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Effect of module design and flow patterns on performance of membrane distillation process

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HIGHLIGHTS

- Effect of fiber configurations and flow patterns on MD performance has been studied.
- Undulating fibers show best performance in terms of flux at low feed flow rates.
- Helical modules and intermittent flows exhibit better energy efficiency.
- Intermittent and pulsatile flows are the best optimum.

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ABSTRACT

The present study highlights the effect of different hollow fiber membrane configurations and flow patterns on performance of membrane distillation (MD) process. The modules with helical and wavy conformations have been tested under various hydrodynamic conditions and their performance has been compared with conventional straight fiber modules. The effect of flow patterns has been studied by applying the intermittent and pulsating flows to straight hollow fiber membranes. A flux enhancement of 47% and 52% with respect to the straight fibers has been observed for helical and wavy configurations, respectively, though packing density of such modules is significantly less than their straight counterparts. For intermittent flow, an improvement of ~30% has been recorded. The difference is more prominent at low flow rates and approaches to the straight fiber performance under steady flow at high Reynolds numbers (*Re*) for all hollow fiber configurations and flow patterns studied. The intermittent flow and wavy fibers exhibit an energy efficiency enhancement of ~180% and ~90% over their conventional counter parts, respectively. In terms of surface and volume based enhancement factor and packing density, intermittent and pulsating flow exhibited the most optimal performance.

1. Introduction

Membrane distillation (MD) is an emerging process based on temperature gradient created across a microporous hydrophobic membrane that allows the passage of vapors only, thus retaining theoretically all non-volatiles present in the feed. The process provides the opportunity to concentrate the solution to their saturation level and the possibility to use waste grade energy. MD as standalone process or in integration with other processes finds interesting potential applications in numerous fields including desalination, wastewater treatment, recovery of minerals from various effluents, semiconductor industry, dairy sector, etc. [1]. Traditionally, MD has been operated in four well known configurations including direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), sweep gas membrane distillation (SGMD) and air gap membrane distillation (AGMD). Some new configurations have also been introduced recently [2–4].

Energy intensive nature and limited flux are the major obstacles in successful and widespread commercial adoption of MD. A

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significant amount of heat is dissipated in the process due to temperature or thermal polarization characterized by the difference in temperatures at the membrane surfaces and in bulk phases [5]. Among all the configurations, thermal polarization is the worst in DCMD which is the most studied configuration of MD. The effect of temperature polarization on flux reduction in membrane distillation has been well acknowledged in numerous investigations [6–8]. In addition to thermal polarization, surface scaling and organic fouling have also been found to depreciate MD performance as observed in various studies [9–12]. Hydrophobic nature of the membranes used makes it more susceptible to organic fouling. Under high convective flux, concentration polarization can also play significant role in limiting the flux of the process.

In order to mitigate thermal polarization, scaling/fouling and possible concentration polarization, MD can benefit from the solutions developed by the process industry to tackle the similar problems in other processes. For instance, most of the conventional techniques applied for fouling and concentration polarization reduction in pressure driven membrane processes [13] may provide interesting solution to mitigate thermal and concentration polarization in MD. However, due to limited flux (and therefore products), the techniques that consume too much energy may not be suitable for MD. After considering these factors, the most interesting techniques for MD are limited to only a few candidates. A pros and cons analysis of different state-of-the-art hydraulic techniques practiced for conventional membrane processes with application potential for MD has been provided in Table 1. Most of these techniques cannot only reduce the fouling in MD but they can also improve temperature distribution within the membrane module. The techniques can also have "wash away" effect on surface scales/crystals.

As pointed out in Table 1, one potentially feasible passive approach for improving heat transfer and reducing fouling in MD can be based on induction of the secondary flows inside the hollow fibers. The generation of secondary flows can be conveniently realized by using the undulating geometries. When a fluid flows in such channels, the centrifugal force caused by the geometry of the channel forces the fluid to flow toward the outer wall, thus creating a secondary flow or counter rotating vortices also referred as Dean Vortices. The phenomenon was first studied systematically by Dean [27] and was applied to pressure driven membrane operations by some groups later on. A good review of the concept as applied to the membrane processes can be found in reference [28]. Helically coiled membrane modules have been effectively used to create such vortices inside the hollow fiber membranes to reduce the fouling in pressure driven processes [29–32]. The secondary flows direct the foulants away from the membrane surface. The same concept has been used to increase heat transfer coefficient in heat exchangers [33–35]. The approach can be very promising for membrane distillation to improve the temperature polarization coefficient of the process both at upstream and downstream and to reduce the fouling and concentration polarization. Similar to helical geometries, crimped or wavy fibers have been used in membrane contactor and heat exchanger applications to increase mass and heat transfer coefficients [36–38]. Fundamental introduction to use of similar geometries for MD applications has been studied recently [17]. These geometries, however, reduce the packing densities of the fibers. Therefore, energy efficiency, area based enhancement factor (increase in flux per unit change in surface area) and volume based enhancement factor (increase in flux per unit change in module volume) should be introduce to comprehend the performance of such geometries.

The use of active techniques including ultrasonic stimulation and air bubbling has also been found affective in elevating the performance of MD [39,40,21]. Another interesting active approach to reduce concentration and thermal polarization can be realized by changing the flow pattern of the fluid flowing in a channel. Intermittent flow and pulsating flow are two common approaches used to realize this objective. The use of intermittent flow has been proven effective in increasing heat and mass transfer for separation and heat transfer applications [41,42]. On the other hand, pulsating flow has gained more attention for medical and biological applications [18,43]. Some studies have shown an improved heat transfer for pulsating flow [44–46]. Moreover, significantly improvement in performance of ultrafiltration has been claimed in another investigation [20].

Despite the use of various membrane configurations and flow patterns mentioned in above paragraphs for conventional pressure driven processes, the use of such approaches for MD applications has not been well explored. Current study aims to investigate the effect of secondary flows and flow patterns on performance of direct contact membrane distillation process. Induction of secondary flows has been realized by using helical and wavy shaped fibers under different hydrodynamic conditions. The pulsating and intermittent flows have been generated by using simple mechanical modifications of the conventional set-up used for MD. A comparative analysis of both approaches in terms of flux enhancement, energy efficiency, area base enhancement factor and packing density has also been provided.

Table 1
A brief analysis of possible hydraulic techniques for fouling and thermal polarization reduction in MD.

Technique	Potential benefits	Potential challenges	Selected references
Induction of secondary flow	No extra equipment required, easy to adopt, strong effect on temperature polarization on up and down stream sides, high shear acting on the surface can remove the attached particles and fouling layer built up, the performance can be tuned simply by changing the coil diameter and pitch.	Although for heat exchangers and low pressure membrane processes, the process has been well studied yet further studies are required to establish the effects for MD	[14–17]
Pulsating and intermittent flows	Reduction in concentration and thermal polarization, relatively simple to incorporate	Additional operational and capital cost associated with the flow patterns generating equipment	[18–20]
Air sparging	Reduction in fouling and thermal polarization	Additional cost related with air sparging equipment, air can occupy the part of membrane modules thus reducing the contacting area, the pores can be occupied by the injected air leading towards reduced vapor pressure	[21,22]
Backwashing	Removal of crystals, scales and deposits partially covering the pores	The pore wetting will occur leading to the post drying requirement, the effectiveness of the technique will be limited to remove deposition, scaling occurred within the pore or at pore mouth, no effect on thermal polarization	[23,24]
Rotating membranes	Reduction in concentration and thermal polarization	High energy consumption, design modification for MD can be complicated, may not be suitable for hollow fibers	[25,26]