^{0.5}Pr^{0.33}\left(\frac{d_h}{l_m}\right)^{0.5} \quad (1)$$

In this work spacers s4 and s6 are considered with mesh lengths (l_m) 4 and 6 mm respectively.

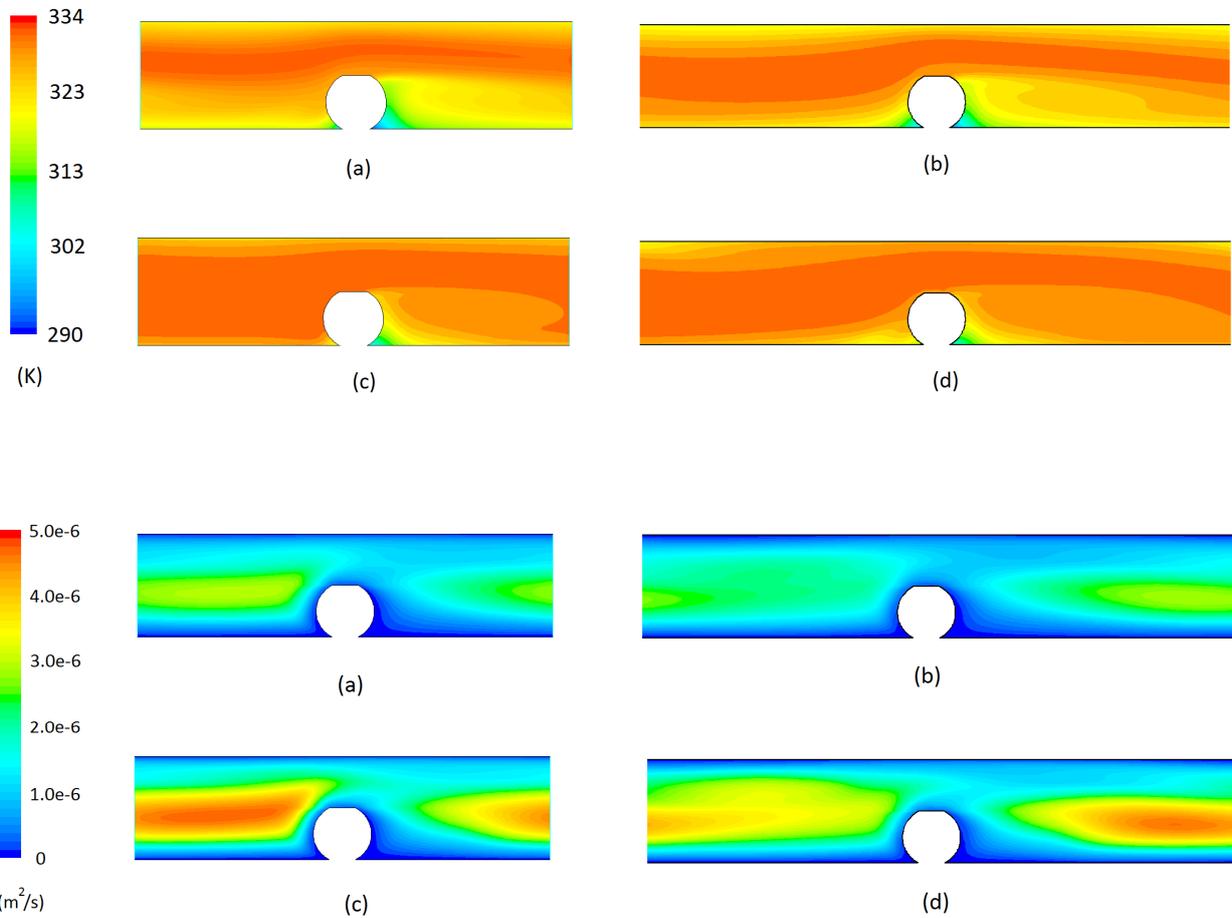


Figure 3. Turbulent viscosity in (a) s4, $m = 0.125$ kg/s (b) s6, $m = 0.125$ kg/s (c) s4, $m = 0.2$ kg/s (d) s6, $m = 0.2$ kg/s.

III. RESULTS AND DISCUSSIONS

For simulations, periodic boundary conditions are used at the opposite vertical faces and mass flow rate is specified in x -direction. At the channel walls no-permeation and no-slip conditions are assumed. Bulk temperature is 57°C whereas constant heat flux of 30 kW/m^2 is imposed on the top and bottom walls for all the simulations. The governing equations are continuity, momentum equations, energy equation and Spalart Allmaras equation which are solved using a CFD code FLUENT 6.3. QUICK scheme is used for discretization of momentum equations whereas Power Law scheme is used for energy and turbulence equations. Pressure-velocity coupling is made through SIMPLE algorithm. The results in spacer-filled are shown in terms of temperature contours for spacers s4 and s6 at two different flow rates in Fig. 2. At lower flow rate of 0.07 kg/s the local temperature is significantly lower behind the spacer filament. At higher flow rate the temperature values are relatively higher and distribution is more uniform. The flow at higher

flow rates / Reynolds number is turbulent. The profiles of turbulent viscosity indicate that turbulence is more in the center of the channel. Above the filament the turbulence reduces and near the top and bottom surfaces it almost diminishes. The spacer s4 has higher flow randomness (or turbulence) before the filament whereas for s6 it is higher after the filament as observed in Fig. 3. The distribution of heat transfer coefficient is shown in histograms in Fig. 4. In both the spacers at a lower flow rate of 0.07 kg/s , the local higher values cover a major portion of the membrane surface area. At a higher flow rate of 0.2 kg/s , major portion of membrane is covered by the average values of heat transfer coefficient in particular in spacer s4. The two spacers are compared in terms of average heat transfer coefficient and pressure drop. In Fig. 5 it is seen that heat transfer coefficient values are almost same for two spacers at three different mass flow rates. Only at $m = 0.125 \text{ kg/s}$, heat transfer with s4 is approximately 10 % higher than s6. The pressure drop is higher with s4 for all flow rates up to 30 %. This indicates that s6 is superior to s4 since it results in almost equal heat

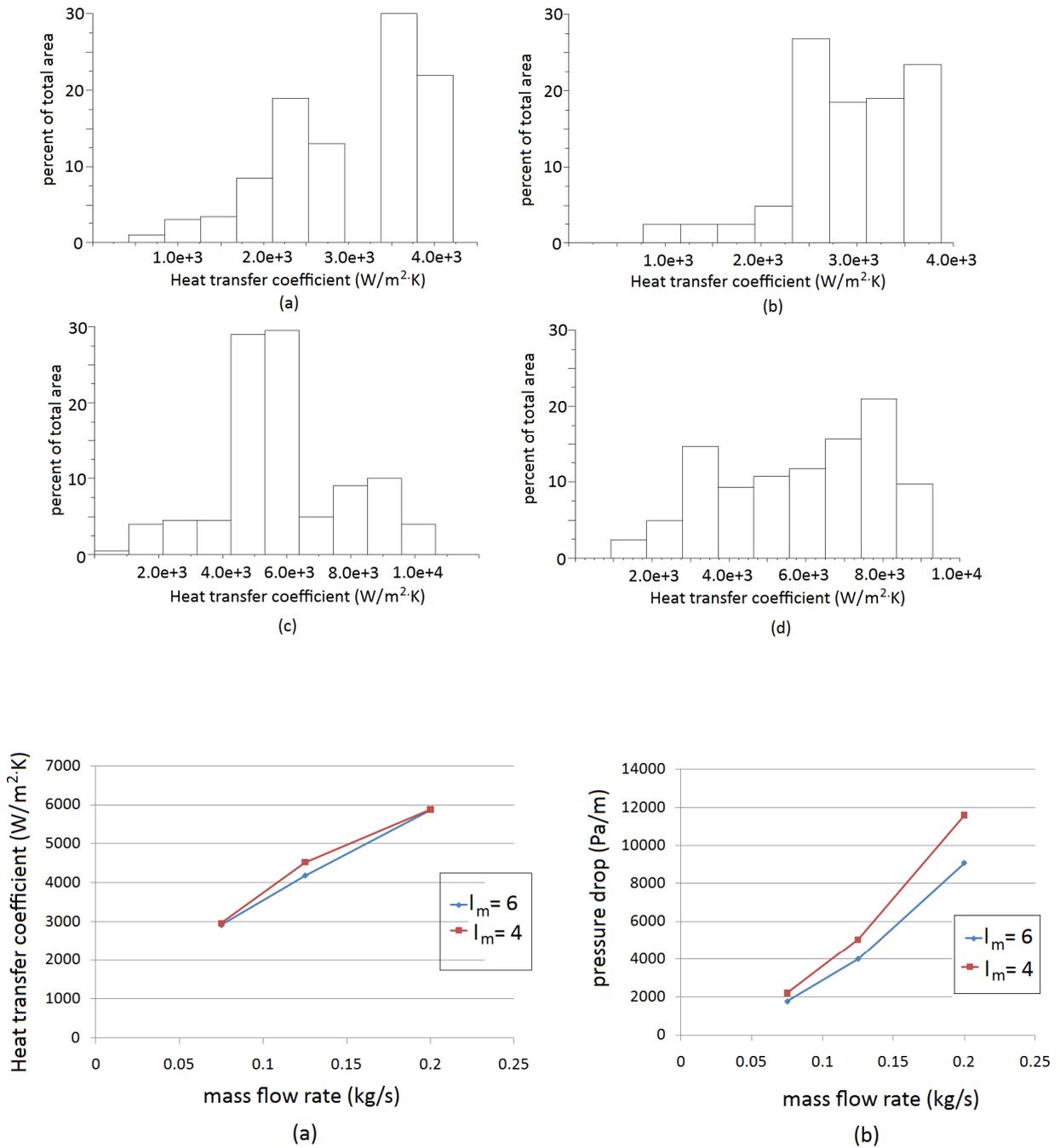
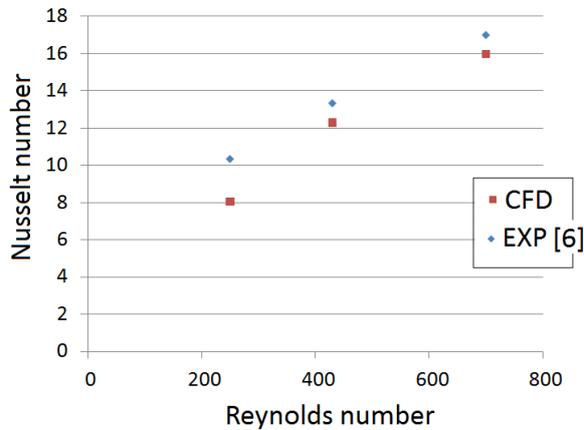


Figure 5. Effect of flow rate on (a) heat transfer coefficient (b) pressure drop.

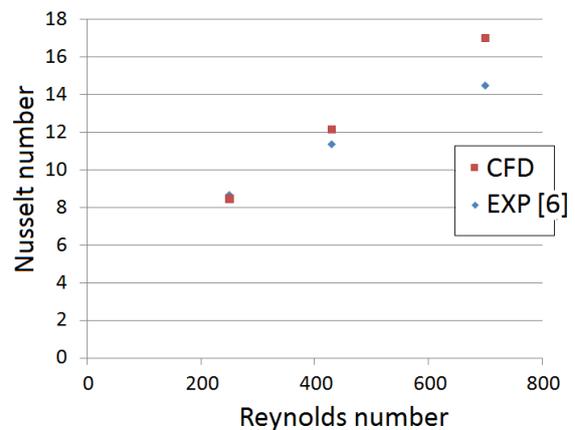
transfer but has less pressure drop value when compared to s4. The CFD results are evaluated against the experimental correlation available in literature [6]. For this purpose Nusselt number is determined. The comparison in Fig. 6 shows that there is satisfactory agreement between CFD and experiments. The difference remains below 25 % for all the cases.

IV. CONCLUSIONS

The temperature profiles in spacers of two different spacings indicate that a low temperature zone exists behind the filament. The flow unsteadiness predicted using turbulent viscosity show that flow unsteadiness is relatively less significant near the filament. The average heat transfer



(a)



(b)

coefficient with s6 is almost same as with s4 but the pressure drop is considerably lower. The agreement of Nusselt numbers obtained from present CFD results with experimental correlation is found to be good.

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REFERENCES

- [1] K.W. Lawson and D.R. Lloyd, "Review, membrane distillation", *Journal of Membrane Science*, vol. 124, 1997, pp. 1–25.
- [2] G.W. Meindersma, C.M. Guijt, and A.B. De Haan., "Desalination and water recycling by air gap membrane distillation", *Desalination*, vol. 187, 2006, pp. 291–301.
- [3] L. Martínez, M.I. Vázquez-González, and F.J. Florido-Díaz., "Study of membrane distillation using channel spacers", *Journal of Membrane Science*, vol. 144, 1998, pp. 45–56.
- [4] L. Martínez, and J.M. Rodríguez-Maroto, "Characterization of membrane distillation modules and analysis of mass flux enhancement by channel spacers", *Journal of Membrane Science*, vol. 274, 2006, pp. 123–137.
- [5] L. Martínez, M.I. Vázquez-González, and F.J. Florido-Díaz., "Temperature polarization coefficients in membrane distillation", *Separation Science and Technology*, vol. 33, 1998, pp. 787–799.
- [6] J. Phattaranawik, R. Jiraratananon, A.G. Fane, and C. Halim, "Mass flux enhancement using spacer filled channel in direct contact membrane distillation", *Journal of Membrane Science*, vol. 187, 2001, pp. 193–201.
- [7] J. Phattaranawik, R. Jiraratananon, and A.G. Fane, "Effects of net-type spacers on heat and mass transfer in direct contact membrane distillation and comparison with ultrafiltration studies", *Journal of Membrane Science*, vol. 217, 2003, pp. 193–206.
- [8] A.M. Alklaibi, and N. Lior., "Flow modification spacers in membrane distillation (MD) channels", *Proceedings of IDA World Congress*, Gran Canaria, Spain, Oct 2007.
- [9] A. Cipollina, A. Di Miceli, J.G. Koschikowski, Micale, and L. Rizzuti., "CFD simulation of a membrane distillation module channel", *Desalination and Water Treatment*, vol. 6, 2009, pp. 177–183.