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Generation Of Potable Water Using Forward Osmosis

Milind Matang

Assistant Professor, Chemical Engineering Department, Veerayatan Institute of Engineering

Abstract: Forward osmosis (FO) represents a tremendous and untapped opportunity with the potential to solve the global water crisis. The biggest challenge facing the application of FO technology is the economical separation of drinking water from its draw solution. In my dissertation, I intent to come up with a proposal on energy-and-cost effective combination of Draw solution and recovery method for the generation of potable water from waste water.

This paper includes comprehensive literature survey on draw solution and methods of recovery. Based on this survey, I have narrow-downed the list of draw solutes, which offers ease of recovery with chemical method, performance efficiency, energy and cost advantage. The prospect of reclaiming water with this select draw solute was studied experimentally to derive final conclusion

Key words —potable wate, forward osmosis.
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1. Introduction

Potable water is one of the major concerns globally due to water scarcity. A substantial growth of the desalination market in countries with physical water scarcity is a fact confirmed by a recent state of the art desalination report [1]. As a result, finding efficient desalination technologies has become an important concern for the scientific community.

In the fields of water purification, wastewater reclamation and seawater and brackish water desalination, reverse osmosis (RO), and nanofiltration (NF) represent the conventional and most widely used techniques [2]. Among all desalination technologies, seawater reverse osmosis (SWRO) is the most internationally widespread technology. RO is a membrane separation process that recovers pure water from an impure or saline water feed by pressurizing it to a level above its osmotic pressure [3]. The membrane rejects the salt ions from the pressurized solution, allowing only the water to pass through it. However, the inherent problems such as membrane fouling and high energy consumption in reverse osmosis require innovation of other energy-efficient alternatives [2].

The scarcity of water has been crucially acknowledged all over the world, especially in the Middle East, which is one of the most water scarce region in the world. The United Arab Emirates (UAE) is home to the world's largest desalination plant that exists in Jebel Ali and uses the method of multi-stage flash (MSF) distillation to desalinate its water [4]. With growing population and economic development, water resources are facing extensive threats in the UAE [9]. Situated near the equator, the UAE is known to be very dry and arid which leads to a high evaporation rate. Furthermore, the insufficiency of rainfall also adds to the scarcity of water in this country [9]. Dubai gets its water from treating wastewater, desalinating seawater, and brackish water and groundwater stored in main aquifers [10]. However, the groundwater has been immensely consumed over the years and is not available in plenty to meet the demands of the population in the UAE, which has unrestrainedly increased owing to its advanced living standards.

With the growing demand in water, its production too has vastly increased in the Emirates. According to statistics provided by dubai water and electricity authority (DEWA), there has been a continuous increase in the quantity of desalinated water demanded in the UAE over the years [10]. Although this increase in quantity demanded has been successfully met by increasing the capacity of installed desalination plants, yet this has resulted in large economic spending in the desalination sector. In fact, the UAE spends nearly $3.2 billion per year on the production of desalinated water to ensure its fast growing needs of drinking water and to offset its dwindling reserves [11,12]. In addition, increasing amounts of fresh water will be required in the future as a result of the rise in population rates and enhanced living standards, together with the expansion of industrial and agricultural activities in the UAE [13].

Unfortunately, the current desalination methods in the UAE require large amounts of energy that is costly both in environmental pollution and in terms of money [14]. The power consumption per unit of distillate for the main MSF desalination units installed by the abu dhabi water and electricity department (ADWEA) ranges from 3.6–5 k Wh/m^3 and that the cost of electric power is almost three times the cost of the steam [15,16]. Thus, the use of MSF desalination process requires extensive economic spending on energy. Therefore, there is a space for introduction of energy-efficient and less-costly desalination technologies, especially in the Middle East including the UAE. In order to economically meet the increasing water demands, new energy-efficient and less-costly desalination techniques need to be introduced.

On the other hand, the competiveness of RO is highly dependent on the price of electricity.

Recently, forward osmosis (FO) or direct osmosis (DO) has gained much attention of the researchers [19–31] and its application has been studied in various fields such as wastewater treatment [7], water desalination [22] and energy generation [24,26]. However, very few publications appear in the literature on the use of FO for desalination and water treatment [7].

FO is a simple natural phenomenon that involves movement of water through a semipermeable membrane under an osmotic pressure gradient. In FO, the more dilute solution to be concentrated is the feed solution (FS), while the more concentrated solution is

referred to as the draw solution (DS) or the osmotic agent [32]. The osmotic pressure difference between the FS and DS is the driving force for the movement of water molecules from the FS to the DS across the semipermeable membrane in FO. The diluted DS is subsequently treated to obtain pure water as product. The flux directions for water in FO and RO is illustrated in Fig. 1.

Recent advances and research in FO have higlighted several emerging applications. FO can be used for osmotic dilution of the saline feed entering the RO plant. Since the energy required for desalination is a function of the salinity of feed water, therefore, dilution of the feed using FO results in lower energy requirements in RO. In addition, FO also reduces the negative environmental impacts of the discharges from desalination plants. Production of fresh water using MSF or RO results in discharge of more concenrated feed or brine to the environment. Again, FO can be used to dilute the brine in order to reduce the impact of its high salinity on the aquatic life and the environment. In agricultural applications, FO can be used to desalinate brackish groundwater alongwith dilution of the fertilizer DS [33].

The main advantage of FO is that it operates under no hydraulic pressures which results in lower membrane fouling and lower or no energy requirement compared pressure-driven processes such as RO.

The concentrated or the DS on one side of the membrane is the source of the driving force in the FO process [7]. The main criterion for selecting the DS is that it must have a higher osmotic pressure than the FS. Moreover, the solute used in the DS must be nontoxic, non-reactive with the FO membrane and must require low energy for separation from the product pure water. Generally, the membrane used in FO can be any dense, non-porous, non-reactive, and selectively permeable material [7].

This article presents a FO system that utilizes a standard membrane used in domestic Ros. For energy-efficient recovery of pure water from the diluted DS, magnesium sulfate was employed as the draw solute. Pure product water was obtained by reaction of diluted magnesium sulfate DS with stoichiometric amount of barium hydroxide solution to precipitate all soluble chemicals as insoluble magnesium hydroxide and barium sulfate. The use of magnesium sulfate as draw solute eliminates the need of energy to recover pure product water in the FO process. Finally, the $MgSO_4$ DS is recovered by reaction of insoluble magnesium hydroxide with sulfuric acid.

2. Draw Solutes: Literature review

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 reconcentration 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 8C. 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 surfacedissociated 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 coworkers [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

3. Experimental Investigation

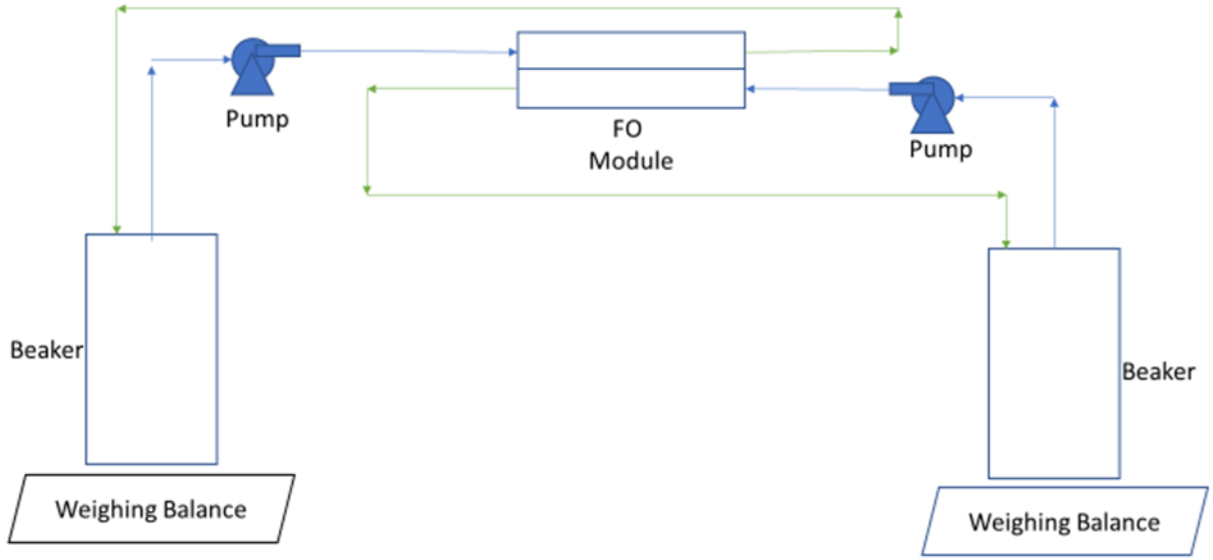
1. Chemicals and material

Unless otherwise specified, all chemicals and reagents used in the experiments were of analytical grade. The solutions were prepared using deionized water with negligible dissolved solid content. The feed solution was prepared using analytical grade sodium chloride (NaCl) purchased from Lab-Chem Corporation Ahmedabad. The draw solution was prepared using analytical grade copper sulfate pentahydrate ($CuSO_45H_2O$) along with Barium hydroxide octahydrate ($Ba(OH)_28H_2O$) was purchased from the lab-Chem Corporation Ahmedabad

2. Description of experimental set up

The experiments were conducted on a bench-scale laboratory system as shown in Fig. 3.

Acrylic boxes (shown in picture) of 6*6 inches served as the central unit for this forward osmosis experimentation. Both boxes have the cuts of 3*3 on the one face. Membrane along with the ring gasket was placed between these two faces. Both the boxes were clamped tightly to prevent any leakage from either side. Once the assembling was done, Feed solution was circulated from the box, which allows for the contact of feed solution with Active side of the membrane; While Draw solution was circulated from other side.



As experiment begins, the Draw solution with draw the water. Consequentially, the volume of Feed solution water in the container decreases. This reduction (water flux) was measured by precision balance of 0.01gm accuracy.

The diluted DS was collected from the beaker containing DS and its changed concentration was measured. Based on the concentration of magnesium sulfate in the diluted DS, stoichiometric amount of barium hydroxide solution was added. This metathesis reaction resulted in formation of two insoluble precipitates namely magnesium hydroxide and barium sulfate. The reaction is as follows:

$Ba(oh)_2 + 2\ MgSO_4 = 2\ BaSO_4 + Mg(oh)_2$

Both magnesium hydroxide and barium sulfate have negligible solubility in water compared with barium hydroxide and magnesium sulfate as indicated in Table 1.

Compound	Solubility (g/100 g H_2O)
Copper sulfate	22.0
Barium hydroxide	4.91
Copper hydroxide	Negligible
Magnesium Sulfate	35.0

The precipitates containing a mixture of magnesium hydroxide and barium sulfate were allowed to settle The top water layer was filtered using standard filter paper supplied by Whatman Ltd. to remove the suspended precipitates.

Two precipitable salts copper sulfate and magnesium sulfate were tested for its potential to draw out potable water from synthetic waste water of known composition.

Compound	Concentration (mg/L)
Meat extract	425
Starch ($C_6H_{10}O_5$)	111
Saccharose ($C_{12}H_{22}O_{11}$)	36
Sodium chloride ($NaCl^-$)	250
Magnesium chloride. ($MgCl_2\ 6H_2O$)	7
Calcium chloride ($CaCl_2\ 2H_2O$)	5
Potassium phosphate (KH_2PO_4)	6
Sodium sulfate (Na_2SO_4)	148
Sodium bicarbonate ($NaHCO_3$)	200

4. Result and discussion

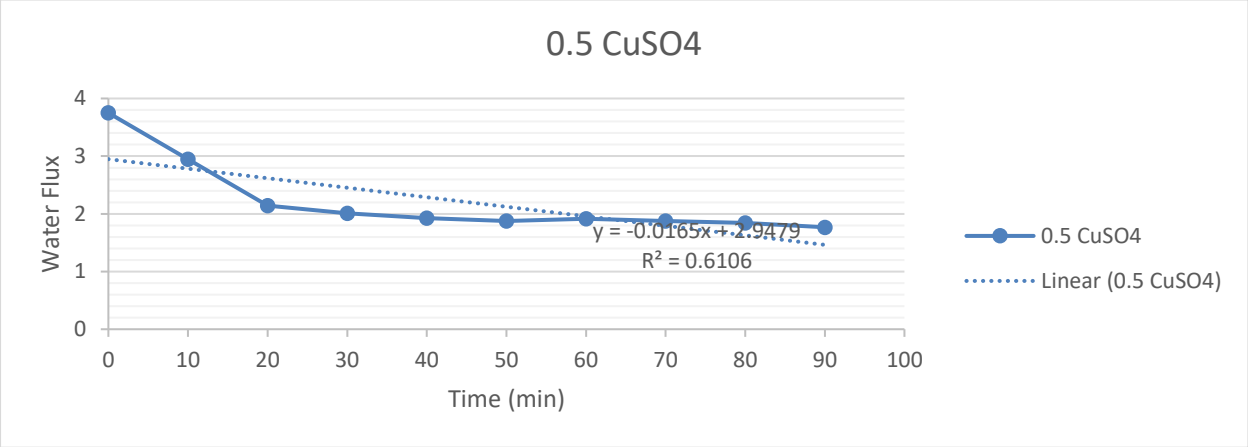
Initially, the set up was tested for feasibility with basic forward osmosis system featuring sodium chloride as Draw solution. System proved feasible as flux rate generated was in the range of 5 L/M2H, which is appreciable for RO membrane diverted for FO application.

Compared with monovalent inorganic salt DS, precipitable salts (magnesium sulfate and copper sulfate) have a lower osmotic pressure, especially at higher concentrations [7]. However, the use to magnesium sulfate as draw solute in FO is useful in terms of product water recovery. Magnesium sulfate is highly soluble in water and pure product water can be recovered from the diluted DS by

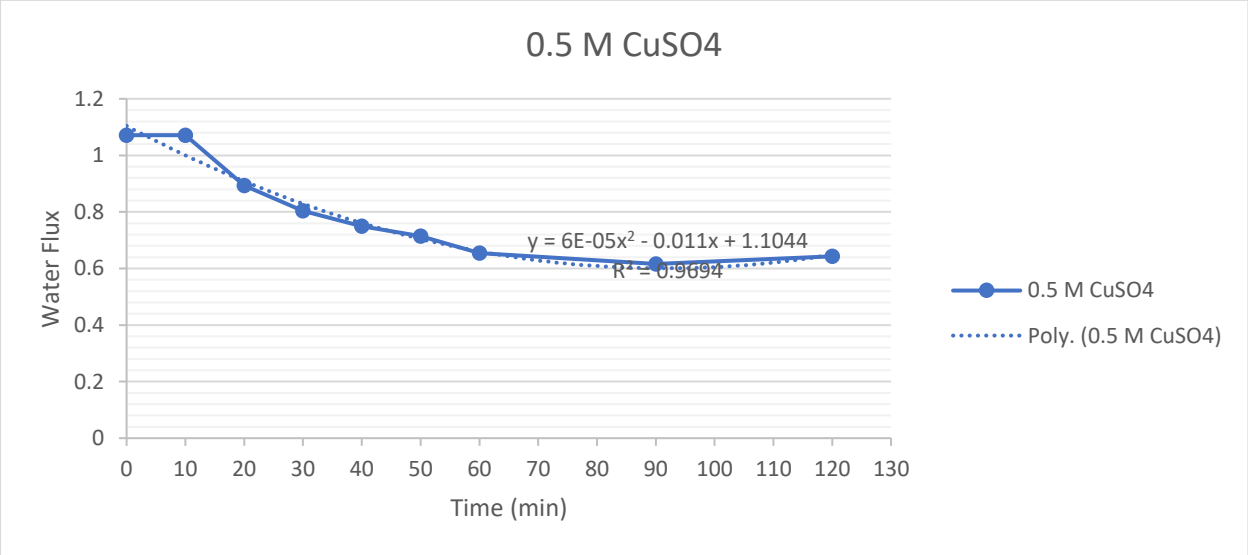
metathesis reaction with barium hydroxide to precipitate all soluble chemicals as insoluble magnesium hydroxide and barium sulfate.

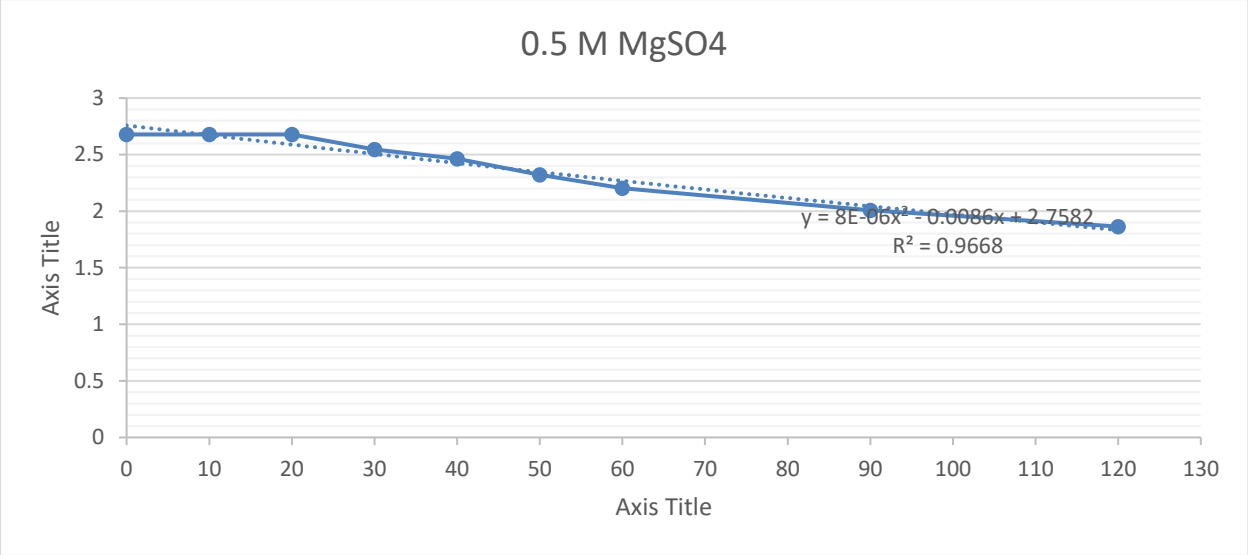
Following graph shows the water flux obtained for both the solution. Mannesium sulphate as cpmpared copper sulphate has high osmotic potential. For synthetic water of know generation magnesium sulphate reclaimed the water at the rate of 2.5 liter/m2h.

Graph 1: Water Flux V Time For Copper Sulfate as Draw solution and distilled water as feed solution



Graph : Cuso4 as DS and Synthetic water as feed solution





Graph of water flux v/s time for magnesium sulfate as DS and Synthetic water as FS

5. Conclusion

In this study, standard RO membrane was used for water re-claimation. For energy-efficient recovery of pure product water, $MgSO_4$ Cuso4 were used as the draw solute. In case of Cuso4,flux generation was very low in the range of 1 liter/m2h, whereas for MgSo4, a water flux of 3-L/m^2 h was obtained.

Final product water, containing 350 ppm of dissolved content, was recovered from the diluted $MgSO_4$ DS by metathesis precipitation reaction with barium hydroxide to produce insoluble magnesium hydroxide and barium sulfate precipitates. Water flux can further be increased by increasing the concentration of $MgSO_4$ in the DS. The insoluble magnesium hydroxide can be reacted with stoichiometric amount of sulfuric acid to recover the magnesium sulfate DS.

The recovery of pure water from $MgSO_4$ DS using FO eliminates the need of high-pressure pump as in case of RO. The recovery of water from the feed to the DS in FO and the precipitation reaction used in this study require no energy. Although the FO technique presented in this paper is feasible yet it adds to increased chemical and raw material cost of the desalination process. A detailed economic analysis must be performed in order to evaluate the economic feasibility of the FO technique presented.

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