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Copper sulfate as draw solute in forward osmosis desalination

Raafat Alnaizy *, Ahmed Aidan, Muhammad Qasim

Department of Chemical Engineering, American University of Sharjah, P.O. Box 26666, Sharjah, United Arab Emirates

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ABSTRACT

Copper sulfate is presented as a viable draw solute in forward osmosis (FO) for brackish water desalination. In this study, the osmotic pressure of copper sulfate was calculated as a function of concentration. An investigation into the osmotic pressure revealed that copper sulfate draw solution cannot generate enough osmotic pressure to extract water from seawater feed. A laboratory-scale FO unit utilizing a commercial flat-sheet cellulose acetate membrane was used to desalinate brackish water using 200,000 ppm copper sulfate draw solution. An average water flux of 3.57 L/m^2 h was observed. Product water with a salt content of 100 ppm was recovered from the diluted copper draw solution without using any energy. The product water was recovered by metathesis precipitation reaction of copper sulfate with barium hydroxide to remove the soluble chemicals as insoluble copper hydroxide and barium sulfate. At the end, copper sulfate draw solution was recovered by the reaction of copper hydroxide with sulfuric acid.

Introduction

Pure water is an essential input to sustain a healthy environment in our society. About three quarters of the earth is water and approximately 97% of it comes from the sea while 2% of it is held within blocks of ice [1]. Although water is available in abundance, fresh water is not easily accessible from its infinite source. Over the past decades, the society has become increasingly aware of the role fresh water plays as a critical resource as well as its vulnerability in terms of quality [2]. Many countries in the world suffer from a scarcity of pure drinking water. In addition, increasing amounts of fresh water will be required in the future as a result of the increase in population as well as enhanced living standards and the expansion in the industrial and agricultural sectors [3].

In the field of water purification, water reclamation, and desalination, hydraulic pressure-driven membrane process are used extensively. These processes include microfiltration (MF), ultrafiltration (MF), nanofiltration (NF), and reverse osmosis (RO) [4]. Reverse osmosis (RO) is the most widely used desalination technique around the world. Unfortunately, the conventional membrane desalination techniques require large amounts of energy that is costly both in environmental pollution and in terms of money [1]. Currently, the typical energy requirement for seawater RO desalination with energy recovery devices is 3–7 kWh/m^3. In case of brackish water, the energy requirement is 0.5–3 kWh/m^3 [5,6]. In order to economically meet the increasing water demands, new energy-efficient and less-costly desalination techniques need to be introduced. As a result, finding efficient desalination technologies becomes an important concern for the scientific community.

Recently, there has been a rapid increase in the study of forward osmosis (FO) [7–17] and its applications in various fields [18–24]. Unlike hydraulic pressure-driven desalination techniques, FO is simply a natural osmosis process that involves permeation of water from a low-concentration solution into a high-concentration solution across a semipermeable membrane due to difference in osmotic pressure. The low-concentration solution is called the feed solution and is typically seawater or brackish water that needs to be desalinated. On the other hand, the high-concentration solution is called the draw solution which is prepared using a solute of high osmotic pressure. It is the osmotic pressure difference between the feed and the draw solution that causes water in the feed solution to flow into the draw solution. The salts are rejected and remain in the feed solution due to the semipermeable nature of the membrane. Fig. 1 shows the FO process.

After extraction of water from the feed into the draw solution, pure product water must be recovered from the diluted draw solution using a suitable energy-efficient technique. As a result, most research on FO focuses on finding suitable draw solutions of high osmotic pressure, suitable membranes that allow high water flux and high salt rejection, and energy-efficient techniques for the recovery of product water [8,25].

Review of forward osmosis draw solutions

The high osmotic pressure of the draw solution is the source of driving force for water in FO process. The draw solution may also

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* Corresponding author. Tel.: +971 502341744.
E-mail address: ralnaizy@aus.edu (R. Alnaizy).

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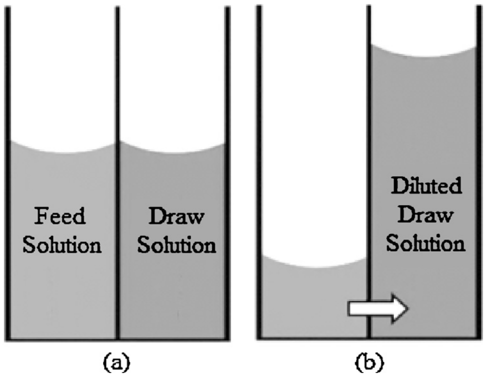

Fig. 1. (a) FO process with the feed solution (brackish or seawater) separated from a draw solution by a semipermeable membrane and (b) Permeation of water from the feed to the draw solution (from a solution of low osmotic pressure to a solution of high osmotic pressure).

be referred as osmotic agent, osmotic media, osmotic engine, or driving solution. When selecting a draw solution, the main criterion is that it should have a higher osmotic pressure than the feed solution. The higher the osmotic pressure of the draw solution, the more suitable it is in FO applications. In addition, the draw solution must require low energy for regeneration or re-concentration and must be easily separated from the pure product water. Other desired characteristics of the draw solute include low toxicity, chemical inertness toward the membrane material, high osmotic pressure, and high solubility [26].

In the past few decades, various chemicals have been tested as solutes for draw solutions in the FO process [8,26,27]. Batchelder [28] used volatile solutes, such as sulfur dioxide, for desalination of seawater. In this case, the volatile solutes are removed from the product water by a heated gas stripping operation. Glew [29] expanded on the idea of Batchelder [28] by using mixtures of water and another gas (SO_2) or liquid (aliphatic alcohols) as FO draw solutions. The removal of volatiles gases from product water requires energy in the form of heating.

Frank [30] used aluminum sulfate as draw solute. Water was separated from the draw solution by the reaction of aluminum sulfate with calcium hydroxide to precipitate the draw solute. However, the water flux has not been reported.

Kravath and Davis [31] and Stache [32] used glucose and fructose solutions as draw solution, respectively. Yaeli [33] recovered product water from glucose draw solution using pressure-driven process of RO.

McGinnis [34] used a two-stage FO process in which the seawater is first contacted with concentrated KNO_3 solution. After diffusion of water from the saline feed solution into the KNO_3 draw solution, a significant amount of KNO_3 is precipitated by cooling. The remaining diluted KNO_3 solution is contacted with SO_2 solution in the second stage of the FO process. Finally, product water is recovered from the SO_2 solution by heating. Again, in this case, energy in the form of cooling and heating is required to recover pure product water from the draw solution.

Elimelech and coworkers [13,35,36] used highly soluble ammonium bicarbonate as draw solute that resulted in high water flux. The recovery of product water from the draw solution required moderate heating up to 60 °C. Upon heating, the soluble ammonium bicarbonate draw solute decomposes into ammonia and carbon dioxide gas that escape out of the solution to produce pure product water. Ng et al. also used ammonium bicarbonate as draw solution [37].

Magnetic nanoparticles have been used as FO draw solutions by Adham et al. [38]. The product water is separated from the draw solution by using a magnetic separator. Adham et al. also used albumin and dendrimers as draw solutions with different separation methods [38].

Recently, several new types of draw solutions have been suggested for use in FO. Chung and co-workers [39] studied the application of 2-methylimidazole-based organic compounds as draw solutes. In this study, recycling of the draw solutes is done using FO–MD integrated process. Chung et al. [40,41] also studied the use of magnetic nanoparticles as draw solutes where product water is recovered by application of magnetic field.

Wang et al. [42] suggested use of polymer hydrogels as the draw agent. Hydrogels are three-dimensional network of polymer chains that are linked by physical or chemical bonds. The polymer hydrogels are used to drive water across the semipermeable membrane in FO. The polymer hydrogels entrap the water molecules and become swelled. After extraction of water from the feed solution, pure product water is recovered from the swelled hydrogels using temperature, pressure, or solar irradiation as external stimuli.

Chung [43] used super hydrophilic nanoparticles as the draw solute. Nanoparticles coated with acrylic acid and triethylene glycol were prepared and dissolved in water to be used as draw solution. The separation of nanoparticles from product water was done using an ultrafiltration (UF) system.

Shon and coworkers [44] used fertilizer draw solution for extraction of water from the feed solution. In this case, the recovery of product water was not required since the diluted draw solution was directly applied for fertigation.

Chung et al. [45] explored polyelectrolytes of a series of polyacrylic acid sodium salts as draw solutes. The draw solutes were re-concentrated through a pressure-driven UF process. Chung [46] also investigated the draw solutions of surface-dissociated nanoparticles in FO processes and their regeneration through an integrated electric field-nanofiltration system for water reclamation.

Stewart et al. [47] used phosphazene salts as draw solutes. The water flux through the FO membrane has been reported. However, the recovery of product water from the phosphazene salt draw solution has not been discussed. In another work, Wilson and co-workers [48] used a mixture of carbon dioxide, water and tertiary amines as draw solution. This mixture has been names switchable polarity solvent (SPS). The tertiary amines are soluble in water only in the presence of carbon dioxide. After extraction of water from the feed solution into the SPS draw solution, product water is recovered by heating the draw solution to strip carbon dioxide. The removal of carbon dioxide from the SPS draw solution results in separation of tertiary amine from the product water due to increased hydrophobicity of the SPS draw solution.

All of the aforementioned FO efforts, summarized in Table 1, require some form of energy to recover pure product water from the diluted draw solution. In our previous study, magnesium sulfate draw solution has been successfully used to desalinate both brackish and seawater [49]. Compared to previous FO efforts, the use of magnesium sulfate as draw solute required no energy for the recovery of product water. In this case, the product water was separated from the diluted magnesium sulfate draw solution by metathesis precipitation reaction. The diluted magnesium sulfate draw solution was reacted with barium hydroxide solution at room temperature to precipitate all soluble chemicals as a mixture of magnesium hydroxide and barium sulfate precipitates. The magnesium sulfate draw solution was also recovered by the reaction of the precipitate mixture with sulfuric acid solution to convert insoluble magnesium hydroxide to soluble magnesium sulfate to be reused as draw solution.

Based on the same principle of metathesis precipitation, the objective of this paper is to investigate the use of copper sulfate as draw solute in order to reduce the energy consumption associated