Desalination 423 (2017) 12–20

Contents lists available at ScienceDirect

Desalination

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

Forward osmosis desalination using ferric sulfate draw solute

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A R T I C L E I N F O

Keywords:
Forward osmosis
Desalination
Ferric sulfate
Draw solution
Water flux

A B S T R A C T

Lack of suitable draw solutes is one of the major limiting factors hindering commercial realization of forward osmosis (FO) desalination process. This study investigates the feasibility of ferric sulfate as draw solute in FO desalination. A laboratory-scale, cross-flow FO apparatus utilizing commercial FO membrane (cellulose triacetate-based) was used to desalinate synthesized (5000 ppm NaCl) brackish water and (40,000 ppm NaCl) seawater using 280,000 ppm ferric sulfate draw solution at ambient conditions. The observed average water flux was 3.75 and 1.61 L/m^2 h in case of brackish and seawater, respectively. Using deionized water as feed solution, reverse ferric sulfate flux of 1.88 g/m^2 h was observed. Product water was recovered from the diluted draw solution by precipitation reaction using barium hydroxide. Pure water samples with salt contents of 60 and 80 ppm were obtained by desalinating brackish and seawater feed, respectively.

1. Introduction

Forward osmosis (FO) is a natural osmotic process that involves permeation of water molecules across a semipermeable membrane from a feed solution of higher water chemical potential (lower osmotic pressure) to a solution of lower water chemical potential (higher osmotic pressure). Ideally, the semipermeable membrane allows only water molecules to pass through while the salts are rejected by the membrane and remain in the feed solution. Typical feed solutions for FO desalination process include brackish and seawater. The solution of lower water chemical potential is often termed as the draw solution, osmotic agent, or osmotic media and is typically a highly concentrated salt solution. After extraction of water molecules from the feed solution, pure water has to be subsequently recovered from the draw solution.

Research investigations into FO have been mainly stimulated to provide solutions to the increased need and challenges in the desalination industry. These include augmenting the global supply of pure water in a sustainable manner, decreasing the aggravated cost and energy requirements, and providing alternative solutions to the current energy-intensive conventional desalination processes such as thermal and reverse osmosis (RO) desalination [1–7]. Compared to conventional desalination technologies, FO is considered cost-effective and energy efficient since it neither requires high hydraulic pressure nor high thermal energy [8,9]. It also exhibits lower and reversible membrane fouling [10–14], promotes higher salt rejection [15–20], and minimizes brine discharge [17,21]. Despite its inherent advantages and extensive industrial and academic research efforts involved, commercial deployment of FO desalination has not been adequately possible owing to some major limitations including unavailability of suitable FO membranes, concentration polarization effects, and lack of suitable draw solutes that are easy to regenerate and separate from product water [8,17,21–23].

Development of draw solutes is one key area of research in FO desalination. The ideal draw solute for FO desalination must meet the following criteria: (i) ability to generate high osmotic pressure, (ii) highly soluble in water, (iii) chemically inert to the FO membrane, (iv) non-toxic and safe to human health and environment, (v) ability to minimize the concentration polarization effects and reverse draw solute flux, and (vi) easily separable from product water [24–29]. Based on these criteria, several novel draw solutes and product water recovery methods have been proposed for FO applications. These research efforts are presented in Table 1 along with a summary of product water recovery technique and the advantages and disadvantages for each draw solute [30–77].

Generally, the draw solutes can be classified as volatile, organic-based, inorganic-based, and nanoparticle-based draw solutes. Despite extensive research on the applicability of different types of draw solutes, FO desalination technology is still in its infancy owing to several existing challenges related to energy efficiency, toxicity, produced water flux and quality, and reverse salt flux of each type of draw solute [28]. Volatile draw solutes [30–37] generally offer low osmotic pressure and low regeneration [27]. In addition, heating is required in most cases in order to recover product water which tends to decrease the energy efficiency of the FO process. All these factors combined together

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http://dx.doi.org/10.1016/j.desal.2017.08.019
Received 12 July 2017; Received in revised form 25 August 2017; Accepted 25 August 2017
0011-9164/

Table 1
Typical draw solutions used in the FO desalination of salty water.

Draw solute type	Draw solute/solution	Recovery method	Advantages and disadvantages	Reference
Volatile draw solutes	Sulfur dioxide (SO_2)	Heated gas stripping operation	Simple, requires energy, harmful to human health	[30]
	Mixture of water with SO_2 or aliphatic alcohols	Heating/distillation	Simple, requires energy, harmful to human health	[31]
	Potassium nitrate (KNO_3) and SO_2	Heating and cooling	Requires energy, involves multiple steps for product recovery	[32]
	Ammonium bicarbonate (NH_4HCO_3)	Heating to 60 °C	High water flux, energy-efficient, poor water quality	[33–35]
	Switchable polarity solvent (SPS)	Bubbling air or nitrogen with mild heating	Energy efficient, membrane degradation, poor product quality	[36]
	Dimethyl ether	Exposure to air	Energy efficient, fire hazard	[37]
Organic-based draw solutes	Fructose	None (pure water not produced)	Applicable only for emergency water supply	[38]
	Glucose	RO	Safe draw solute, requires energy	[39]
	EDTA sodium salt	Nanofiltration (NF)	High water flux, requires energy	[40]
	Polyacrylic acid sodium salt (PAA—Na)	Ultrafiltration (UF)	High water flux, requires energy	[41]
	Sodium lignin sulfonate (NaLS)	None (pure water not produced)	Low cost, natural abundance, toxicity	[42]
	Poly (sodium 4-styrenesulfonate) (PSS)	UF	High water flux, low reverse draw solute flux, requires energy	[43]
	2-methylimidazole-based compounds	FO-membrane distillation (MD) integrated process	High osmotic pressure, high internal concentration polarization, requires energy	[44]
	Poly (sodiumstyrene-4-sulfonate-*co*-n-isopropylacrylamide) (PSSS–PNIPAM)	MD	Ability to desalinate seawater, requires energy	[45]
	Poly (amidoamine) terminated with sodium carboxylate groups (PAMAM-COONa)	MD	High water flux, requires energy	[46]
	Hexavalent phosphazene salts	Not reported	Product water recovery not investigated, possibility of membrane hydrolysis	[47]
	Poly (aspartic acid sodium salt) (PAspNa)	NF or MD	High water flux, requires energy	[48]
	Electric-responsive hyaluronic acid/polyvinyl alcohol (HA/PVA) polymer hydrogels	Electric field	High water flux, requires energy	[49]
	Thermo-responsive microgels	Centrifugation at 40 °C	High water flux, heating (energy) required	[50]
	Thermo-sensitive polyelectrolytes	Hot UF (HUF)	Low energy required, low water flux	[51]
	Semi-INP hydrogels	Heating to 40 °C	Low energy required, low water flux	[52]
	Gluconate salts	NF	High water flux, poor water quality	[53]
	Protonated betaine *bis*(trifluoromethylsulfonyl)imide ([Hbet][Tf2N])	Temperature change	High water flux, hot draw solution required, poor product quality, RO or NF required to reach the drinkable water level	[54]
	Polymer-based cationic polyelectrolyte	UF	Low osmotic pressure, poor product quality	[55]
	Ferric-lactate complex	NF	High water flux, requires energy	[56]
	Poly(isobutylene-*alt*-maleic anhydride)	MD	High water flux, requires energy	[57]
	Hydrogel-polyurethane interpenetrating network (HPIPN)	Concentrated sunlight	High water flux, low water recovery	[58]
	Oligomeric poly(tetrabutylphosphonium styrenesulfonate)s	Heating	High water flux, heating involved	[59]
	EDTA complexes	NF	High solubility, nontoxic, requires energy	[60]
	Polymer hydrogels	Pressure or temperature stimuli	High water recovery, susceptible to microbial contamination	[61,62]
Nanoparticle-based draw solutes	Magnetic nanoparticles	Canister separator or magnetic field	Simple and easy product water recovery, susceptible to nanoparticle aggregation	[63–65]
	Surface dissociated nanoparticles	Electric field integrated with NF	High osmotic pressure, required energy, complicated process	[66]
	Citrate-coated magnetic nanoparticles (cit-MNPs)	Not reported	High water flux, product water recovery not investigated	[67]
	Carbon quantum dots (CQDs)	MD	High osmotic pressure, high water flux, ability to desalinate seawater, requires energy	[68]
	Dextran coated magnetic nanoparticles	Magnetic field	Environment friendly, low cost, poor water quality	[69]
	Poly(sodium styrene-4-sulfonate)-*co*-poly(N-isopropylacrylamide) (PSSS-PNIPAM)-coated magnetic nanoparticles	Magnetic separation after heating and UF	High water flux, requires energy, involves multiple steps for product recovery	[70]
	Poly(N-isopropylacrylamide-co-sodium 2-acrylamido-2-methylpropane sulfonate) P(NIPAM-co-AMPS) nanogels-coated magnetic nanoparticles	Magnetic field combined with a thermal stimulus	Low water flux	[71]
	Nanocomposite polymer hydrogel	Magnetic heating	Low water flux, low water recovery	[72]
Inorganic draw solutes	Calcium chloride ($CaCl_2$)	None (pure water not produced)	High water flux, pure water cannot be produced, diluted draw solution can only be reused as cationic exchange solution or in other applications	[73]
	Magnesium sulfate ($MgSO_4$)	Precipitation	No energy required, chemicals required	[74]
	Copper sulfate ($CuSO_4$)	Precipitation	No energy required, cannot desalinate seawater, chemicals required	[75]
	Ferric and cobaltous hydroacid complexes	NF	High water flux, requires energy	[76]
	Triton X100 with Na_3PO_4	Two stage UF-NF	Minimized reverse draw solute flux, requires energy	[77]