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Combined influence of temperature and flow rate of feeds on the performance of forward osmosis

Alaa H. Hawari [a,*], Nagla Kamal [a], Ali Altaee [b]

[a] Department of Civil and Architectural Engineering, College of Engineering, Qatar University, P.O. Box 2713, Qatar
[b] University of Technology Sydney, School of Civil and Environmental Engineering, Ultimo, NSW 2007, Australia

HIGHLIGHT

- The impact of temperature and flow rate on the FO performance was evaluated.
- At FS-AL, dilutive CP was aggravated by increasing draw solution flow rate.
- Membrane flux decreased by increasing DS temperature over 26 °C.
- A thermo-osmosis effect was responsible for reducing the flux at high temperature.
- Membrane flux increase by increasing feed temperature from 20 °C to 32 °C.

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ABSTRACT

The effect of the membrane orientation, feeds flow rate, feeds temperature, and combining effect of both temperature and flow rate on the membrane flux was investigated in order to enhance the performance of forward osmosis (FO) process. Results from experimental work demonstrated that the concentrative internal concentration polarization (CICP) could be mitigated by increasing the feed solution flow rate and using a spacer. On contrary, the severity of dilutive internal concentration polarization (DICP) phenomena was aggravated by increasing the draw solution flow rate. It was also found that when increasing the draw solution (DS) temperature from 20 °C to 26 °C the flux increased linearly and then started decreasing when temperature increased over 26 °C due to the development of a temperature gradient. The experimental results also showed that the membrane flux increased by 93.3% due to temperature increase from 20 to 26 °C and the flow rate from 1.2 to 3.2 L/min using a 0.5 M NaCl solution as the draw solution and distilled water as the feed solution (FS).

1. Introduction

Forward osmosis (FO) filtration process depends on the chemical potential between two solutions with different concentrations separated by a semi-permeable membrane. In the FO process, water diffuses from the low concentration solution (Feed Solution (FS)) to the high concentration solution (Draw Solution (DS)) due to the osmotic pressure gradient [1,2]. Recently, FO has been introduced as a feasible technology for desalination due to its low energy requirements when it is compared to other desalination processes [3].

FO membranes are asymmetric in nature composed of a dense selective layer for salt rejection supported on a porous layer which provides the required mechanical strength for the membrane [2]. Two different membrane orientations could possibly be applied in the FO process. The first orientation is when the membrane active layer is facing the draw solution, also known as the pressure-retarded osmosis (PRO-mode). The second orientation is when the active layer is facing the feed solution while the porous support layer is facing the draw solution, also known the FO mode [4]. In both orientations the actual net driving force is significantly less than the theoretical driving force [5,6]. The reduction in the net driving force is mainly due to concentration polarization (CP) phenomena [1,2,4,5,7]. Concentration polarization can be either external concentration polarization (ECP) or internal concentration polarization (ICP). If the concentration polarization happens on the membrane active layer it is referred to as external while if it happens on the porous support side of the membrane it is referred to as internal. Depending on the orientation of the membrane, CP can be further categorized into concentrative external concentration polarization (CECP), dilutive external concentration polarization (DECP), concentrative internal concentration polarization (CICP) and dilutive internal concentration polarization (DICP). When the active dense selective layer is facing the feed solution the phenomenon is

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* Corresponding author.
E-mail address: a.hawari@qu.edu.qa (A.H. Hawari).

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called concentrative external concentration polarization (CECP). The phenomenon is called dilutive external concentration polarization (DECP) when the membrane active layer is facing the draw solution. Similarly the ICP may be dilutive or concentrative in nature depending on the membrane orientation. Concentrative internal concentration polarization (CICP) takes place when the membrane active layer is facing the draw solution whereas, dilutive internal concentration polarization (DICP) takes place when the membrane active layer is facing the feed solution. In general, concentration polarization is considered to be one of the major contributors to the membrane flux reduction in the forward osmosis [4,6,8–10]. Different attempts have been done in order to reduce the effect of CP in the FO membranes. Some researchers have tried to fabricate membranes that would minimize the ICP by increasing the porosity of the support layer, decreasing the thickness of the support layer, reducing the tortuosity of the support layer or by increasing the membrane's hydrophilicity [11–18]. Other researchers used tailor-made draw solutions of high solubility and high diffusion coefficients which would produce high osmotic pressure (i.e. driving force) and at the same time would reduce the CP effect [19,20]. The impacts of operating conditions on the CP in FO have been studied by several researchers. Suh and Lee [20] investigated the effect of flow rate on CP using simulated data. They used a cross flow velocity between 0.0214 and 0.364 m/s where the flow was laminar and it was equally adjusted on both sides of the membrane. It was found that the membrane flux could be increased by increasing the cross flow velocity and decreasing the DECP or CECP. However, the reduction in the DECP or CECP has been offset by increasing the CICP or DICP, respectively. Another simulation study by Gruber et al. [21] studied the impact of cross flow velocity on the membrane flux in FO. They used a cross flow velocity between 0.001 and 1.0 m/s at both sides of the FO membrane. It was also found that the membrane flux could be enhanced by decreasing the ECP due to the increase in the tangential flow along the membrane. Jung et al. [22] simulated the effect of the feed solution flow rate on the performance of FO using 100 cm^3/min as an inlet draw solution flow rate and 10–3000 cm^3/min as the feed solution flow rate. They found that increasing the feed solution flow rate would decrease the ECP and thus increasing the membrane flux. However, the recovery rate decreased and the flow rate of feed solution needs to be optimized. An investigation of the effect of flow rate on FO has been experimentally carried out by Phuntsho et al. [23] using feed solution flow rate between 0.1 and 1.2 L/min and 0.4 L/min for the draw solution flow rate. It was found that the increase in the feed solution flow rate caused a decrease in the CECP and thus increased the water flux but resulted in a decrease of the recovery rate as other studies mentioned. Zhang et al. [24] experimentally investigated the impact of spacers to reduce the effect concentration polarization using 13.5 cm/s as a cross flow velocity on both sides of the membrane. It was found that when the feed solution was placed against the active layer, placing the spacer in the feed side away from the membrane produced more water flux than placing the spacer in contact with the membrane. However, the opposite happened in the other side of the membrane; placing the spacer in contact with the membrane reduced the DICP and produced more water flux than when placing it away from the membrane in the draw side. Park and Kim [25] simulated the impact of spacer on forward osmosis using 10 cm/s cross flow velocity and found that placing the spacer in contact with the membrane created a dead zone near the location of the attachment to increase the CP effect and reduce the local water flux.

The main objective of this study was to experimentally investigate the effect of different operating conditions on the membrane flux on the FO process. The effect of the membrane orientation, the DS and the FS flow rate, the DS and the FS temperature, and the combining effect of both temperature and flow rate on the membrane flux was investigated for the first time in order to enhance the FO process. The objective was to improve the membrane flux by reducing the effects of CP in the FO process.

2. Materials and methods

2.1. Draw and feed solutions

A draw solution (DS) was prepared by mixing a laboratory grade NaCl (Fisher, USA) with distilled water (DW). The concentration of draw solution (DS) was 0.5 mol/L (29 g/L) whereas the feed solution (FS) was either distilled water (DW) or 0.086 mol/L (5 g/L) NaCl which resembled the concentration of brackish water (BW).

2.2. FO membrane

The membrane used in this study was a Thin-Film Composite (TFC) forward osmosis membrane provided by Hydration Technology Innovations (HTI Inc.). The TFC membrane is composed of a polyester (PE) mesh embedded on a polysulfone (PSF) substrate to form the support layer. The active rejection layer of the membrane was formed by interfacial polymerization to form the polyamide dense selective layer. The maximum operating temperature for the membrane is 71 °C. The maximum operating transmembrane pressure for the membrane is 0.7 atm. The TFC membrane can operate with a solution pH range between 2 and11.

2.3. FO bench-scale unit

Sepa CF forward osmosis cell supplied by Steritech™ Co. was used in this study. The rectangular cell is made of stainless steel with outer dimensions of L = 213 mm, W = 165.1 mm, and D = 50 mm with an active area dimensions of L = 147 mm and W = 95.25 mm. The cell is held by a cell body holder. The cell is composed of two distinct compartments which are separated by the FO membrane. One of the compartments is for the DS and the other compartment is for the FS. Four stainless steel cup style feed tanks supplied by Steritech™ Co. with a capacity of 9 L (2.4 gal) were used as storage tanks for feed and draw solutions. The DS and the FS flows were set in a counter current flow direction. Inner and outer O-rings made of viton were installed in the DS compartment to prevent leakage from the FO cell and to hold the membrane in place. Two Sepa CF spacers were installed in each side of the FO membrane with dimensions of 147 mm length and 95.25 mm width supplied by Steritech™ Co. The spacers were installed in order to promote turbulent flow. Fig. 1 represents a schematic diagram for the FO system used in this study. Two Micropumps A-Mount Gear Pump model EW-74,013-40 with Console Drive, PEEK Gears/PTFE seals from Cole-Parmer Co. were used to circulate and control the DS and the FS flow rates. Two flow meters F-550 provided by Blue-White industries, Ltd. with a range of 0.38–3.8 L/min (0.1–1.0 GPM) were installed in the DS and FS lines to monitor the flow rate in the system. Feeds pressure was measured by two pressure gauges which are provided by Sterlitech and with a range of 0–1500 psi (0–100 bar) and installed on the DS and the FS lines. The temperature of the feed and draw solutions was controlled using two water bath units. Each water bath unit contained a stainless steel coil and one MX-CA12E MX Immersion Circulator. The MX-CA12E MX Immersion Circulator can provide temperature in the range of 10-135 °C with a temperature stability of 0.07 °C. The stainless steel coils were separately connected to the draw and feed lines just before the solution enters the FO cell. A conductivity meter C5111 from Agilent Co. was used to measure the conductivity and temperature of the feed and draw solutions. The range of the used conductivity meter is between 2 and 19,990 μS/cm and a temperature range between 0 and 60 °C which covers concentrations and temperatures used in this research. The meter has a cell constant of 1.0 ± 0.2 and a probe diameter of 12 mm made of glass. The permeate flux was determined by measuring the change in the feed solution weight using an EW-11017-04 scale from Ohaus Ranger