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Vacuum membrane distillation for desalination of water using hollow fiber membranes

Andy Chenggui Sun [a], Walter Kosar [b], Yufeng Zhang [c], Xianshe Feng [a,*]

[a] Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1
[b] Fluoropolymers Group, Arkema Inc., King of Prussia, PA 19406, USA
[c] State Key Laboratory of Hollow Fiber Membrane Materials and Processes, School of Material Science and Engineering, Tianjin Polytechnic University, Tianjin 300160, China

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ABSTRACT

Vacuum membrane distillation (VMD) for desalination of water using hollow fiber membranes with a shell-side feed configuration was investigated. The effects of membrane permeability, water salinity, feed temperature and flow rate on the water permeation rate were evaluated, and the water vapor pressure buildup in the fiber lumen was analyzed. The pressure buildup of water vapor in the fiber lumen was shown to adversely affect the driving force for water vapor permeation through the membrane pores, and a mathematical model was developed to describe the mass transfer in VMD by incorporating the permeate pressure build up. The model predictions were validated with experimental data. The higher the membrane permeability, the more significant the permeate pressure build-up. This is especially important to consider in module design for practical applications. For VMD of saline water, the membrane played a dominant role in the overall mass transfer process, and the significance of the effect of liquid phase resistance on water permeation depended on the membrane permeability. An increase in operating temperature increased the water productivity in VMD, primarily due to increased driving force for permeation, whereas the permeability of the membrane was not significantly affected. A factorial design experiment was carried out to illustrate the effects of main factors involving membrane permeability and operating parameters (feed concentration, temperature and flow rate) on the VMD performance, and some interactions among the effects were shown to occur as well.

1. Introduction

The scarcity of drinking water has been a global problem for years, and desalination of seawater and brackish water has become one of the most promising methods to produce fresh water. Recently, membrane distillation has attracted significant attention as a potential technology for desalination of saline water, where the brine solution passes along the surface of a microporous hydrophobic membrane and water evaporates into the pores of the membrane at the brine–membrane interface, which is then withdrawn as the product from the downstream side of the membrane. A primary advantage of membrane distillation over the traditional thermal process is that membrane distillation can operate at a temperature much lower than the boiling point of the liquid feed, and thus solar and geothermal energies or low grade heat from other energy sources can be utilized [1,2]. A comprehensive review of membrane distillation can be found in the literature that covers the basic process principles, membranes, heat and mass transfer characteristics, and potential applications [3–5].

There are primarily two modes of operation to carry out membrane distillation. In one mode, a stream of cold water (relative to a hot brine) is allowed to contact one side of the membrane while the other side of the membrane is exposed to the hot brine. This will produce a vapor pressure difference between the two membrane interfaces, thereby transferring water vapor from the hot brine through the membrane pores to the cold water stream which also serves to condense the vapor. This is the so-called direct contact membrane distillation, where there is a direct heat transfer from the hot brine to the cold water across the membrane by conduction, resulting in a significant energy loss [6–9]. Alternatively, instead of using cold water, vacuum may be applied to induce evaporation of water from the brine and water vapor transport through the pores in the membrane. The water vapor withdrawn is to be condensed in a separate condenser. Such a process mode is called vacuum membrane distillation (VMD) [3–5]. Compared to the direct contact membrane distillation, the heat loss from the saline water due to thermal conduction across

* Corresponding author. Tel.: +1 519 888 4567x36555; fax: +1 519 746 4979.
E-mail address: xfeng@uwaterloo.ca (X. Feng).

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the membrane is much less significant in VMD, and a substantially high water vapor flux may be achieved if a reasonably high vacuum can be maintained at the permeate side. In addition, there is little or essentially no temperature polarization on the permeate side because of the vapor phase of the permeate which is removed instantly. When applied for desalination of saline water, VMD can approximately be considered to consist of the following steps: evaporation of water at the brine/membrane interface, diffusion of water vapor through the membrane pores, and withdrawal of water vapor from the membrane unit under vacuum. The membrane acts as a physical support to provide a stable vapor/liquid interface. The energy for water evaporation comes primarily from the brine solution. The mass transfer through the membrane and the heat and mass transfers in the liquid phase are generally considered to be the main parameters determining the performance of VMD [10,11], while the evaporation of water is expected to be fast enough that it does not limit the overall mass transport process.

Wirth and Cabassud [12] analyzed the energy consumption of VMD for seawater desalination, and VMD was shown to be advantageous over reverse osmosis, another membrane process that uses tight membranes under high operating pressures to overcome the osmotic pressure. In theory, as the salinity of feed water increases, the water vapor pressure (which is approximately proportional to mole fraction of water) decreases and the osmotic pressure (which is approximately proportional to the molar concentration of salt in the solution) increases; however, the reduction in water vapor pressure is far less significant than the increase in the osmotic pressure. Thus, unlike in reverse osmosis, the permeation flux of water in VMD is expected to be not very sensitive to salt concentration in the feed. This hypothesis is supported by the experimental data of Wirth and Cabassud [13] who observed a flux decline of less than 30% when the salt concentration in the feed increased by 20 times. This aspect is particularly important for desalinating brines at high salinities where the osmotic pressure may be excessively high for reverse osmosis to work effectively. A detailed analysis of energy consumption and water production costs for desalination by membrane distillation can be found in a very recent review article by Khayet [14].

Suitable hydrophobic membranes for desalination by VMD are mainly produced from polytetrafluoroethylene, polypropylene and poly(vinylidene fluoride) (PVDF). The hydrophobicity of the membrane is needed to prevent penetration of the aqueous brine solutions to the membrane pores so that the pores will be filled with water vapor instead of the saline liquid. Not only will this minimize the mass transfer resistance in the membrane because water vapor is much more permeable than a liquid in a given membrane, the concentration polarization on the feed side will also be reduced if the liquid is not contained in or restricted by the pores, thereby achieving maximum permeation flux. PVDF membranes have received significant attention in recent years due to their good hydrophobicity as well as the availability of different polymer grades and the versatility of forming asymmetric membranes (in the form of flat sheets, hollow fibers, or other geometry) using various methods, including nonsolvent- and thermally-induced phase inversions and electro-spun nanofiber membranes (see, for example, [15–21]). A great deal of work has been done on fabrication of PVDF hollow fiber membranes for membrane distillation [22–26], and some of the work focuses on fine tuning of membrane structures to improve the membrane performance [27–29]. It has been reported that relatively thick membranes (ca. 100–200 μm) with spongy structures having pore sizes smaller than 0.2 μm in diameter are desired to maintain a good thermal resistance and mechanical strength [30].

A main advantage of hollow fiber membranes is their high membrane packing densities. The hollow fiber walls are self-supporting and do not require external support, and as a result it is much easier to manage fluid flow in hollow fiber modules than in plate-and-frame and spiral modules. The feed solution may flow inside the fiber lumen (bore-side feed), and the permeate is collected from the external surface of the fiber wall on the shell side of the membrane module. Alternatively, the feed solution may flow on the shell side (i.e., shell-side feed), while the permeate is collected from the lumen side. Table 1 summarizes the hollow fibers (and capillary membranes) reported in the literature for use in VMD. Both bore-side feed and shell-side feed have been used for VMD, and each mode has its own advantages and potential problems. In bore-side feed, there will be a relatively uniform flow

Table 1
Hollow fiber membranes used for vacuum membrane distillation.

Membrane	Feeding mode	Fiber diameters ID/OD (μm)	Pore structure	Ref.
Poly(vinylidene fluoride)	Shell side feed; tube side feed	ID 2600, OD unknown	Mean pore diameter 0.2 μm, porosity unknown	[12,13]
Poly(vinylidene fluoride)	Tube side feed	ID 476–534, OD 798–898	Mean pore diameter 0.062–0.15 μm, effective porosity $\varepsilon/l = 71–1516\ m^{-1}$	[15]
Polyethylene	Shell side feed; tube side feed	ID 700, OD unknown	Mean pore diameter 0.1 μm, porosity unknown	[12,13]
Polypropylene	Tube side feed	5500/8600	Nominal pore diameter 0.2 μm, porosity 75%	[31,32]
Polyethylene	Tube side feed	268/368	Pore diameter 0.087 μm, porosity 66.3%	[33]
Polypropylene	Tube side feed	275/405	Pore diameter 0.044 μm, porosity 50%	[33]
		343/443	Pore diameter 0.074 μm, porosity 53.3%	
		358/442	Pore diameter 0.056 μm, porosity 47.3%	
Polypropylene coated with a silicone fluoropolymer	Shell side feed; tube side feed	200/305	Max. pore size 0.1 μm, porosity 50%	[34]
		280/380	Max. pore size 0.1 μm, porosity 50%	
		330/630	Max. pore size > 0.2 μm, porosity 65%	
Poly(vinylidene fluoride)	Tube side feed	520/900	Mean pore diameter 0.32 μm; effective porosity $\varepsilon/l = 118\ m^{-1}$	[35,36]
Poly(phthalazinone ether sulfone ketone) coated with silicone polymers	Tube side feed	1000/1300	Pore size and porosity unknown; liquid water entry pressure 0.12-0.18 MPa	[37]
Poly(vinylidene fluoride)	Tube side feed	800/1100	Mean pore size 0.16 μm; porosity 85%	[38]
Poly(vinylidene fluoride) blended with PVP	Tube side feed	ID 1187–1522; OD 1531–1899	Mean pore size 0.12–0.25 μm, porosity 70.6–83.6%	[39]
Poly(vinylidene fluoride)	Tube side feed	ID 704–1009; OD 1114–1347	Mean pore size 0.28–0.82 μm, porosity 68.6–79.2%	[40]
Polypropylene	Shell side feed	220/300	Mean pore diameter 0.2 μm, porosity unknown	[41]

Note: Unless specified, it is unclear whether the reported pore size refers to diameter or radius.