

Desalination by ammonia–carbon dioxide forward osmosis: Influence of draw and feed solution concentrations on process performance

Jeffrey R. McCutcheon, Robert L. McGinnis, Menachem Elimelech*

Department of Chemical Engineering, Environmental Engineering Program, Yale University, P.O. Box 208286, New Haven, CT 06520-8286, USA

Received 26 May 2005; received in revised form 17 October 2005; accepted 30 October 2005

Available online 5 December 2005

Abstract

Forward (direct) osmosis (FO) using semi-permeable polymeric membranes may be a viable alternative to reverse osmosis as a lower cost and more environmentally friendly desalination technology. The driving force in the described FO process is provided by a draw solution comprising highly soluble gases—ammonia and carbon dioxide. Using a commercially available FO membrane, experiments conducted in a crossflow, flat-sheet membrane filtration cell yielded water fluxes ranging from 1 to 10 $\mu\text{m/s}$ (2.1 to 21.2 $\text{gal ft}^{-2} \text{d}^{-1}$ or 3.6 to 36.0 $\text{l m}^{-2} \text{h}^{-1}$) for a wide range of draw and feed solution concentrations. It was found, however, that the experimental water fluxes were far lower than those anticipated based on available bulk osmotic pressure difference and membrane pure water permeability data. Internal concentration polarization was determined to be the major cause for the lower than expected water flux by analysis of the available water flux data and SEM images of the membrane displaying a porous support layer. Draw solution concentration was found to play a key role in this phenomenon. Sodium chloride rejection was determined to be 95–99% for most tests, with higher rejections occurring under higher water flux conditions. Desalination of very high sodium chloride feed solutions (simulating 75% recovery of seawater) was also deemed possible, leading to the possibility of brine discharge minimization. © 2005 Elsevier B.V. All rights reserved.

Keywords: Forward osmosis; Osmosis; Desalination; Concentration polarization; Internal concentration polarization; Draw solution

1. Introduction

A worldwide shortage of unimpaired freshwater has forced the tapping of saline water sources in water-starved countries. Current desalination technologies, such as reverse osmosis (RO), are, however, expensive and energy intensive. Limited recovery, typically 35–50% for seawater [1], is another drawback of RO. The remaining liquid, now concentrated brine, is discharged into the ocean. This is a critical environmental drawback to RO and limits its use to coastal areas since brine from brackish groundwater desalination cannot be disposed of inland in an economical manner.

Forward (or direct) osmosis (FO) is a technology that may be able to desalinate saline water sources at a reduced cost and at high recovery. In forward osmosis, like RO, water transports across a semi-permeable membrane that is impermeable to salt. However, instead of using hydraulic pressure to create the driv-

ing force for water transport through the membrane, the FO process utilizes an osmotic pressure gradient. A “draw” solution having a significantly higher osmotic pressure than the saline feed water flows against the permeate side of the membrane, and water naturally transports across the membrane by osmosis. The osmotic driving forces in FO can be significantly greater than hydraulic driving forces in RO, potentially leading to higher water flux rates and recoveries. The lack of hydraulic pressure may make the process less expensive than RO, while the minimization of brine discharge reduces the environmental impact of the desalination process.

Previous work on osmosis through semi-permeable membranes, while limited, still exposed the two significant drawbacks of FO. Membrane technology has advanced around the prospect of RO, not FO. Research conducted on osmotic processes concluded that RO membranes were not ideal for osmosis as water flux was found to be low [2–5]. Finding easily separable draw solutes is the second drawback of FO. Several patents describe different configurations for the use and removal of FO draw solutes [6–14]. Choosing a tailored FO membrane as well as an appropriate draw solute is critical in making the desalination

* Corresponding author. Tel.: +1 203 432 2789; fax: +1 203 432 2881.
E-mail address: menachem.elimelech@yale.edu (M. Elimelech).

process feasible. In the work presented in this paper, a membrane specifically designed for FO was used and our draw solutes and solute composition were chosen based on several important chemical attributes.

The ideal draw solute has several characteristics. The solute(s) must have a high osmotic efficiency, namely high solubility in water and relatively low molecular weight, which can lead to high osmotic pressures. The solute must also be easily and inexpensively separated to yield potable water, without being consumed in the process. We have recently demonstrated that these criteria are satisfied by using a draw solution of highly soluble gases—ammonia (NH_3) and carbon dioxide (CO_2) [15]. These gases are highly soluble in water and have a low molecular weight while also being relatively easy to remove from water. We have shown that by proper management of ammonia and carbon dioxide ratios and ammonium salt speciation, we can generate very high osmotic driving forces [16]. Upon moderate heating (near 60°C) [17], the ammonium draw solutes decompose into ammonia and carbon dioxide gases that can be separated by standard means. The separated gases can then be used to regenerate the draw solution. This draw solute separation step in the FO desalination process will not be addressed in this paper.

The objective of this paper is to investigate the relationships among the draw solution concentration, feed water salinity, and permeate flux behavior in the ammonia–carbon dioxide FO process. The ammonia–carbon dioxide draw solution concentration is varied over a wide range (up to 6 M), processing feed waters with salinities as high as 2 M sodium chloride (NaCl). On the basis of these results, the mechanisms governing the permeate water flux behavior in the ammonia–carbon dioxide FO process are elucidated and discussed.

2. Materials and methods

2.1. Ammonia–carbon dioxide draw solution and sodium chloride feed solution

The draw solution is made by mixing ammonium bicarbonate (NH_4HCO_3) and ammonium hydroxide (NH_4OH) with deionized water at proper proportions to produce a solution of the desired concentration of ammonium salts [15,16]. Higher concentrations of ammonia and carbon dioxide salts require a higher ratio of ammonia to carbon dioxide, which favors the formation of ammonium carbamate, a highly soluble ammonium salt. The ammonia to carbon dioxide molar ratios used ranged from 1.2 for the 1.1 M draw solution to 1.4 for the 6 M draw solution.

The feed solution was composed of NaCl dissolved in deionized water. Concentrations ranged from 0.05 to 2 M. The 2 M NaCl concentration is indicative of 75% recovery of a 0.5 M NaCl solution, which is close to an initial seawater concentration. The temperature of the feed solution was 50°C .

2.2. Forward osmosis membrane

The membrane tested in this work was provided by Hydration Technologies Inc. (Albany, OR). The proprietary FO membrane, denoted as CA in this paper, is thought to be made from a

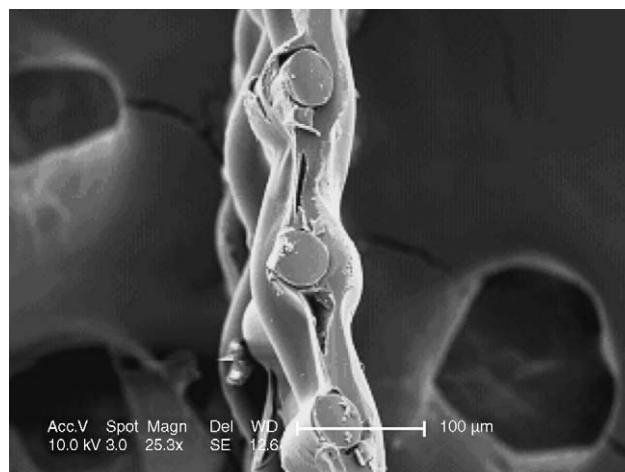


Fig. 1. SEM image of a cross-section of the forward osmosis (CA) membrane. A polyester mesh is embedded within the polymer material for mechanical support. The membrane thickness is less than $50\ \mu\text{m}$.

hydrophilic cellulose-based polymer [13]. Fig. 1 shows a cross-sectional view of the membrane taken by SEM, indicating that the thickness of the membrane is less than $50\ \mu\text{m}$. It is evident that the structure of the CA membrane is quite different from standard RO membranes. RO membranes typically consist of a very thin active layer (less than $1\ \mu\text{m}$) supported by a much thicker porous polymer supporting layer [18]. These layers are mechanically supported by a fabric support layer. Fig. 1 indicates that the CA FO membrane lacks any thick fabric layer. An embedded polyester mesh provides the mechanical support normally provided by the thick fabric layer [13].

2.3. Forward osmosis crossflow set-up

Fig. 2 depicts the apparatus employed in our laboratory-scale FO experiments. The crossflow membrane unit is a SEPA cell (GE Osmonics, Trevose, PA), modified to have channels on both sides of the membrane. The ammonia–carbon dioxide draw solution is flowing on the permeate side and the NaCl solution on the feed (active layer) side. Co-current flow is used to reduce strain on the suspended membrane. Mesh spacers are inserted within both channels to improve support. The spacers also promote turbulence and mass transport. Variable speed peristaltic pumps (Manostat, Barrington, IL) are used to pump the liquids. A constant temperature water bath (Neslab, Newington, NH) is used to maintain the feed solution temperature, whereas the draw solution temperature is kept constant by a heating mantle (Glas-Col, Terre Haute, IN). Both the feed and draw solutions were held at the same temperature (50°C) during the FO tests and were controlled to within $\pm 1^\circ\text{C}$.

2.4. Water flux and salt rejection measurements

Water flux is determined by measuring the weight change (Ohaus, Pine Brook, NJ) of the draw solution over a selected time period at the initial stage of the process. As water transports by osmosis across the membrane from the saline feed water

Download English Version:

<https://daneshyari.com/en/article/639532>

Download Persian Version:

<https://daneshyari.com/article/639532>

[Daneshyari.com](https://daneshyari.com)