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Numerical analysis of membrane distillation using hollow fiber membrane modules: a review

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ABSTRACT

Hollow fiber is one of the most widely used membrane types in the field of membrane-based water treatment, as hollow fiber membranes contain self-supporting structures and are easy to scale up due to their high productivity-per-unit volume. In the commercialization of hollow fiber membranes, module configuration is a key issue that is closely related to system performance. Especially for membrane distillation process, proper design of hollow fiber membrane module is necessary considering mass and heat transport. In an effort to enhance such performance, the inner-workings of the transport phenomena inside these membrane modules are investigated via various numerical approaches. A review of membrane module configurations allows for an examination of recent advances, applications, and numerical approaches related to hollow fiber modules; this is accomplished by a consideration of the characteristics of membrane distillation processes. Based on an analysis of previous research studies, and in an attempt to contribute to improved performance, potential challenges and applications of novel hollow fiber membrane modules are suggested.

Keywords: Hollow fiber membrane; Module design; Numerical analysis; Optimization; Membrane distillation

1. Introduction

In recent years, thermally-driven membrane processes such as membrane distillation (MD) have garnered much attention due to their low dependence on the salinity of a feed solution and their low fouling propensity. As it utilizes a microporous hydrophobic membrane, MD is based on the thermal gradient between the membrane's feed and permeate sides. Because this process can be operated using wasted grade heat, to include geothermal energy and solar energy, MD has also emerged as an alternative energy-saving desalination process that is suitable for specific purposes, such as the treatment of shale gas produced water.

Depending on the vapor pressure gradient across the membrane, a membrane's material is one of the most crucial aspects to be developed. Regarding the MD process, the MD membranes must exhibit high permeability, low fouling propensity, high chemical stability, and high thermal stability. In particular, hydrophobicity was seen as the most important indicator of membrane development, as it is a leading determinant of scaling potential as well as mass transfer resistance to vapor transportation through the membrane pores [1].

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In addition to selecting the appropriate membrane type, it is also important to consider how one intends to assemble the membranes in order to reduce concentration and/or thermal polarization and achieve a low fouling propensity. Thus far, most lab research has focused on the flat sheet membrane module, which has limitations in terms of its membrane area and energy consumption. In industrial practices, the application of hollow fibers is preferred due to their large membrane area-per-unit volumes and low TP/CP levels. A high rate of mass transfer through the high contact membrane surface is another major advantage of this type of fiber. However, if the membrane module is improperly designed, the resulting poorly-devised hollow fiber membrane can lead to reductions in water production and membrane lifespan as well as increases in energy consumption [2]. This is because poor module designs do not result in favorable flow conditions, low-pressure drops, or high packing densities and therefore cannot ensure system wide thermal stability or high heat recovery processes [3].

This paper will discuss various published studies on membrane module configuration (section 2), consider numerical approaches to hollow fiber modules (section 3), review relevant challenges, and suggest future research avenues for hollow fiber membrane modules (section 4). In this paper, the authors aim to contribute to the enhancement of system performance by using numerical approaches to consider membrane module designs in the analysis of membrane distillation process.

2. Hollow fiber membrane module configurations

The hollow fiber module was first introduced by the Dow Chemical Company (USA); notably, Dow's hollow fiber module design was inspired by the heat exchanger model [4]. In this design, each individual hollow fiber is held between two metal plates via uniform packing, and tens or even thousands of hollow fibers are packed together inside the shell.

In the water treatment industry, hollow fiber modules are preferred because they are associated with high water productivity-per-unit volumes and lead to reductions in concentration polarization (CP) and temperature polarization (TP) [5]. However, ideal water productivity can be restricted by a poor module design; additionally, high levels of heat loss and energy consumption and short membrane lifespan are two other problems associated with this membrane distillation process.

Yang et al. [6] altered the structure of hollow fiber membranes at the microscopic level in an effort to enhance fluid mixing and thereby increase the amount of heat transferred along the fiber. They also investigated various types of microstructures and discovered an optimal design for the achievement of the highest possible water productivity levels—the membrane distillation (MD) process. Hung et al. [7] introduced the practice of incorporating baffles around the individual fibers in order to improve performance. Similarly, via the use of computational fluid dynamics (CFD) simulations, Yu et al. [8] studied how to enhance heat and mass transfer performance during direct contact membrane distillation (DCMD), which incorporates annular baffles attached to the shell wall. Furthermore, Yang et al. [9] investigated the effects of promoters and baffles on both hollow fibers and shells. This work demonstrated that changes in fluid dynamics along the shell channel can lead to significant improvement of MD performance.

Dual hollow fiber membrane modules, as the name implies, consist of two or more hollow fiber bundles; these not only increase the surface area to facilitate mass transfer, but also allow for better hydrodynamics. Dual modules enhance the permeate flow rates in the separation of both gases and liquids. These modules can adopt various shapes–they can come in the form of U-shapes, coils, spirals, French horns, or one-ended U-shapes-depending on the processes and mechanical strengths of the module deemed suitable for a particular process [10,11]. However, while this module design can help to improve mass transfer processes, fiber geometry has been given less attention during efforts to increase mass transfer rates. Studies have shown a flux enhancement of 20%–28% with different baffle shapes, and an 18%–33% improvement can be achieved by placing spacers between the fibers. Moreover, following the application of wavy, twisted, or braided fiber geometries, the flux can be enhanced by 36% without the use of an external turbulence promoter [12]. Similarly, it has been shown that different module geometries, including helically coiled, sinusoidal, twisted, and meandering shapes, can increase mass transfer rates when compared with those of conventional straight fibers [13]. Researchers have therefore engaged in healthy discussion regarding the effects that active and passive techniques applied to hollow membrane modules can have on the mass and heat transfer processes [14].

3. Numerical approaches to hollow fiber membrane modules

This paper describes an analysis of various hollow fiber configurations, conducted using numerical approaches. For this purpose, we investigated the mass and heat flux through the inner and outer membrane surfaces. We explored the heat exchange behaviors that occur between the shell and lumen sides of a membrane; furthermore, we studied the important factors of temperature and concentration profiles.

As previously mentioned, a hollow fiber module is a configuration in which a bundle of cylindrical pipe-like membranes are packed into a shell. Two streams of liquid are then flowed through both the lumen and shell sides of the module. Notably, not all fibers are identically straight, and the random distribution of these fibers in a hollow fiber module can induce differences in mass and heat transfer behavior. As experimental approaches cannot precisely explain what occurs inside a channel, numerical approaches—such as computational fluid dynamics (CFD)—are widely employed in the modeling of hollow fiber membrane processes; this allows us to better understand the effects of various operating conditions on the module's performance. During this examination, we focused on using numerical approaches to model mass transfer and heat transfer processes in hollow fiber membrane modules; we aimed to gain a deeper understanding of the mechanisms at play and contribute to the development of performance improvement by engaging in novel module design.

The driving force of MD is the thermal difference between the feed and permeate sides; additionally, a hydrophobic microporous membrane acts as a physical barrier in that it allows only water vapor to pass through its micro-sized pores [15]. The mass flux of the membrane distillation process can be calculated using the following equation:

$$J_s = R_{\text{total}}\Delta P \tag{1}$$

where ΔP represents the vapor pressure difference between the membrane surfaces on the feed and permeate sides, and R_{total} indicates total resistance to the mass transfer process. Considering various resistance factors such as membrane (R_m), solution concentration (R_c), and membrane fouling (R_f), total resistance can be expressed as follows [16]:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_m + R_c + R_f} \tag{2}$$

If we assume that no fouling is observed during relatively low salt concentration MD processes, R_c and R_f can be neglected; this is relevant when the ion concentrations of feed solutions are disregarded and when no membrane fouling is observed.

Using an experimental approach, we can estimate the membrane resistance factor by fitting the data. However, R_m can also be estimated using various models to represent the different types of MD systems. In general, three popular models, based on molecular transport and diffusion, are widely applied during such modeling efforts. These include the Knudsen diffusion model, the molecular diffusion model, and a combination of both (also referred to as the Dusty-gas model); these models consider the mean free path (λ), membrane pore size (r), and Knudsen number, k_n, which is defined as the ratio of the mean free path to the membrane pore size, $k_n = \lambda/r$,. Three regions can be identified based on the mean free path and Knudsen figures: the Knudsen diffusion region ($\lambda > 1$ or $r < 0.5$), the molecular diffusion region ($\lambda < 0.001$ or $r > 50$), and the transition region ($0.01 < \lambda < 1$ or $0.5 < r < 50$). As it represents the controlling factor in model selection, the mean free path can be calculated as follows [17]:

$$\lambda = \frac{k_b T}{\pi\left(\frac{\sigma_w + \sigma_a}{2}\right)^2 P_a} \frac{1}{\sqrt{1 + \frac{m_w}{m_a}}} \tag{3}$$

where k_b represents the Boltzmann constant, T indicates the absolute temperature, and P_a signifies the air pressure inside the membrane pore (≈101 kpa). Furthermore, σ_w and σ_a denotes the molecule collision diameters of water and air. Moreover, m_w and m_a represent the molar masses of that water and air, respectively.

For the Knudsen diffusion region, R_m is calculated as follows [16]:

$$R_m = \frac{\varepsilon}{\tau\delta}\frac{M}{RT}\frac{1}{D_k} \tag{4}$$

where ε, τ, and δ indicate membrane porosity, membrane tortuosity, and membrane thickness, respectively. Additionally, R, T, and M represent the gas constant, temperature, and molar weight, respectively. Here, we assume that each membrane pore is of uniform size.

For the molecular diffusion region, we can apply the molecular model to calculate the membrane transfer coefficient without considering fouling or the resistance of the solution concentration [16]; this can be accomplished using the following equation:

$$R_m = \frac{\varepsilon}{\tau\delta}\frac{M}{RT}\frac{p_a}{pD_{wa}} \tag{5}$$

For the transition region, the mass transfer phenomena through a hydrophobic membrane pore can be calculated using a combination of the Knudsen and molecular diffusion models [16]; this is also referred to as the Dusty-gas model and is exemplified by the following equation:

$$R_m = \frac{\varepsilon}{\tau\delta}\frac{M}{RT}\left(\frac{1}{D_k} + \frac{p_a}{pD_{wa}}\right)^{-1} \tag{6}$$

where the diffusion coefficients can be expressed as follows [18]:

$$D_k = \frac{2}{3} r \sqrt{\frac{8RT}{\pi M}} \tag{7}$$

$$pD_{wa} = 4.46 \times 10^{-6}\,\mathrm{T}^{2.334} \tag{8}$$

The key equations for MD process using hollow fiber membrane module are summarized in Table 1.

4. Membrane module modeling and optimization

In general, hollow fiber modules apply separation processes, and their performance has been studied quantitatively using either a mathematical modeling approach or an empirical correlation method. However, the effects of geometrical characteristics on such a module's flow state (such as its turbulent flow motion) or on its process performance have yet to be fully elucidated. One proposed solution known as computational fluid dynamics (CFD) provides an effective approach to such an investigation. Over the past few decades, as a result of advancements in computational power, it has become easier for researchers to investigate the physical phenomena involved in membrane separation during various membrane distillation processes [20–23].

With regard to hollow fiber module-applied membrane processes, studies of CFD and its applications are rarely found; however, some researchers have developed models to investigate various relevant factors such as module type, flow type, and the like [6,8,9,20–23]. However, very few published papers have broached the subject of hollow fiber module-applied membrane separation processes.

Table 1
A summary of the key equations for MD process using hollow fiber membrane module

Membrane distillation				References
Mass transfer	Deterministic model	Water flux	$J_s = R_{\text{total}}\Delta P$ $J = \frac{\varepsilon}{\tau}\frac{M}{RT}\left(\frac{1}{D_k}+\frac{p_a}{pD_{wa}}\right)^{-1}\frac{dP_w}{dr}$	[12]
		Mass transfer coefficient	$\frac{1}{R_{\text{total}}} = \frac{1}{R_m + R_c + R_f}$ $R_{\text{total}} = R_m = \frac{\varepsilon}{\tau\delta}\frac{M}{RT}\left(\frac{1}{D_k}+\frac{p_a}{pD_{wa}}\right)^{-1}$	[16]
		Diffusion coefficient	$D_k = \frac{2}{3}r\sqrt{\frac{8RT}{\pi M}}$	[18]
	Experiment-based model	Water flux	$J = C\frac{M}{RT}\frac{dP_w}{dr}$	[12]
		Mass transfer coefficient	$\frac{1}{r}\frac{d}{dr}(rJ) = 0,$ $P_w = \gamma\exp\left(A-\frac{B}{C+T}\right)x_w \text{ at } r = R_o$ $P_w = \gamma\exp\left(A-\frac{B}{C+T}\right) \text{ at } r = R_i$	
Heat transfer	Deterministic model	Heat flux	$Q = \left(\frac{1}{h_{f\left(d_i/d_o\right)}}+\frac{1}{h_m+\frac{J\Delta H_v}{T_{fm}-T_{pm}}}+\frac{1}{h_p}\right)^{-1}\left(T_f - T_p\right)$	[19]
		Heat transfer coefficient	$h_m = \frac{k_m}{d_i\ln\left(d_i/d_o\right)} = \frac{k_g\varepsilon + k_m(1-\varepsilon)}{d_i\ln\left(d_i/d_o\right)}$ $h_{\text{overall}} = \left(\frac{1}{h_f\left(d_i/d_o\right)}+\frac{1}{h_m+\frac{J\Delta H_v}{T_{fm}-T_{pm}}}+\frac{1}{h_p}\right)^{-1}$	
		Evaporation efficiency	$\text{EE} = \frac{Q_{\text{evaporation}}}{Q_{\text{total}}} = \frac{Q_{\text{evaporation}}}{Q_{\text{evaporation}}+Q_{\text{conduction}}} = \frac{JH_v}{JH_v + h_m\left(T_{fm}-T_{pm}\right)}$	[15]

4.1. Hollow fiber membrane

4.1.1. Membrane length

Related to the topic of the heat and mass transfer processes that occur during MD using hollow fiber modules, Yu et al. [20] explained how mass transfer rates and thermal efficiency are affected by operating conditions and local heat flux changes that occur along a fiber's length. These researchers built a two-dimensional heat transfer model using Fluent 6.3 to represent the DCMD process. They found that local heat fluxes increased to a certain point, after which an opposite trend along the fiber length was observed. However, the temperature polarization (TP) coefficient maintained the same profile across the entire fiber length.

Additionally, the authors also found that the Nusselt number (Nu) reached its highest values at the entrances of the feed and permeate sides. Furthermore, the heat transfer coefficient of the feed side was typically half that of the permeate side. These results indicate the importance of hydrodynamic behavior on the feed side in the process performance of hollow fiber module-applied DCMD. Moreover, the authors concluded that even a higher feed and permeate circulation velocity could enhance the transmembrane flux, as greater heat loss inevitably occurred as a result of thermal efficiency decreases at higher permeate velocities. It was also found that under the same conditions, mass flux decreased with increasing module length.

4.1.2. Membrane geometry

It must also be noted that microstructural changes in a hollow fiber itself can give rise to transmembrane flux along the hollow fiber module-applied membrane during the separation process. Applying a CFD modeling approach, Yang et al. [6] researched how to optimally design a hollow fiber microstructure. Analyses of heat transfer, mass transfer, and flow field distributions were conducted for 10 different geometries. Yang et al. built a three-dimensional (3D) CFD model to investigate the optimization of geometric fiber structures and lengths during MD processes and explored the effects of hollow fiber modules with straight, wavy, and gear-shaped fiber types. After adjusting the model's hydrodynamics via flow motion changes along the fiber, the authors recorded 57% and 66% improvements to the temperature polarization coefficient and the permeate mass flux figure, respectively, when using gear-shaped fibers. As compared with other fiber types, the gear-shaped structure induced the highest mass flux figure and the highest temperature polarization coefficient (TPC). Yang et al. [6] also proposed that gear-shaped fiber modules improve mass flux at extremely low Re values and are associated with the lowest hydraulic energy consumption (HEC) levels [6]. Thus, their study contributed to a new perspective on hollow fiber membrane development for high-level water production projects.

4.2. Packing density

Lian et al. [21] developed a 3D model of a vacuum membrane distillation (VMD) module in which seven fibers are bundled together; using a "mass jump" method, they investigated the impact of packing density, operating parameters, and feed concentration on the permeate flux of the hollow fiber VMD module. Results indicated that both feed temperature and cross-flow velocity significantly impacted the permeate flux at different packing densities; for example, a 56% increase in packing density induced a 24% decline in flux at an operating temperature of 70°C, whereas a more than 50% decline in flux was observed at a low cross-flow velocity of 0.0072 m s^{-1}. Additionally, an increase in feed concentration resulted in a flux decline, though the decline rate was 28% lower than the theoretical value predicted using Raoult's law.

4.3. Turbulence promoter

Regarding the hydrodynamic consequences of mass and heat transfers, Yu et al. [8] investigated the effects of the MD intrinsic mass transfer coefficient on the process performance of both non-baffled and baffled CFD modules. Following the application of baffles, the TPC decreased significantly with each increase in the mass transfer coefficient of the membrane, while the permeate mass flux demonstrated a rising trend. Turbulence, which is generated by the baffles, did not affect system performance or lead to improvements in the low mass transfer coefficient of the membrane. However, considering the high value of the mass transfer coefficient of the membrane, baffles can greatly enhance the permeate flux and TPC levels.

Generally, TPC decreases with increasing operating temperatures. In this study, the authors found that a more significant improvement in TPC was observed in the baffled module than in the non-baffled module. Thus, a higher permeate flux value can be obtained using a baffled module. However, with respect to the temperature rise experiment, the baffled module was less effective due to the heat/mass transfer rate (which is dominated by transport resistance). However, the authors concluded that the hydrodynamic approaches maintained significance when the heat transfer was partially shifted to the boundary layer at a high operating temperature.

In an extended exploration of Yu's work [8], Yang [9] designed several types of modified hollow fiber modules and various turbulence promoters to investigate heat and mass transfer enhancements to MD processes. As compared with the original modules (which contained no turbulence promoters), the modules with associated turbulence promoters yielded much slower heat transfer rates and decreasing trends along the fiber length. The authors also observed 57% and 74% improvements in the TPC and mass flux figures, respectively, in the 6-fold modified module (Quad spacer 0.2 × 2. 0 × 30). The temperature profiles and flow distributions taken from various CFD studies indicate the presence of improvements to shell side hydrodynamics and enhancements to heat transfer processes resulting from the appropriate selection of turbulence promoters. Thus, a well-designed module can stimulate significant improvement of a liquid boundary layer-dominant heat transfer process. Their study therefore contributed to a new perspective on these process-enhancing strategies.

Kaya et al. [22] used ANSYS Fluent V14.5 to investigate the effects of different inlet and outlet configurations on shear stress distribution and pressure loss in the various hollow fiber module types. To this end, the author examined the classical inlet-outlet configuration module and the tangential inlet-outlet configuration module. Compared with the classical module, the tangential inlet-outlet module induced higher levels of shear stress, and more homogeneous velocity profiles were observed. However, experimental studies showed that the pressure drops in both models were nearly identical at a steady state.

In recent years, researchers have also attempted to improve the performance of hollow fiber module-applied membrane processes via the novel design of liquid distributors. Wang et al. [23] used CFD simulations to desk three types of novel liquid distributors—flat-plate, dome-like, and pyramidal—to facilitate the enhancement of the permeate mass flux during the VMD process. Results indicate that an even liquid distribution can be obtained from an optimally-designed liquid distributor. Notably, the pyramidal and dome-like distributors performed better than the flat-plate distributor. Concerning the cross-flow membrane module (CF-MM) with no distributor, the permeate flux figure increased to roughly 5% of that of the flat-plate distributors and to about 6%–12% of that of the pyramidal distributors when the max permeate flux was set at roughly 72 L/m^{2}h. Thus, we found that optimized liquid distributors can significantly enhance permeate mass flux during VMD processes.

5. Future challenges and conclusions

Since most breakthroughs have focused on membrane preparation and synthesis, improvements of hollow module design should be studied in an effort to solve other problems, including membrane fouling-induced high energy consumption, low water productivity, and short membrane lifespans, which are the key challenges facing the commercialization of membrane processes. It should be noted that CFD-based models can yield qualitative results, such as detailed explanations of mass transfer improvements that result from changes to operational conditions.

However, extensive and comprehensive CFD modeling studies are still needed to facilitate a complete investigation of novel membrane module designs. Most of the utilized hollow fiber modules were based on more traditional shell side or bore side modules. Regarding the membrane distillation processes, it is hard to estimate to yield expected water production per unit membrane area because mass and heat are transferred simultaneously. Novel designs of these modules based on different shapes and hollow fiber membrane lengths and diameters are critical components of performance improvement and must be investigated. Finally, and perhaps most importantly, the systematic optimization of operating conditions (including flow velocity, applied external pressure, and temperature) and module design (to include packing density, fiber length, shell diameter, and spacer morphology) should be effectively completed via the use of CFD modeling techniques.

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