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Improving the performance of direct contact membrane distillation utilizing spacer-filled channel

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HIGHLIGHTS

- 3D CFD modeling is used to improve the performance of DCMD module.
- The effect of the filament orientation on DCMD module was investigated.
- Spacers enhanced heat transfer coefficient by approximately two times.
- The presence of spacer in membrane module increased the pressure drop.

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ABSTRACT

This study describes the effect of the presence and filament orientation of spacers on the flow pattern and heat transfer enhancement for a commercial direct contact membrane distillation module. In this research, both experimental and computational fluid dynamics (CFD) simulations are carried out when the two sets of spacer filaments are oriented at an angle of 45° to the channel axis and also when the top filaments are oriented at an angle of 30°, 45°, 62° and 90° while the bottom filaments are being parallel to the direction of flow. Fluid flow and heat transfer through empty and spacer-filled channel at various filament orientations and Reynolds number are simulated. Besides predicting the Nusselt number and total drag coefficient, the simulated results allow deeper understanding of the role of spacer presence and its filament orientation in fluid and heat flow structure. It is found that the degree of enhancement in heat and mass transfer depends on filament orientation of spacers. The simulated results show that when the two sets of spacer filaments are oriented 45° to the direction of flow, the wall shear stress and the Nusselt number are pronounced and increased by approximately two times over the empty channel.

1. Introduction

Hydrodynamics and thermal condition of the fluid flowing adjacent to the membrane surface can create pronounced effect on mass transport process across the membrane surfaces. The major problems in various pressure-driven membrane transport processes are recognized as concentration polarization (CP) and fouling. This leads to an increase in membrane resistance and resulting in reducing membrane flux. Hence, reduction of concentration polarization and fouling for many membrane applications are accomplished by increasing the wall shear stress as well as eddy promotion. To overcome these problems, several researchers have used frame-like turbulence stimulus (spacer) in different membrane modules to enhance wall shear stresses and reduce the polarization effect across the membrane [1–4].

Membrane distillation (MD) is a novel thermally-driven technology for high-quality water production. MD has many advantages over the conventional separation processes such as reverse osmosis (RO), microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF). Hence, MD process has been considered as the most attractive substitution for the conventional separation processes due to its lower driving pressure, cost, and energy demand [5,6]. Nowadays, the direct contact membrane distillation (DCMD) gained the most attention among the four typical MD configurations. This is due to the fact that no external devices are needed for permeate condensation. In direct contact MD configuration, the driving force of the overall process are the vapor pressure difference and the liquid temperature at the two membrane interface that remains in direct contact with hydrophobic microporous membrane. Polarization phenomena are considered the key process

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that affects the MD performance. For example, the existence of temperature polarization due to the temperature difference between permeates and feed causes a significant loss of the thermal force. Therefore, reduction of polarization can be achieved by utilizing net-like turbulence promotors permeate (spacer). This spacer enhances permeate flux by increasing significantly heat transfer coefficient in a favorable way [7–10].

Glatzel and Tomas designed the first net-type spacer that made from expanded aluminum and investigated its effect in pressure drop and heat transfer [1]. They found that changing the spacer orientation has a significant effect on total drag and heat transfer coefficient. However, their results were not correlated into semi – empirical formulas. Hickes found out that the existence of spacer affect both mass flux and pressure drag. They found out that spacer orientation has significant impact on pressure drop and shear stress. Several studies conducted extensive testing on wide range of commercial spacers and addressed the benefits of different spacer geometries in reducing polarization phenomena [11–15]. Furthermore, they determined the effect of spacer on fluid flow and heat transfer behavior.

Da Costa et al. [14] developed correlations for ultrafiltration membrane module that can be used to design net-like turbulence stimulus. The design variables were orientation angle, spacer thickness, porosity, net size and filament size. The influence of spacer structures on fluid behavior was estimated to by visualization of fluid structure. They modified Grober's mass transfer correlation to account for any spacer geometry configurations. Their results showed that the pressure drop can be lowered by using spacer porosity of 60–70% at higher cross flow velocity. Moreover, the permeate flux can be enhanced for hydrodynamic angles of 60°–90°.

Phattaranawik et al. [7,8] assessed experimentally the effect of more than 20 different structures of spacers on heat and mass transfer. They developed heat transfer correlation for spacer inside DCMD using heat/mass transfer analogy. They found out that permeate flux has increased 60% and heat transfer coefficient doubled compared with empty channel. The most favorable spacer structure is made of hydrodynamic angle and porosity of 90° and 0.6, respectively.

Computational fluid dynamics (CFD) has become an attractive method in the field of membrane science. CFD has been used by many researchers to study the effect of spacer configurations on the heat and fluid behavior. Furthermore, CFD is used to improve the performance of modules and achieve the optimum spacer shape in terms of mass transfer and pressure drop.

Several studies reported 2D and 3D CFD modeling of fluid flow and mass transfer in a spacer filled rectangular channel [16–23]. They studied the effect of different types of filament and spacers on shear stress distribution and pressure distribution inside the channel. Furthermore, CFD simulations were used to find favorable spacer structure for spiral-wound membrane modules [16,17]. They examined three different configurations of spacer; namely cavity, snaky (zigzag), and submerged. They studied wide range of filament diameter and net size of these spacers. They found out that that zigzag spacer configuration has the highest performance in terms of concentration polarization and permeate flux.

Recently, several studies determined the flow structure in a turbulence promoter (spacers) for three different transverse filament arrangements using commercial software package (Fluent) [24–27]. It was reported that the selection of most appropriate spacer structure involves a trade-off between pressure drop and the increase in operating cost. Karode and Kumar [18] carried out CFD simulations for flat sheet geometry. Their results showed that the major pressure drag was due to abrupt change in the flow direction in the plane of intersection of spacer filaments.

Ahmad and Lau [28] carried out CFD simulations using commercial software (Fluent) to determine the mass transfer coefficient, the concentration polarization behavior, and average wall shear stress over membrane surface for various types of conditions. It was found that the concentration polarization (CP) can be minimized by raising the cross flow velocity (high Reynolds number). Santos et al. [29] carried out CFD simulations and experiments to investigate rectangular cross-section filament spacer. The results showed that the transfers filaments is the major parameter controlled the fluid flow patterns, while the longitudinal filaments had insignificant effect.

Although several studies were conducted to determine the effect of spacer on heat and mass transfer enhancement in different membrane systems, but the investigation of spacer filled channel in DCMD module is still limited. Although few studies obtained a semi-empirical correlation to analyze the heat and mass transfer phenomenon in the DCMD, but they assumed a simplified one dimensional solution. Therefore, the main goal of this research is to investigate experimentally and numerically the effect of spacer filament orientation (when the two sets of spacer filaments are oriented at an angle of 45° to the channel axis) on heat transfer enhancement and pressure drag for typical direct contact membrane distillation. Furthermore, this research aims to improve DCMD effectiveness by the utilizing different spacer geometries. Finally, this paper describes CFD simulations in spacer-filled channel when the top filaments are oriented at an angle of 30°, 45°, 62° and 90° while the bottom filaments are being parallel to the flow direction.

2. Materials and methods

The DCM distillation test system used in these experiments is shown schematically in Fig. 1. It is worth mentioning that the spacer is mounted horizontally in the in DCMD channel. Permeate flow is maintained countercurrent to the feed. Hydrophobic microfiltration membrane has been used for the investigation. The membrane has a nominal pore size of 0.2 μm, height of 100 μm, void fraction of 80%, and thermal conductivity of 0.25 W m^{-1} K^{-1}. In all the experiments, the membranes are in direct contact with both permeate and concentrate. The MD module channel length is 400 mm and the channel width is 50 mm while the thickness of the channel is 3.5 mm. The polypropylene spacer filaments (commercial poly-net spacer) are idealized as cylindrical rods with equal filament diameter 2 mm (see Table 1). The top filaments are oriented at an angle of 30°, 45°, 62° and 90° while the bottom filaments are being parallel to the flow direction. The spacer is placed below and above the membrane to form channels for hot and cold liquid and support the membrane. The perpendicular distance between filaments single mesh is 5 mm. The mass flow rate is maintained at constant value in order to ensure that the convection heat transfer coefficients are kept constant. Permeate flux is measured by timing and weighing the water. The feed inlet flow rate increased from 1 L/min to 2.6 L/min to investigate the effect of feed inlet flow rate on permeate flux. Such feed/permeate flux corresponds to

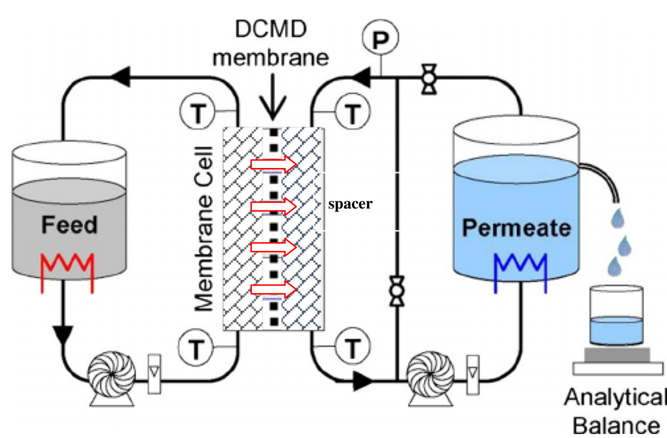

Fig. 1. Schematic diagram of the experimental setup.