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Modeling the Effect of Spacer Orientation on Heat Transfer in Membrane Distillation

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Abstract**—**Computational fluid dynamics (CFD) simulations carried out in this paper show that spacer orientation has a major influence on temperature patterns and on the heat transfer rates. The local heat flux values significantly vary from high to very low values at each filament when spacer touches the membrane surface. The heat flux profile is more uniform when spacer filaments are not in contact with the membrane thus making this arrangement more beneficial. The temperature polarization is also found to be less in this case when compared to the empty channel.

Keywords**—**heat transfer, membrane distillation, spacer, temperature polarization.

I. INTRODUCTION

NET-TYPE spacer is widely used in the feed and permeate channels of the membrane modules. The advantage of spacer is that it disrupts the concentration and thermal boundary layer thereby increasing the permeation rates. The disadvantage on the other hand is that it results in higher pressure drops and stagnant zones in the channel. These zones in the membrane channels increase temperature polarization thereby decreasing the driving force for permeation. The spacer orientation and dimensions are however crucial parameters that affect the values of pressure drop and size or location of the stagnation regions.

Limited studies have been conducted to find the effect of spacer on the membrane distillation performance. Martínez et al. [1, 2] compared open separator and screen separator (or spacer) and showed that screen separator results in wakes and turbulence which reduces temperature polarization. Phattaranawik et al. [3, 4] carried out experiments for direct contact membrane distillation and noticed product flux enhancement due to presence of spacer. Alklaibi and Lior [5] performed simulations for three different spacer arrangements namely the zigzag, non-central suspended and central suspended. The central suspended spacer was found to be the suitable configuration. Cipollina et al. [6] conducted 3D simulation for spacer-filled membrane distillation channel. The paper showed that spacers considerably improve the temperature gradients for this process. The review of references [1-6] indicates that none of the papers has investigated the effect of placement / orientation of spacer in the feed and product channel of membrane distillation module which is an important geometrical parameter. In the present work therefore we examine the effect of spacer orientation on the temperature polarization and the heat transfer rate.

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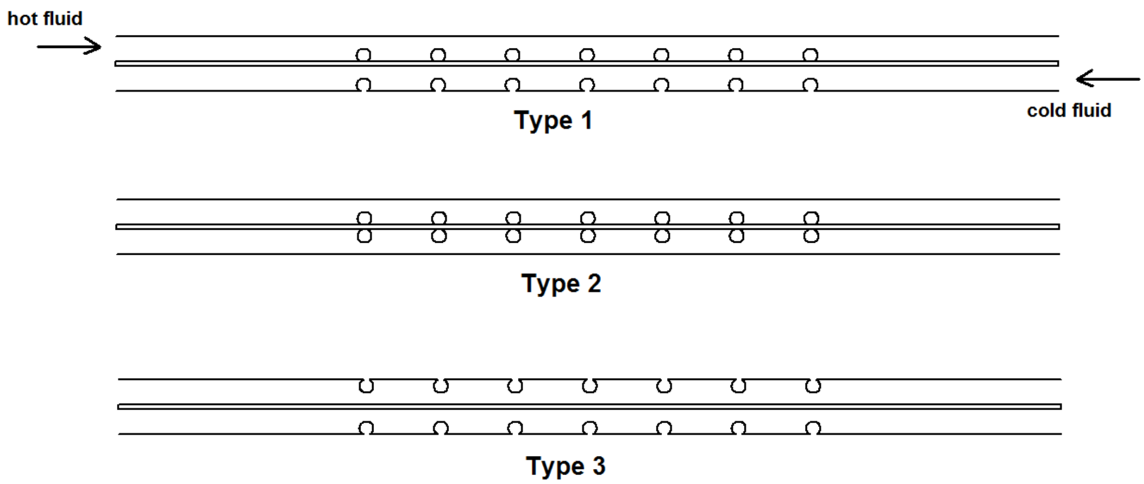
II. MODELING PROCEDURE

The spacer-filled channel contains number of cells and flow becomes repeating after first few cells. It is thus suitable procedure to restrict the computational flow and heat transfer analysis to few filaments. For CFD modeling therefore in this paper the domain consist of seven filaments as shown in Fig. 1. Three spacer types / orientations are considered:

(a) Type 1 – Feed and permeate channel filaments both touch the bottom of the channels.
(b) Type 2 – Filaments in feed channel touch the bottom while in permeate channel touch the top. This means the filaments touch the membrane surface in both the channels.
(c) Type 3 – Filaments in feed channel touch the top surface while in permeate channel touch the bottom (of the channel).

The flow direction is of counter-flow type for all simulations as shown in Fig. 1. The temperature of hot fluid is 57 °C whereas of cold fluid is set to 27 °C. The fluids are assumed as water of constant density and thermal conductivity and viscosity varying with temperature. The membrane is assumed to be impermeable of constant thermal conductivity of 0.2 W/m·K. The overall channel length is 38 mm and distance between first and last filament is 18 mm. The height of channel is 1 mm and membrane thickness is 0.2 mm. The feed and permeate channel heights are 1 mm each whereas spacing between filaments l_m is 3 mm. The governing equations are continuity, momentum and energy equations which are solved using a CFD code FLUENT 6.3.



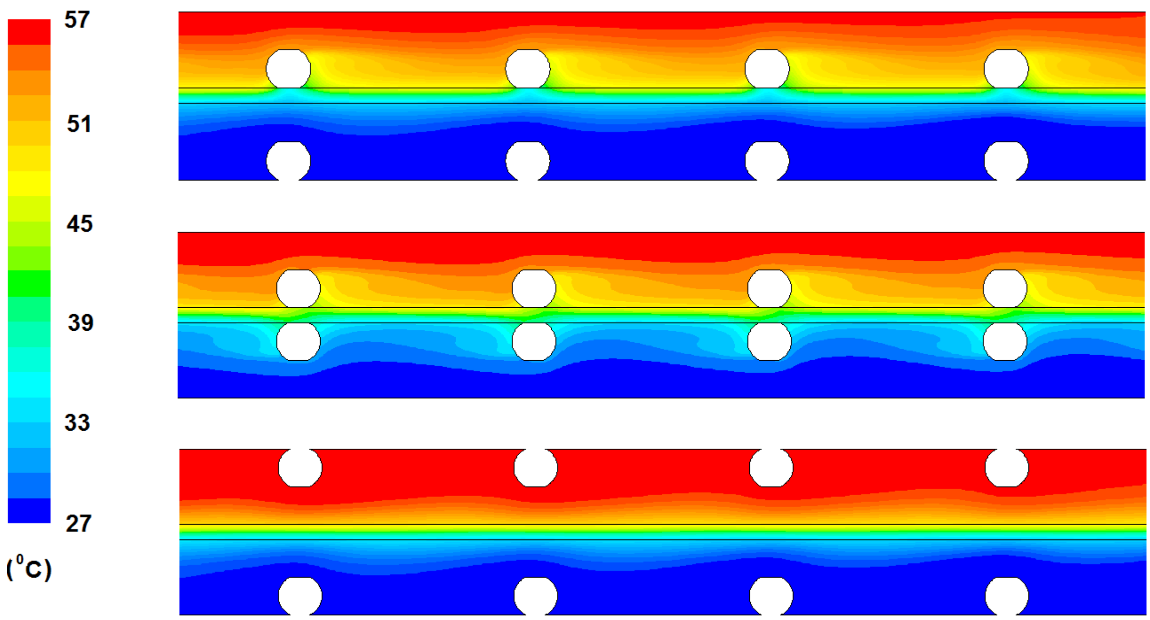


Fig. 2 Temperature profiles in spacer-filled channels

III. RESULTS AND DISCUSSIONS

The comparison of spacer types is done at inlet velocity (equal for feed and permeate streams) of 0.05 and 0.15 m/s. The temperature contours in the three cases at a velocity of 0.05 m/s are shown in Fig. 2. For type 1 in which space filaments touch the membrane in the hot channel, a significant low temperature region (behind the filaments) exists in lower portion. In the cold channel a wavy pattern in the temperature contours is seen due to disruption of the temperature polarization layer at each filament. In type 2 recirculation wakes / vortices occur near the membrane at both hot and cold sides. This results in formation of dead zones and increase in the thermal boundary layer thickness. In type 3 the high velocity fluid flow takes place in the region above the filaments in the cold channel and below the filaments in the hot channel. The vortices thus generated do not contact the membrane wall and smoothly varying temperature profile forms near the membrane. The spacers are also compared in terms of local heat fluxes plotted at the top surface of the cold channel as depicted in Fig. 3. At an inlet velocity of 0.05 m/s, the heat flux is observed low (around 6000 W/m^2) very near the filaments for spacer type 1. Somewhere at a distance ⅔ l_m measured from one of the filaments, there are local peaks up to 15000 W/m^2. At higher inlet velocity the profile of heat flux values remain almost same as can be seen in Fig. 3b. The range however changes from 6000-15000 to 7000-19000 W/m^2 approximately. In type 2 spacer the heat flux pattern is relatively smooth with maximum value in the center of the two filaments. The reason is that in type 1 the higher shear stress at the membrane on the hot side exists in the center of the two filaments whereas on the cold side the higher shear stress exists directly above the filaments. In case of spacer type 2 the shear stress is higher in the center of the filaments on both sides. In spacer type 3 the local heat flux has higher and more uniform values ranging between 14000 – 17000 and 19000 – 21000 W/m^2 respectively at velocities of 0.05 and 0.15 m/s.

The three arrangements are also evaluated in terms of temperature polarization index φ (calculated in hot fluid channel). The definition of this parameter used in this paper is:

$$\varphi = \frac{T_{\text{in}}}{T_{\text{m}}}$$

where T_m and T_{in} are temperatures respectively of inlet fluid and at the membrane surface. A lower value of φ means less temperature gradient in the channel and is desirable. In Fig. 4 φ values are shown for the considered spacers and for the empty channel. The comparison indicates the undesirable

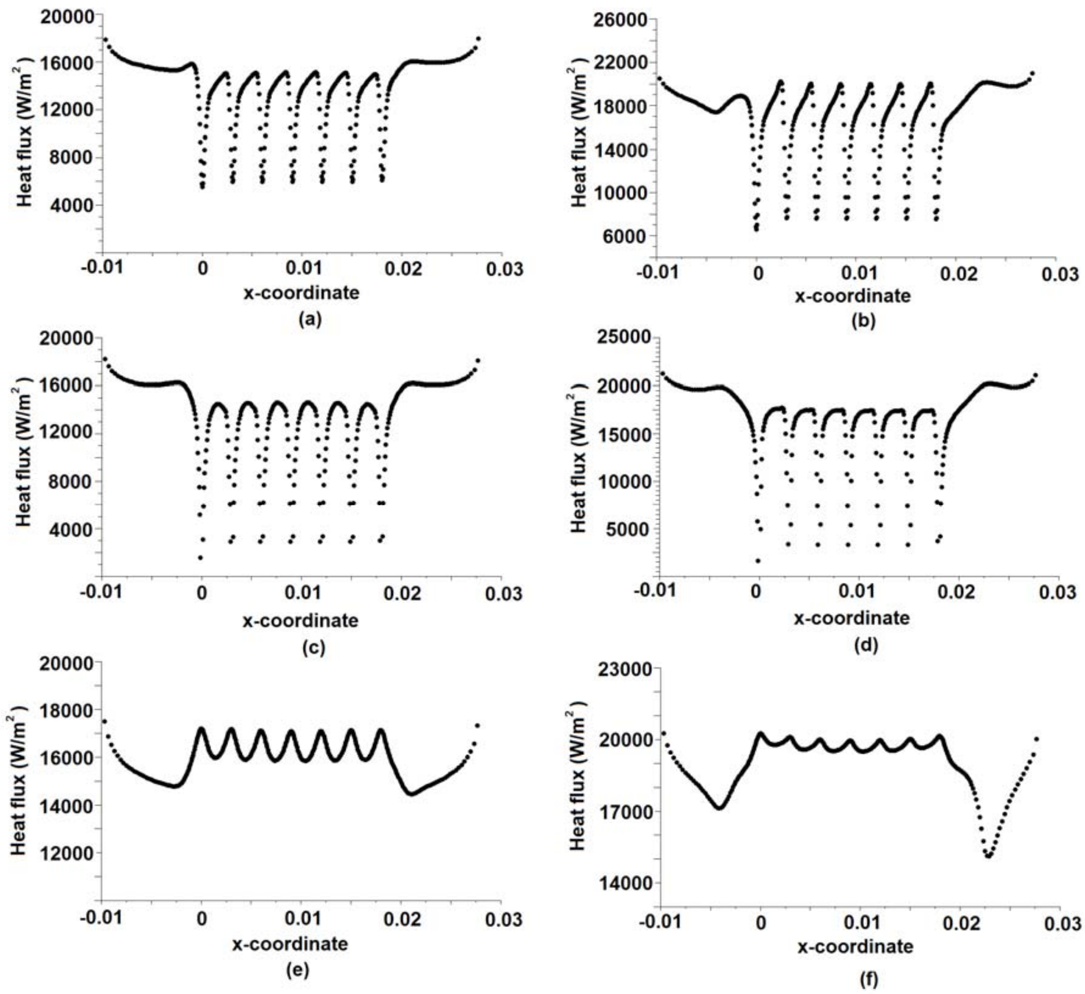


Fig. 3 Heat flux variation in spacer (a, b) type 1 (c, d) type 2 (e, f) type 3 at velocities 0.05 and 0.15 m/s

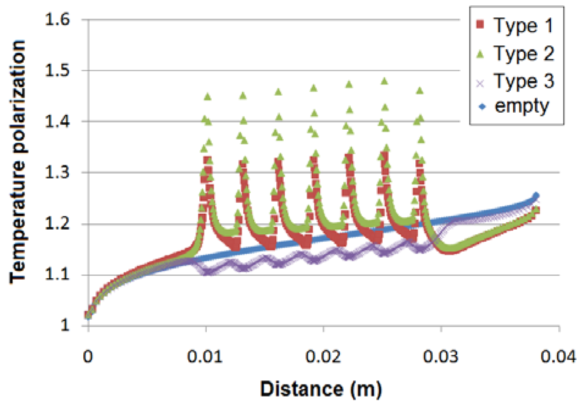


Fig. 4 Comparison of temperature polarization index in empty channel with different spacer types

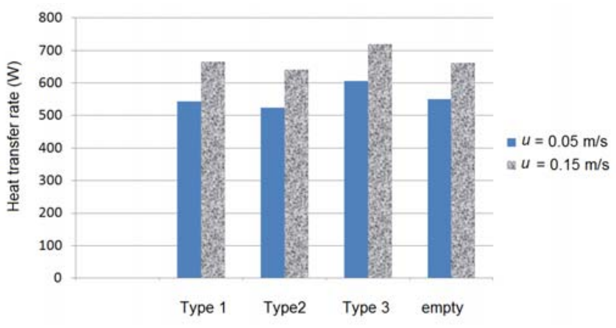


Fig. 5 Heat transfer rates in empty and spacer-filled channels

characteristics of spacer types 1 and 2 due to higher φ values rising up to 1.34 and 1.47 respectively close to the filaments. For a significant portion these φ indices are much greater than the empty channel. The spacer 3 has the most suitable plot as temperature polarization is lower than the empty channel case at all the locations.

The average heat transfer rate is calculated for three spacers and for empty channel and shown in Fig. 5. It is seen that heat transfer is maximum with type 3 for both the velocities. The spacer 1 and 2 has lower heat transfer than the empty one. The effectiveness of spacer-filled channel can however increase with an increase in channel length as periodic disruption of thermal boundary layer takes place. In empty channel the boundary layer thickness continuously increases in the flow direction.

IV. CONCLUSIONS

The study shows that spacers with filaments touching the membrane (either on one or both sides) involve flow separation and recirculation near the membrane. This creates a low temperature zone behind the filaments which decreases heat transfer. The heat flux profile in such cases includes significant variation with low value in the vicinity of the filaments and a higher value in the center of the filaments. The spacer performance is better when filaments do not contact the membrane surface as heat transfer rates remain higher on almost the entire surface. The spacer with such an arrangement is optimal as it leads to higher average heat flux without stagnant zones along with pressure drop equal to the other two arrangements.

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