Desalination 367 (2015) 197–205

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Factors contributing to flux improvement in vacuum-enhanced direct contact membrane distillation

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HIGHLIGHTS

- VEDCMD has higher water flux than DCMD and PEDCMD.
- Higher flux with vacuum applied may be partially due to lower membrane compaction.
- Higher flux with vacuum applied may be partially due to lower membrane air pressure.
- Pressure differences due to vacuum or pressure enhancement has a minimal effect on flux.

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 2 April 2015
Accepted 3 April 2015
Available online 17 April 2015

Keywords:
Direct-contact membrane distillation
Flux improvement
Membrane compaction
Membrane pore pressure

ABSTRACT

Low water flux in membrane distillation (MD) is a concern for full-scale application. In the past decades, attempts have been made to improve water flux in MD and vacuum-enhanced direct-contact MD (VEDCMD) has been proven to be an effective configuration to achieve this. However, only qualitative assessments of the factors that might improve water flux have been reported in the literature. In this study, a mechanistic investigation of the factors contributing to higher water flux in VEDCMD was performed. Direct-contact MD (DCMD) and pressure-enhanced DCMD (PEDCMD) configurations were also investigated for comparison. Less membrane compaction was identified as one dominant factor contributing to improved water flux in VEDCMD as very little compaction occurred in VEDCMD compared to that which occurred in DCMD and PEDCMD. Lower air pressure inside the membrane pores was found to be the other dominant factor contributing to improved water flux in VEDCMD; the air pressure was calculated as the average of the feed and distillate pressures in VEDCMD and as the distillate pressure in DCMD and PEDCMD. Pressure difference, as is present in both PEDCMD and VEDCMD, was found to have a minimal effect on water flux.

1. Introduction

Membrane distillation (MD) is a thermally driven membrane process in which separation occurs through a phase change. The driving force in MD is the vapor pressure difference resulting from the temperature difference across the membrane. Because of the high latent heat of evaporation of water, MD is an energy-intensive process [1]. However, it can be combined with low-grade ("waste") heat to reduce energy costs [2–8].

MD has advantages over conventional membrane processes (e.g., reverse osmosis) because the driving force of MD does not decrease significantly with increasing feed-water salinity [9]. This has inspired interest in MD for treatment of high-salinity brines [10–12] and complex feed waters such as flowback and produced waters in the oil and gas industry. More recent interest in MD results from the higher rejections of MD membranes over reverse osmosis membranes; theoretically, MD can achieve 100% rejection of salts and non-volatile organics. For this reason, MD is well suited to remove salts and low-molecular-weight contaminants (e.g., boron, trace organic compounds, and urea) that may pass through other treatment methods such as reverse osmosis [13–16]. MD could be considered as a replacement treatment option or as a side-stream treatment, whereby a side stream of reverse osmosis permeate could be further polished for these contaminants and then blended with the bulk permeate to achieve treatment objectives. In all cases, maintaining membrane hydrophobicity is key for achieving high rejection of the membrane [17].

When treating more complex feedwaters, it has been found that high water fluxes can cause faster transport of fouling and scaling material to the membrane surface and thus, high water fluxes are detrimental to membrane flux over time [10]. On the other hand, when treating feed waters with relatively low fouling and scaling potentials, obtaining

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http://dx.doi.org/10.1016/j.desal.2015.04.002
0011-9164/

high water flux is desirable [9]. Approaches to improve water flux have included developing novel membranes [18], deaerating feed waters [2,19], and using vacuum in the membrane module [20,21]. Schofield et al. [19] and Cath et al. [20] employed equal vacuum on both the feed and distillate sides of the membrane and observed higher water fluxes compared to the traditional DCMD configuration (without hydraulic pressure or vacuum employed). Cath et al. [20] also used vacuum only on the distillate side while keeping the feed side at atmospheric pressure and this led to even greater flux improvement. This process, called vacuum-enhanced DCMD (VEDCMD), was patented in 2010 [22].

Increased flux with the application of vacuum has been partially or fully attributed to decreased air pressure inside the membrane pores, decreased temperature polarization, decreased membrane conductive heat loss, and increased pressure difference across the membrane [19–21]. However, the mechanisms for improved flux have not been systematically evaluated and the dominant factors affecting flux enhancement have not been clearly identified. It is possible that only one or two factors may explain flux improvement and of these factors, mechanistic evaluations of air pressure inside the membrane pores have been inconclusive. In two different studies, one where vacuum was employed on the distillate side of the DCMD membrane [21] and the other where vacuum was employed on both the feed and distillate sides [19], the pore pressure (sum of air pressure and water vapor pressure inside the pores [23,24]) was assumed to be equal to the vacuum pressure of the distillate stream. It is unlikely that the same assumption is valid for both scenarios. Therefore, in determining the dominant factors affecting water flux in VEDCMD, analyses must go beyond what has been done previously in the literature. Furthermore, there is no consensus in the literature on the role of membrane compaction on water flux. One study from the literature that employed hydraulic pressures of equal magnitude on the feed and distillate sides of the membrane observed flux reduction compared to traditional DCMD systems; membrane compaction was suggested to be the reason [25], especially for membranes with low porosities [26]. Another study that employed hydraulic pressure only on the feed side observed no flux change [20], and it was postulated that membrane compaction was one of the factors that increased water flux (opposite to [25]), while other factors reduced water flux, leading to the near constant overall water flux.

The overall objective of this study is to evaluate the dominant factors responsible for improved water flux when vacuum is employed in DCMD. Because employing vacuum only on the distillate side of the membrane (as in VEDCMD) leads to greater flux improvement than any other configuration, VEDCMD is the main focus of this study. To achieve the overall objective, first, the dominant factors contributing to higher water flux in VEDCMD are evaluated theoretically. Second, the magnitude of air pressure inside the membrane pores in VEDCMD is quantified and its effect on water flux is evaluated. Third, membrane compaction is measured and the effect of membrane compaction on water flux is evaluated. Results from this study will aid in better understanding of the factors leading to enhanced water flux in VEDCMD and in turn, facilitate application of VEDCMD especially in treatment of water with low fouling and scaling potential where high water flux is desirable.

2. Materials and methods

2.1. Experimental setup

Three DCMD configurations were evaluated: traditional DCMD without hydraulic pressure or vacuum applied; VEDCMD with vacuum applied on the distillate side; and pressure-enhanced DCMD (PEDCMD) with hydraulic pressure applied on the feed side. The PEDCMD configuration was used for comparative purposes by creating the same hydraulic pressure difference as used in VEDCMD. A bench-scale system with a modified acrylic membrane cell was used to study these configurations. The membrane cell utilized a flat-sheet membrane with 118 cm^2 (13.5 cm by 8.7 cm) of effective membrane surface area. DCMD and PEDCMD used the same setup (Fig. 1a) with a needle valve at the outlets of both the feed and distillate sides to adjust the pressure inside the membrane cell. In VEDCMD (Fig. 1b), the distillate-side pump was on the outlet of the membrane cell to create a vacuum on the distillate side by drawing water from the cell. The pressures on the feed and distillate sides were maintained at 20/20 (feed/distillate) kPa in DCMD; 60/20, 80/20, and 100/20 kPa in PEDCMD; and 20/−20, 20/−40, and 20/−60 kPa in VEDCMD. All pressures in the current study were reported as gauge pressures. All tests were performed using the same feed temperature (40 °C), distillate temperature (20 °C), and fluid flow rates (1.0 L/min) on both the feed and distillate sides. A 35 g/L NaCl solution was used as the feed solution and deionized (DI) water was used on the distillate side. The feed solution and the DI water were re-circulated counter-currently on their respective sides of the membrane. As water evaporated through the membrane, excess water from the distillate reservoir overflowed into a beaker on an analytical balance. The overflow rate was used to calculate the water flux. The test was stopped when the flux was stable for 30 min. To create turbulent flow and reduce temperature polarization, spacers were placed in the flow channels on both the feed and distillate sides. A bench conductivity meter (Traceable™, VWR International, USA) was used to measure the feed and distillate conductivities. Temperatures, pressures, and dissolved oxygen (DO) concentrations were monitored using dual-channel digital thermometers, pressure gauges, and DO probes at the inlet and outlet of the membrane cell. Average DO values were calculated and used to investigate oxygen (i.e., air) transport across the membrane. The DO probes (YSI 556 MPS, YSI Environmental, Yellow Springs, OH) had a response time of 2–8 s according to the manufacturer.

2.2. Membrane characterization

A single-layer flat-sheet polytetrafluoroethylene membrane (GE Water & Process Technologies, Minnetonka, MN) was used in this investigation. A new membrane coupon was used for each test. Membrane properties (thickness, porosity, tortuosity, and average pore size) were determined for the unused membrane and the membranes after flux testing.

2.2.1. Membrane thickness and compaction measurements

Membrane thickness (δ) was measured from scanning electron micrographs of membrane cross sections. Three membrane coupons were taken from the same roll of membrane. For each coupon, membrane thickness was measured at three different locations to calculate the average membrane thickness and standard deviation. Each membrane coupon was frozen in liquid nitrogen and cut with a blade.

Multiple regression analysis was performed using Minitab® 17.1.0 to statistically evaluate membrane compaction. The new (unused) membrane was set as the control and the various pressure scenarios (e.g., 60/20, 20/−20) were set as the variables. A p value less than 0.05 was considered significant [27].

2.2.2. Membrane porosity and tortuosity measurements

Membrane porosity (ε) was determined by [28]:

$$\varepsilon = 1 - \frac{m}{\rho_p \times A \times \delta} \quad (1)$$

where m and A are the mass and surface area of the membrane coupon, respectively (assumed constant before and after flux testing), and ρ_p is the reported density of the polymer material (2.2 g/cm^3 [29,30]). Although additives may be included during the membrane manufacturing