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An experimental study for the characterization of fluid dynamics and heat transport within the spacer-filled channels of membrane distillation modules

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ABSTRACT

The thermo-fluid dynamic behavior of spacer-filled channels for membrane distillation was investigated experimentally. Several different geometry were investigated thanks to customized reference spacers manufactured using a 3D printer. In particular, two sets of experiments were conducted: in the first set, cylindrical filaments were orthogonally arranged and the flow attack angle was made to vary from 0° to 90°; in the second set, the flow attack angle was kept symmetrical and the filament angle was made to vary from 30° to 150°. Each spacer was tested for Reynolds numbers between 200 and 900 in the hot channel, while maintaining a constant temperature difference of 13 °C between the hot and the cold channels. Thermochromic Liquid Crystal (TLC) sheets were used for surface temperature measurements. Results showed that, for all spacers, the heat transfer coefficient increases with hot feed flow rate and that the combination of attack angle 45° and filament angle 90° gave the highest heat transfer. Pressure drop measurements showed that spacers could be categorized into two groups relevant to the values of the Darcy friction coefficients (*f*). One group, associated with spacer designs with filament angles greater than 90°, led to high *f* values, while the other, associated with filament angles less than 90°, led to moderate *f* values.

1. Introduction

Among separation processes commonly adopted in the desalination industry, membrane separation processes are very rapidly developing. A huge variety of membranes are currently adopted for different separation processes, such as micro-, ultra-, and nano-, filtration (MF, UF, and NF, respectively), reverse osmosis (RO), electro-dialysis (ED), and membrane distillation (MD).

The development of such processes is strongly linked on one hand to the design and manufacture of new materials that maximize the specific fluxes and selectivity, and on the other hand to the design and manufacture of membrane modules with optimized geometry in order to achieve various goals, such as smaller dimensions (i.e. compactness), lower pressure drops, high separation efficiencies, durability, etc.

Besides the very fast development of membrane materials technology, there is also a relevant interest towards the optimization of the whole membrane separation modules, with the aim of obtaining significant improvements in the separation efficiencies and other global performance measures relevant to each of the various membrane processes.

The characterization of the thermo-fluid dynamic efficiency of the module may be performed on the basis of two quantities: polarization and pressure drop. Polarization may be defined as the sharp concentration or temperature gradient near the surface of the membrane resulting from the no-slip condition. Concentration polarization is of concern when the driving force for the separation process is due to the difference in the chemical potential and/or in the activity of the liquid on the two sides of the membrane (e.g. ultra-filtration, reverse osmosis). On the other hand, Temperature polarization occurs in the case when the driving force for the separation process is due to the temperature difference of the liquid on the two sides of the membrane, as in membrane distillation. Invariably the effect of polarization is to diminish the actual driving force effecting separation as a result of a decrease in the trans-membrane gradient of the relevant quantity (e.g. chemical potential or temperature). Therefore one of the main goals in the design of the membrane module geometry is that of minimizing the relevant

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polarization phenomenon by promoting appropriate mixing levels in the liquid streams through the use of spacers with purposely chosen shapes and sizes for flat sheet and spiral wound modules.

The other parameter pertaining to the thermo-fluid dynamic characterization, also to be minimized, is the pressure drop across the module length. Pressure drop affects directly the energy requirements for pumping and circulating the liquid streams. Moreover it may well cause a reduction of the driving force available for separation in processes where the driving force is linked to a pressure difference across the two faces of the membrane, as in the case of ultra-filtration and reverse osmosis, thus reducing the overall process efficiency. It should also be noted that the occurrence of a significant pressure drop across the channel length may become detrimental for the mechanical resistance of the module itself, particularly for those modules designed to work at low pressure as in the case of membrane distillation.

The combined objective of reducing the temperature/concentration polarization phenomenon, while keeping the pressure drop at low values, is the main priority of any optimization study of the membrane module geometry.

Numerous modeling studies have been presented in the literature to characterize the fluid flow in spacer-filled channels for both RO and MD [1–10].

Geraldes et al. [1] studied concentration distribution for NF spiral wound modules filled with ladder type spacers under laminar conditions. The results showed that the average concentration polarization is proportional to the channel length from the inlet for membranes with longitudinal adjacent filaments. For membranes with adjacent transverse filaments, it is independent of the length of the channel. Their experimental results had good agreement with the CFD simulation.

For a deeper understanding of the transport phenomena in spiral wound membrane elements, Koutsou et al. [2] have presented a numerical and experimental study where spacers are used to improve mass transport characteristics and to lessen fouling and concentration polarization phenomena. Their results showed that a transition to unsteady flow started at Re = 35–45. The Navier-Stokes equations were solved in three-dimensional geometries, which closely simulated their experiments.

In regard to experimental studies, it was noticed that only a few works studied the MD modules optimization. Phattaranawik et al. [3] investigated the effect of spacers on mass flux enhancement for DCMD. The developed model showed that spacers promoted mass flux. Their results showed that a higher polarization coefficient also enhances the mass flux across the membrane. They used mass transfer correlations - by analogy - to predict heat transfer coefficients in spacer-filled channels. The results showed good agreement with their experimental data. In another study, Phattaranawik et al. [4] carried out an extensive investigation with 20 different spacers for DCMD, and found out that maximum heat transfer was achieved with a spacer having a hydrodynamic angle of 90° and a porosity of 60%. This increase was twice with respect to an empty (spacer less) channel. The mass flux was enhanced up to 60%. Mojab et al. [5] used Particle Image Velocimetry (PIV) with refractive index matching to measure the time averaged flow field. They performed a steady-state solution of the Navier Stokes equations and obtained a good agreement between experimental and numerical results for the velocity field.

Santos et al. [6] conducted experimental and numerical (CFD) investigations on different flow aligned-spacers with different longitudinal and transverse filaments designs for a range of Reynolds numbers between 50 and 600. The CFD and the experimental results showed agreement when a modified friction factor was applied that was in a linear relationship with the Sherwood number. Their results also indicated that only the transverse filaments determine the flow and mass transfer patterns in flow-aligned spacers. Martinez-Diez et al. [7] conducted an experimental study of the relationship between the heat transfer coefficient and the feed flow rate for two different spacers (coarse and fine). They concluded that spacers generate eddies and wakes that affect temperature polarization and enhance permeate flux, and that the effects are more pronounced for the case of coarse spacers.

Cipollina et al. [8] conducted CFD simulations of the flow and temperature fields in a spiral wound MD module channel. The CFD results show the effect of spacers on temperature gradients within the flow field. Preliminary results showed that temperature polarization increases in the presence of transversal filaments. In another study, Cipollina et al. [9], used CFD to characterize the fluid flow and temperature fields for different commercial and custom spacer geometries. Longitudinal filaments adjacent to the membrane surface were observed to have an effect on polarization phenomena. CFD predictions showed a reduction of the temperature difference between the bulk flow and the membrane surface, varying from 2 °C (standard spacers) to 1 °C (custom multilayer geometries).

Shakaib et al. [10] applied 3D-CFD for modeling pressure drop in spacer filled channels. Two spacers of diamond and parallel type with different geometric parameters were used. They concluded that: (i) transverse filaments create an important flow recirculation whose size depends on the distance between filaments; (ii) pressure drop increases with a decrease in filament spacing; (iii) thin parallel spacers and diamond spacers with a 60° flow attack angle provided lower pressure drop; (iv) the lowest critical Reynolds number for diamond spacer was found to be as low as 75 for small flow attack angles and can reach 200 for higher flow attack angles.

1.1. Membrane distillation

Membrane distillation (MD) is an emerging membrane separation process that involves the transport of vapor through porous hydrophobic membrane. The main driving force in MD process is the vapor pressure difference induced by the existing temperature difference between the warmer feed evaporator channel and the cooler permeate condenser channel. Due to its characteristics of low grade thermal energy requirement, low operational pressure and temperature and high compact design, the MD new evolving technology has a promising potential for the production of pure water from saline water, or industrial waste water. One main advantage of MD technology is that evaporation and condensation surfaces are tightly packed hence, leading to a compact system with low capital cost per unit product. Indeed, the low temperature levels required to operate the MD (40°–80 °C) makes it a good candidate for renewable energy or waste heat sources.

The classification of MD systems is related to the adopted condensation methods. In general, MD systems are classified into four different configurations [11]. These include the direct contact membrane distillation (DCMD), the air gap membrane distillation (AGMD), the sweeping gas membrane distillation (SGMD) and the vacuum membrane distillation (VMD). The succession of these different configurations was dictated by a need to improve the performance of the process. The DCMD is the simplest configuration that has liquid phases (hot feed and cold permeate) in direct contact with both sides of the porous hydrophobic membrane. The vapor diffusion path is limited to the thickness of the membrane, therefore reducing, the mass and heat transfer resistances would enhance the process.

In order to characterize the polarization phenomena, the focus of the current experimental study was kept on the spacer-filled channel only (and not on the membrane itself) as used in DCMD spiral wound or flat plate modules which can be studied by imposing a realistic thermal boundary condition at the walls, independent of whether there is or not a membrane and a vapor flux. Accordingly, two sets of experiments were conducted to obtain optimum flow and filament angles for the spacers. In the first set of experiments, spacers with two layers of orthogonally arranged cylindrical filaments are used while the flow angle is changed from 0° to 90°. In the second set of experiments, the flow angle is kept symmetrical while different spacers with different filament angles changing from 30° to 150° with 30° increments are used.

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