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Research Article

Thermal-Depression Regeneration of Forward (Direct) Osmosis Desalination Technique

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ABSTRACT

Forward osmosis (FO) desalination is exhibited utilizing dimethyl ether (DME) as a fresh draw solute, integrated with a thermal-depression regeneration (TDR) system that employs low-grade heat for draw recovery. Unlike traditional reverse osmosis (RO) which needs high hydraulic pressure and is susceptible to membrane fouling, FO is driven by osmotic pressure gradients and therefore operates at low pressure, greatly reducing fouling risk and energy use. DME displays high osmotic activity in water (osmotic pressures up to 4 MPa, 2.1 MPa at 7 wt% DME), appropriate to extract water from seawater feeds. FO experiments attained steady water fluxes of 2–3 $L\cdot m^{-2}\cdot h^{-1}$ (LMH) utilizing a polyamide membrane with a brackish feed, confirming good membrane compatibility and sturdy performance. The volatile DME draw solution is efficiently regenerated by controlled depressurization with moderate thermal input, lever aging DME's low boiling point to separate it from water without extensive post-treatment. The ending of 99% of the DME is recovered and recycled, with any permeating DME outgassing for capture, developing in trivial solute carryover to the product water. By utilizing low-grade thermal energy for regeneration, the incorporated FO–TDR approach functions with minimal electrical input and accomplishes a specific energy consumption as low as 0.46 kWh per cubic meter of drinking hwater produced. This DME-driven FO system focuses FO's advantages RO such as lower fouling propensity and decreased energy demand—while achieving high water flux with slight draw solute leakage. These consequences underline FO's potential as a main technology for energy-efficient desalination, with the likelihood for hybrid or modular integration into sustainable desalination technology systems.

Keywords: Adequate water, water treatment, GCC countries, seawater, desalination, Thermal-Depressurization Regeneration, reverse osmosis (RO), SWRO, Forward Osmosis

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1.0 INTRODUCTION

Water scarcity is becoming an increasingly critical global challenge, particularly in arid regions and industrial environments that necessitate substantial amounts of clean water. As the need for freshwater rises, desalination has emerged as a prominent solution for transforming seawater into drinkable water among the various desalination methods, forward osmosis (FO) has gained attention as an energy-efficient alternative to traditional reverse osmosis (RO)[1]. FO operates by leveraging the osmotic pressure gradient to facilitate the transfer of water from a low-salinity feed solution to a high-salinity draw solution, which can subsequently undergo further processing. Nonetheless, the effectiveness of FO desalination is largely contingent upon the regeneration of the draw solution, a factor that often introduces challenges related to energy use, efficiency, and scalability. A noteworthy advancement in this field is the implementation of thermal-depression-driven regeneration (TDR) for the draw solution, which presents a promising approach to enhance the efficiency of FO desalination, especially for large-scale applications. This article delves into the principles of thermal-depression regeneration, its benefits compared to conventional methods, and its effects on the overall efficiency and sustainability of FO desalination systems in industrial water treatment scenarios[2] The majority of desalination plants are located in the Gulf Cooperation Countries (GCC) s, where freshwater is limited, and seawater is abundant. Desalination has become increasingly significant globally too, particularly in the Americas and the Asian subcontinent in recent years. The salinity level significantly influences desalination costs; therefore, feed water with minimal impurities is most advantageous for the desalination process. Thermal distillation, electro dialysis (ED), and pressure-driven membrane separation processes are employed for the desalination of brackish and seawater; however, these methods entail significant operational and capital expenses. The primary factors contributing to the high operational costs of membrane-based methods include scaling, pre-treatment, high-energy consumption, and bio-fouling. In contrast, decreased thermal efficiency and scaling represent the significant limitations of thermal distillation methods. Reverse osmosis (RO) is a critical pressure-driven membrane process in which water permeates a semi-permeable membrane while rejecting salts. Reverse osmosis (RO) currently dominates the brackish and seawater desalination markets, accounting for over half of the global desalination capacity that has been installed. The energy costs associated with reverse osmosis (RO) technology remain high when compared to traditional processes for purifying non-saline water[3] in Antonian, A. (2020, C. Suh and S. Lee (2013), Foo, Z. H., et al. (2024), Z. Zhou, J.Y. Lee, and T.S. Chung,(2014) . Advancements in technology have significantly reduced the energy consumption of seawater reverse osmosis (SWRO) compared to thermal desalination methods, establishing SWRO as the benchmark for contemporary desalination technologies. SWRO plants exhibit certain disadvantages, notably a moderately high carbon footprint that exacerbates climate change, subsequently leading to increased ecological imbalance. Forward osmosis (FO) is an energy-efficient and viable desalination method that exhibits reduced susceptibility to fouling. This process is driven spontaneously across a partially porous membrane due to the osmotic pressure difference between two solutions with varying salinity levels. The FO technique is applicable in various contexts that necessitate infrequent membrane replacement and low or no-pressure operation. FO can be integrated with other post-treatment processes, including ultrafiltration, nanofiltration, low-pressure reverse osmosis, or membrane distillation. The integration of solar energy with the FO module in a hybrid system influences the overall electricity consumption during the post-treatment phase of the process. Ge et al. developed equipment for forward osmosis-membrane distillation (FO-MD) capable of recovering polyelectrolytes post-FO. Research indicates that significant rejection of polyelectrolytes occurs at temperatures ranging from 50 to 70 °C. The hybrid FO-MD system exhibits optimal efficiency when operated at a solution concentration of 0.48 g/mL and a temperature of 66 °C. This hybrid FO-MD process was employed for the treatment of toxic and dyed wastewater. Figure 1 below illustrates the FO-MD process utilised for wastewater treatment. Nonetheless, FO desalination has encountered several challenges, primarily involving a) the selection of a suitable draw agent accompanied by an effective regeneration process, and b) the material and structure of the membrane. Numerous studies have focused on enhancing membranes, while limited research has addressed the improvement of energy efficiency in draw agent regeneration methods mentioned Antonian, A. (2020, C. Suh and S. Lee (2013), Foo, Z. H., et al. (2024), Z. Zhou, J.Y. Lee, and T.S. Chung,(2014). The FO technique relies on osmosis to facilitate the movement of water from a solution with lower osmotic pressure to one with higher osmotic pressure through a partially permeable membrane. The choice of an appropriate drawing solution and the attainment of high flux are critical for the design of an optimal forward osmosis process. Establishing a straightforward and economical approach for the separation and regeneration of draw solution is a key focus in the design of a forward osmosis system. This study presents the development of a forward osmosis (FO) system and an integrated thermal-depression regeneration method. This research examines the use of gas compounds with high water solubility as draw agents in the forward osmosis process. The decrease in water solubility occurs during the regeneration phase through adjustments in operating temperature or pressure, aimed at optimizing energy consumption and maximizing both the quantity and quality of clean water produced. The osmotic pressure of potential gas draw agents is estimated using Van't Hoff's ideal law. The initial phase of the FO desalination system involves extracting fresh water from feed water (FW) via an osmotically driven mechanism utilizing a liquefied gas draw solution. The subsequent phase employs depression-thermal separation to regenerate the osmotic agent (or draw solute) and generate clean water. The regeneration of the draw solute is an energy-intensive process in forward osmosis, significantly influencing the feasibility of this method. Easy separation serves as a benchmark for selecting the optimal draw solute; additionally, factors such as non-toxicity, low cost, and high osmotic strength are also significant as per M. Park, J.J. Lee, S. Lee, and J.H. Kim(2014), G. Blandin, A.R.D. Verliefde, C.Y. Tang, and P.L. Clech (2014). In addition to conventional inorganic solutes, recent research has focused on various regenerable and stable draw solutions with improved osmotic potential, including organic solutes Nonetheless, the aforementioned systems continue to face several challenges. Thermoresponsive materials, including ionic liquids (ILs), serve as effective draw solutes due to their ionic characteristics, which generate high osmotic pressure. Additionally, the chemical structures of ILs' anions and cations can be modified to exhibit the desired thermodynamic properties.

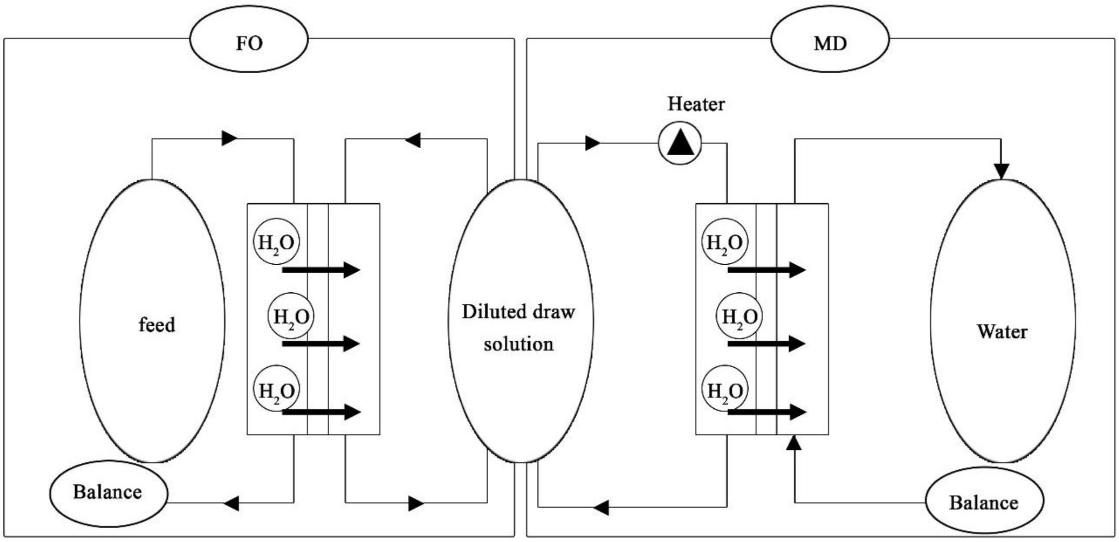


Fig 1. Hybrid FO-MD procedure for treating wastewater

Draw solution selection is crucial for sustainable and cost-effective clean water from saline feed water. The essential criteria for choosing an osmotic agent are high water solubility, high osmotic pressure, and easy, affordable separation of the draw solution in the regeneration process to provide clean water. Initial studies predicted whether the selected gaseous draw solution increases osmotic pressure. Concentration polarization (CP) hinders membrane-based desalination. The effects of draw agent/feed water concentration and flow rates on CP, rising temperature, and water flux are examined to determine the best FO desalination working conditions. Final mentions include draw solution separation and thermal-depression regeneration system clean water production. Q. Saren, C.Q. Qiu, and C.Y. Tang, (2011, G. Blandin, A.R.D. Verliefde, C.Y. Tang, A.E. Childress, and P.L. Clech, (2013) The draw solution's simulated regeneration process's specific energy consumption (SEC) was compared to current desalination methods, and the suggested FO desalination process with thermal-depression regeneration system is cost-effective for clean water. FO desalination's key issues are finding a draw solution with a reliable regeneration process, membrane fouling, and creating high-performance FO membranes to reduce ICP effect and reverse diffusion. They used hybrid FO-NF to examine sodium sulphate (Na_2SO_4) draw agent for brackish water desalination[7]. In the FO stage, seawater or brackish feed is drawn through a semipermeable membrane into a concentrated draw solution by natural osmotic pressure (no hydraulic pressure applied). The diluted draw solution is then processed in a **regeneration unit** (a low-pressure reverse osmosis or nanofiltration step) to separate fresh water and reconcentrate the draw agent. This hybrid FO + RO configuration was developed at the Centre for Osmosis Research and Applications (CORA) and later was commercialized. Key advantages demonstrated include lower fouling and significantly reduced specific energy consumption compared to standalone reverse osmosis. Below is a block diagram of the MOD pilot plant process, with major components and conditions labeled.

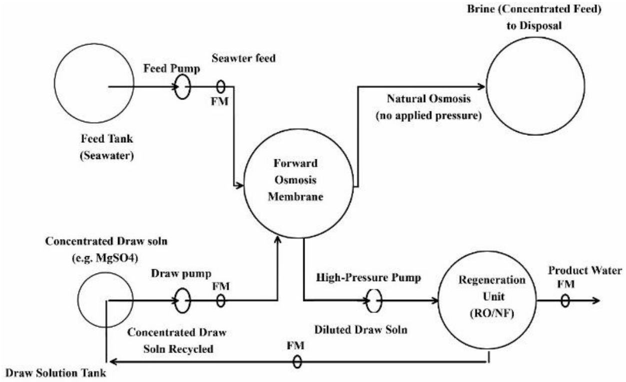


Fig 2. Block diagram of MOD.

Various literatures indicate the requirement for developing a reliable draw agent with characteristics such as Increased osmotic pressure in comparison with seawater, being economic and non-toxic, Minimum reverse diffusion flux to preserve the effective osmotic driving force, Easy separation from the product water that leads to low energy consumption. The Feed Water Supply comprises Pre-treated seawater (or brackish water) feed is stored in a feed tank and delivered by a low-pressure feed pump to the FO module and the water had a silt density index (SDI) of 3–7 after pre-treatment, suitable for FO operation. Typical feed flow rates in the pilot are on the order of 1–3 L/min per side, and the feed is often maintained at ambient temperature 25 °C. No external pressure is applied across the FO membrane (relying solely on the osmotic gradient), which greatly mitigates membrane fouling and energy use. The FO membrane in the pilot is a plate-and-frame or flat-sheet module that allows crossflow circulation of feed and draw streams on opposite sides. As the feed flows along the membrane, water diffuses into the draw solution, concentrating the feed brine. The FO module’s output on the feed side is a concentrated brine (reject) stream, which is either discarded or can be mixed with other brine for disposal. Flow meters (labeled “FM” in the diagram) monitor the feed flow rate into the FO unit, and pressure gauges are present to ensure only minimal pressure (just enough to overcome flow resistance) is applied. This low-pressure FO step provides a first-stage extraction of fresh water driven by osmotic potential difference alone. While the Draw Solution Circulation: On the draw side, a draw solution tank holds a concentrated osmotic agent (e.g. a magnesium sulfate solution was used). A circulation pump drives the draw solution through the FO module counter-current to the feed. The high osmotic pressure of the draw (often 1.7–2.1 M $MgSO_4$ in the pilot tests, corresponding to >100 bar osmotic pressure) pulls water through the membrane. As a result, the draw solution exiting the FO unit becomes diluted (its volume increases while its concentration drops). This diluted drawing solution carries the water extracted from the feed. Flow instrumentation on the draw loop tracks the circulation rate (typically similar to the feed flow, 1–3 L/min) and ensures stable operation. Because FO operates without high hydraulic pressure, membrane fouling is mostly reversible and can be controlled with simple flushing, unlike high-pressure RO fouling. At this point, the process has transferred freshwater from the feed into the draw solution; next, the diluted draw must be processed to yield the final product water. High-Pressure Pump: The diluted draw solution from the FO module is routed to a high-pressure pump that feeds the regeneration unit. In the MOD pilot plant, this pump raises the pressure of the diluted draw solution to up to 60 bar. Notably, this pressure is lower than what would be required to desalinate seawater feed via RO directly – because the draw solution, while diluted, still has a lower osmotic pressure than seawater feed would at equivalent recovery[9]. The pressurization step is the primary energy input of the MOD system, so it is designed for efficiency. In the pilot, a reciprocating pump was used, and a back-pressure regulator controlled the pressure to the target setpoint. Flow meters and pressure gauges on the high-pressure feed line, as well as on the downstream streams, monitor the performance of this stage. By adjusting pump speed and regulator, the operators maintain a constant feed flow (22 L/min was used in tests) into the regeneration membrane at the desired pressure. Regeneration Unit (Draw Solution Separation): The pressurized diluted draw enters the regeneration membrane unit, which in this pilot is a reverse osmosis (RO) module (alternatively a high permeability nanofiltration could be used). Inside the RO, pure water is forced out through the membrane as permeate, leaving behind a reconcentrated draw solution. This product water permeate is the final desalted water, with low TDS (typically <200 mg/L in MOD pilot results. It is collected for use or further treatment (in the pilot, product water met potable standards for salinity and boron). The other output of the RO unit is the draw solution concentrate, which contains the draw solute (e.g. $MgSO_4$) restored to a high concentration. This stream is recycled back to the drawing tank to be used again in the FO stage, closing the loop on the draw agent. The regeneration unit is a critical feature of MOD, enabling reuse of the draw agent; it operates at lower pressure and with membranes optimized for the draw solution characteristics (e.g. high permeability to water, and durable against the draw solute). Energy efficiency is achieved by only applying high pressure to the relatively low-salinity, diluted draw solution, rather than directly to seawater. The results demonstrated a specific energy consumption of 4.9 kWh/m^3 of product water for the FO+RO process, roughly 40% lower than a comparable conventional seawater RO (SWRO) plant (8.5 kWh/m^3). This improved energy efficiency is partly due to the recovery of osmotic energy that the draw solute acts as an intermediary that reduces the osmotic pressure the RO must overcome. Additionally, any waste energy (pressure) in the RO concentrate stream could be recovered via an energy recovery device, further enhancing efficiency. The MOD pilot plant's design highlights its draw agent separation process and overall energy efficiency. The draw solution regeneration via a low-pressure RO/NF unit is central to making the process viable. This step allows the drawing solute (which provides the osmotic driving force) to be continuously recycled with minimal loss. The choice of draw solute (magnesium sulfate) was strategic as it is non-toxic, highly soluble, and can be regenerated by membrane separation cost-effectively . The FO–RO hybrid configuration provides a double-barrier against feed contaminants – the FO membrane retains impurities in the feed concentrate, and the RO membrane polishes the product water. From an energy perspective, the FO stage replaces a portion of the work that would otherwise be done by a high-pressure pump in conventional RO with natural osmotic action. Operating the FO at low pressure greatly reduces fouling and the need for chemical cleaning, extending membrane life and lowering operating cost. The regeneration RO operates at about 30–60% lower pressure than a typical SWRO, due to the lower salinity of its feed. As a result, the MOD process achieved roughly 30–60% energy savings in pilot comparisons with conventional RO Aryafar, M. (2015). In summary, the MOD pilot plant demonstrates a clear process flow that FO extraction of water driven by a drawing solution, followed by efficient draw solution recovery. The block diagram and conditions reflect how each step is engineered to maximize water yield while minimizing energy usage, proving the concept of manipulated osmosis at pilot scale**Error! Reference source not found.**.

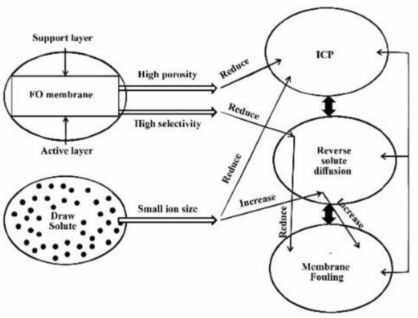


Fig 3. Relationships between ICP, membrane fouling, reverse solution diffusion, membrane characteristics and draw solute in FO B.D. Coday, B.G.M. Yaffe, P. Xu, and T.Y. Cath, (2014) , J. Heikkinen, H. Kyllönen, E. Järvelä, A. Grönroos, and C.Y. Tang, (2017)

1.1 Concept of draw solution

A significant challenge in the forward osmosis process is the development of a suitable draw agent that exhibits enhanced osmotic pressure compared to the feed solution, possesses high water solubility to facilitate increased water flux through the membrane, and can be regenerated in a practical and energy-efficient manner. The selection of a draw agent with increased osmotic pressure is a critical factor for enhancing the forward osmosis method. Inorganic salts, organic salts, volatile compounds, and materials such as magnetic nanoparticles may be investigated for use as draw solutions. The selection of a draw agent requires consideration of several specifications: minimal reverse diffusion to the feed solution, safe handling, cost-effectiveness, nontoxicity, low scaling risk at high concentrations, and ease of regeneration in the forward osmosis procedure. Volatile chemicals, including mixtures of ammonium hydroxide and ammonium bicarbonate, ammonium bicarbonate alone, water with sulfur dioxide and aliphatic alcohols, sulfur dioxide, and mixtures of potassium nitrate with sulfur dioxide and ethanol, have been utilized as draw agentsA B.D. Coday, B.G.M. Yaffe, P. Xu, and T.Y. Cath (2014). Currently, salts are predominantly utilized as draw agents; however, their recycling poses challenges in terms of energy and cost efficiency. To efficiently recover pure water following the FO procedure, one approach involved employing a binary ionic liquid/hydrogel system, as depicted in Figure 4 & 5.

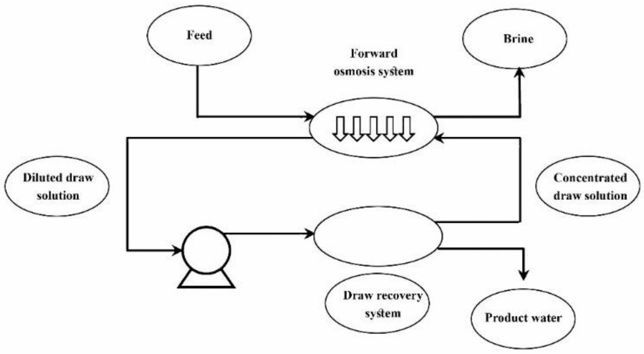


Fig 4. Flow Diagram of Pure water Recovery from FO process

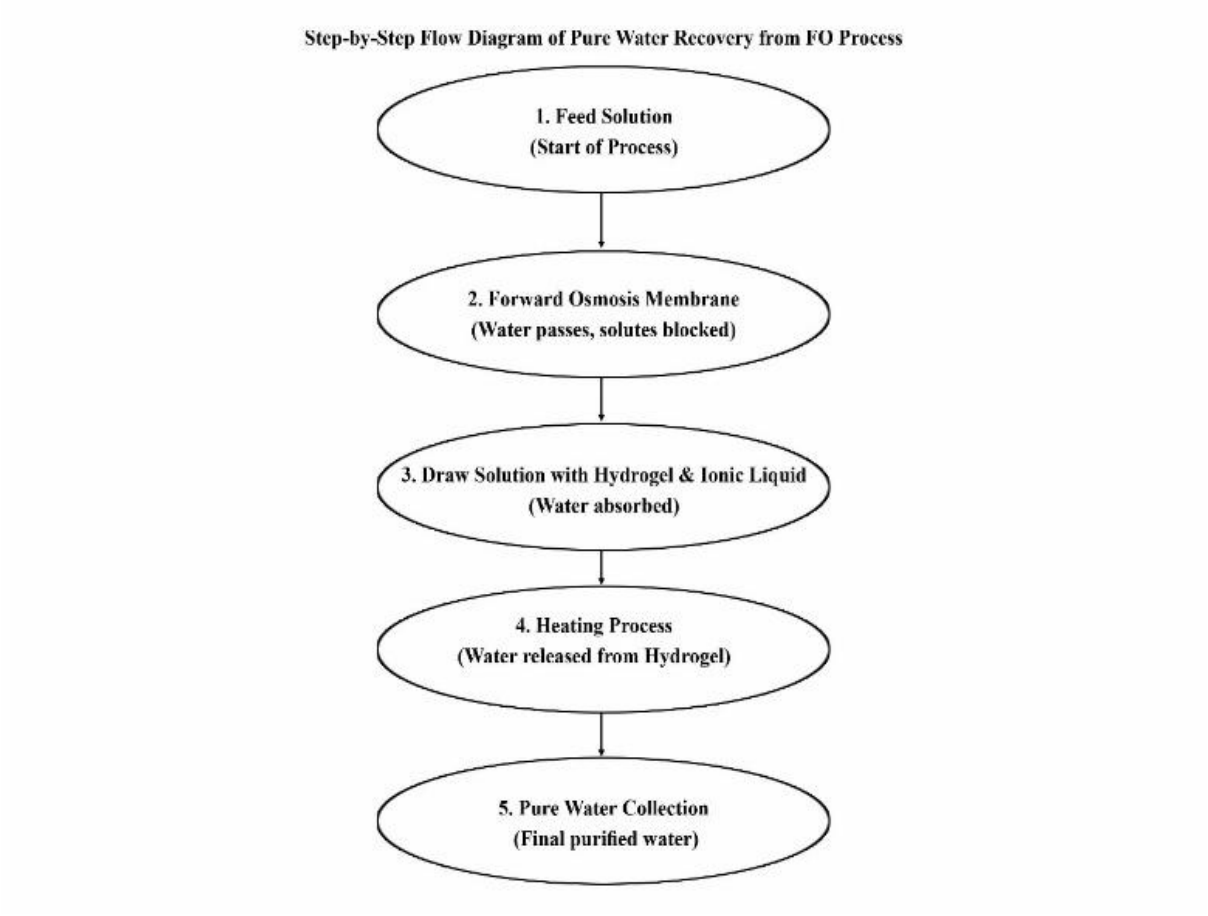


Fig. 5 Flow diagram for pure water recovery from the FO process

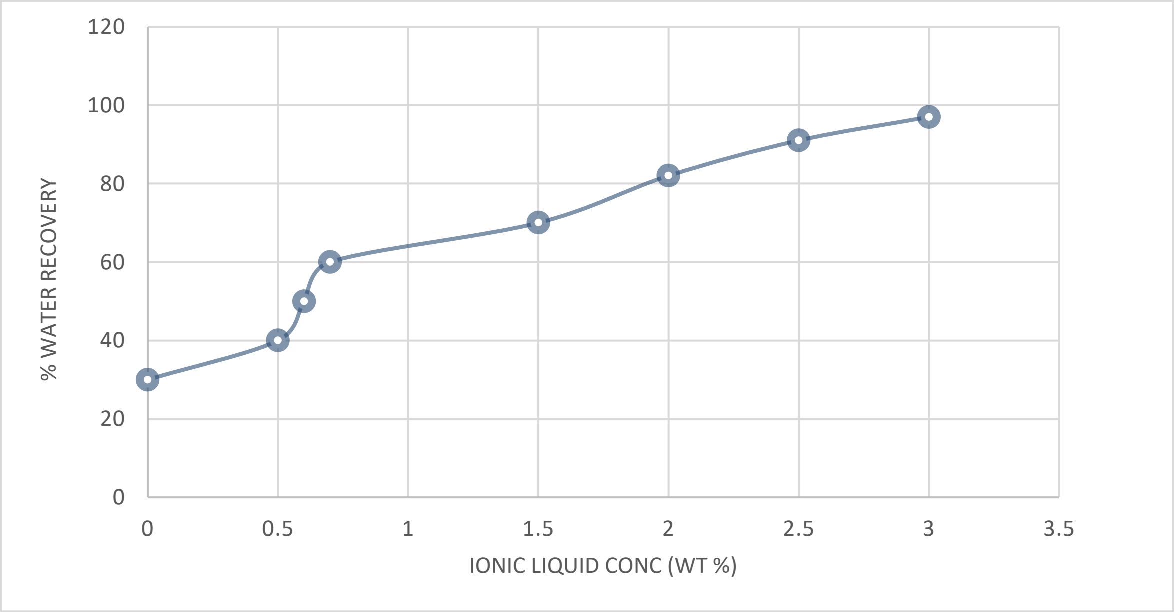


Fig 6. Pure water recovery from the FO process by using a binary ionic liquid/hydrogel system

This graph illustrating the pure water recovery from the FO process using a binary ionic liquid/hydrogel system Gas compounds with high water solubility could be utilized as draw agents in the FO procedure and the draw solution can be removed from water by varying the operating pressure and temperature. The chart of the suggested FO procedure with depression regeneration method using liquefied gas as the draw solution seen in Figure 4.

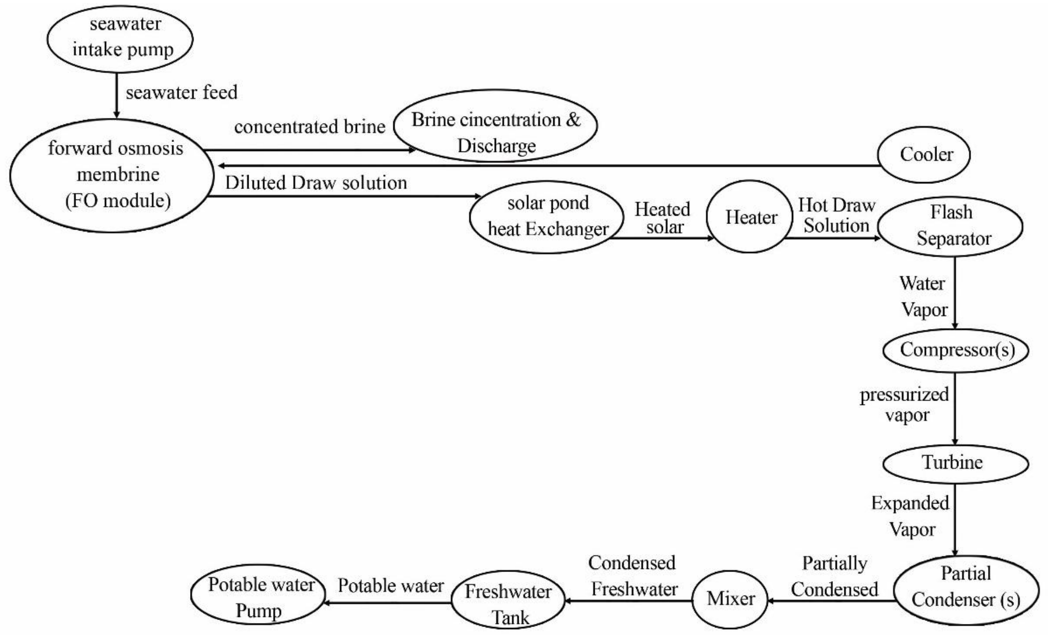


Fig. 7 Block flow diagram of depression regeneration method

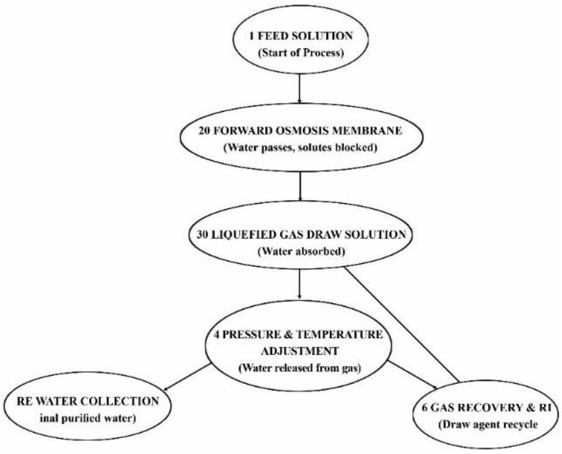


Fig. 8 Flow Diagram of FO process with Depression Regeneration Method

The draw agents have different solubilities in water which affects their osmotic pressure and aids their relative easy regeneration via a depression method. The osmotic pressure of all the proposed draw agents were found using Van't Hoff equation for ideal gas Aryafar, M. (2015)

$$\Pi = MRT \qquad (1)$$

Where M is the solute's molarity and it is the ratio of the moles of the solute (n) to solution volume (V), T is the absolute temperature and R is the gas constant, which is 8.3145 $JK^{-1}mol^{-1}$. At the end of the screen process, only four gases i.e. monomethylamine (836.02 bar), ammonia (643.37 bar), dimethyl ether (196 bar), and sulfur dioxide (38.2 bar) were selected. SO_2 and CH_5N were deleted from the list due to corrosivity and toxicity, respectively. Evaluation of the remaining two gases' draw agents was done by establishing their cost-effective and easy isolation from clean product water using the thermal-depression regeneration procedure. This was accomplished by varying the ammonia solution's osmotic pressure at saturated concentration in water against temperature by using OLI stream analyser software package. Figure 8 depicts that the solubility of ammonia in water decreases after 80 °C while varying the operating pressure has no effect on its solubility. Also, gaseous ammonia can be removed in dilute draw solution at a temperature of 100 °C[13] Y. Wang, M. Zhang, Y. Liu, Q. Xiao, and S. Xu (2016). Furthermore, varying the hydraulic pressure did not affect the osmotic pressure of ammonia draw agent. Therefore, the thermal separation procedure might not be an economical regeneration process by utilizing ammonia as draw solution; hence ammonia was deleted from the list of gaseous draw agents researched upon in this study.

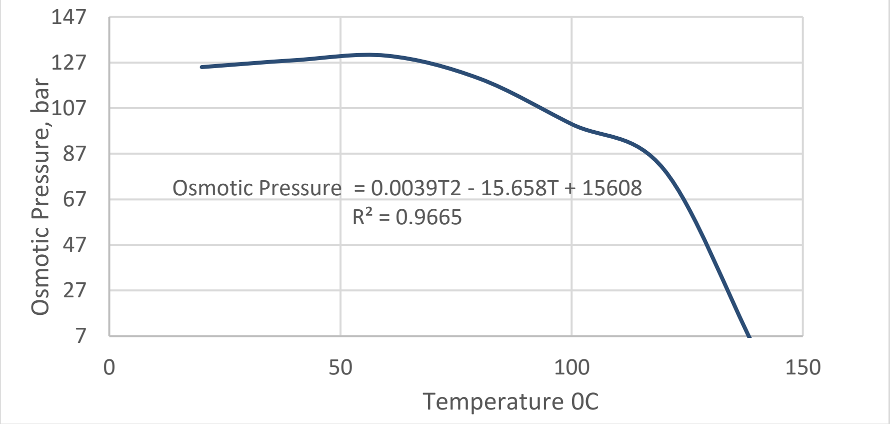


Fig. 9 Osmotic pressure of ammonia Vs operating temperature

Liquefied gas DME can be extracted from a DME-water solution using depression methods, including atmospheric or vacuum gas stripping, during the FO regeneration process. At a pressure of 1 bar, DME exhibits a solubility of 35 (v/v) and an osmotic pressure of 11 (bar). At 4 bar, the solubility of DME increases to 197 (v/v), with an osmotic pressure of 196 (bar). Research conducted by AckzoNobel 2016 indicates that the solubility of DME in water increases with the application of external pressure on the DME-water solution. This method employs a diluted draw agent to extract water through thermal or depressurization techniques, or a combination thereof. Pressure methods encompass vacuum gas stripping and atmospheric gas stripping, while thermal methods involve thermal flashing. The methods discussed may be integrated into a single apparatus. Alternatively, distinct apparatus may be employed for each method. The warm liquefied DME solution released from the compressor may be directed through a heat exchanger to acquire the necessary heat in the thermal flash tank. The flow of water through the membrane is typically affected by thermal conditions. Consequently, the feed solution may be heated, while the draw solution, which is warmed during compression, can be cooled utilizing a heat exchanger. The feed solution can be heated to temperatures ranging from 30 to 50 °C, while concurrently, the draw solution may be cooled to temperatures between 20 and 40 °C. Heating or cooling can be conducted independently for each solution. The entire FO unit can be sustained at a hydrostatic pressure ranging from 3 to 10 bar. DME-water depression regeneration requires less energy compared to other osmotic agent regeneration processes, including NaCl regeneration and the regeneration of various organic or inorganic osmotic agents[15] (2019). Figure 6 depicts the forward osmosis desalination process employing the depression regeneration method.

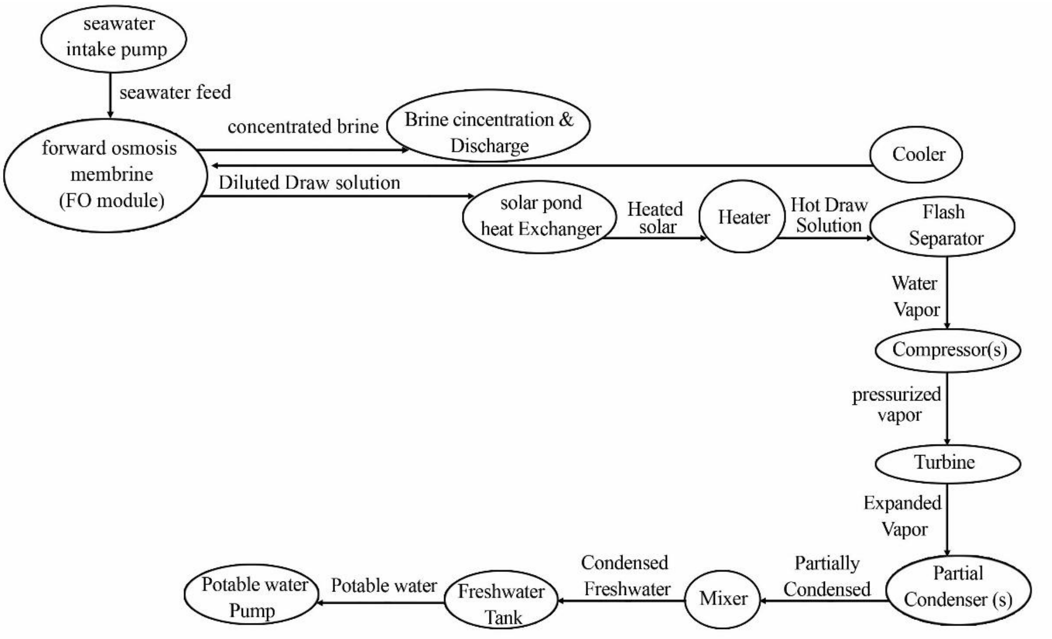


Fig. 10 FO desalination process method using depression regeneration

The potential of utilizing liquefied gas DME as a draw agent in the FO desalination process is assessed by estimating its osmotic pressure through three distinct methods: lowering vapor pressure, depression of freezing point, and calculating the water of hydration. The depression of freezing point aids in the calculation of osmotic pressure in proximity to the solvent's freezing point. The osmotic pressure of a DME-water solution at maximum solubility concentration is seven times greater than that of seawater, supporting the application of DME as a draw agent. The miscibility limit of the DME-water solution indicates that the maximum solubility of DME in water is 34% by weight, while a maximum of 6% water is miscible with DME[15] acoding to H. Asefi, A. Alighardashi, M. Fazeli, and A. Fouladitaja (2019).

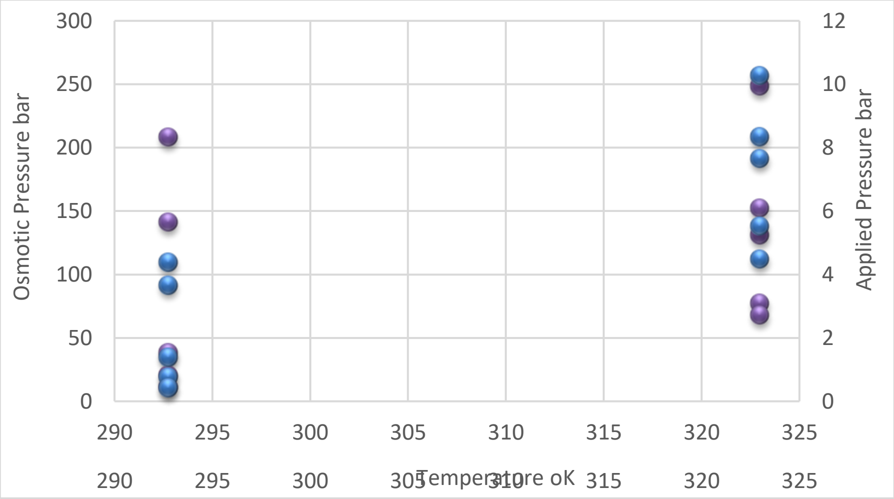


Fig. 11 Estimated Osmotic Pressure of DME-water

Table 1 statical analysis of osmotic pressure (bar)

	Osmotic Pressure (bar)
Mean	109.59
Standard Error	25.35
Median	104.04
Standard Deviation	80.18
Sample Variance	6428.71
Kurtosis	-0.85
Skewness	0.44
Range	237.65
Minimum	10.98
Maximum	248.63
Sum	1095.93
Largest(1)	248.63
Smallest(1)	10.98
Confidence Level(95.0%)	57.36

The results show that DME-water solution is polar, non-ideal with partial miscibility and generates an osmotic pressure at a maximum solubility seven times more than seawater osmotic pressure. Therefore, the liquefied DME-water solution is an ideal candidate as draw agent in the FO desalination procedure, While operating in the FO mode, small solutes such as micro pollutants and urea are better rejected than RO.

1.2 Concentration Polarization in Membrane

Both osmosis and pressure-driven membrane processes experience concentration polarization. It is notably prevalent in osmosis-driven membrane desalination processes, such as forward osmosis (FO), due to the nature of the process. CP is classified as dilutive or concentrative depending on whether the selective layer interfaces with the feed solution or the draw solution, respectively. Internal concentration polarization (ICP) occurs when dilutive and concentrative concentration polarization takes place within the support, while external concentration polarization (ECP) refers to these phenomena occurring at the membrane's boundary. In pressure-driven membrane processes, only the ECP near the selective layer needs to be considered. Recent studies extensively researched the effects of CP, focusing on both ECP and ICP. The FO method utilizing the SL-FS orientation features a highly porous support layer that inhibits the complete mixing of the permeate and draw solution within the membrane support, thereby diminishing the mass transfer rate. As a result, a reduced quantity of the draw solute penetrates the selective layer. The phenomenon occurring in the support is referred to as dilutive ICP. Concentrative ECP takes place on the side of the feed solution as the water flow directs the solute towards the surface of the selective layer from the feed solution [16] (2010).

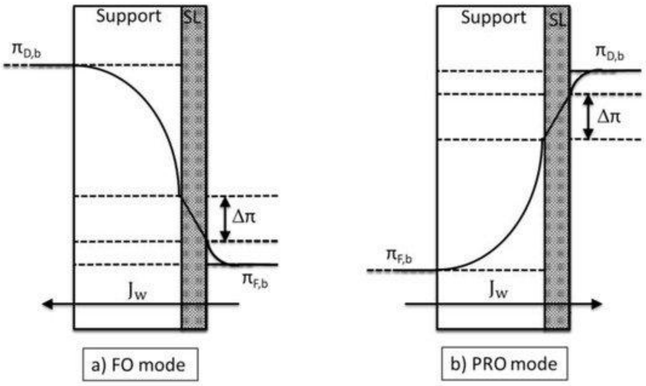


Fig. 12 The selective and support layer (SL) orientation in (a) FO mode and (b) PRO mode.

ICP occurs in the FO procedure when the feed solution is positioned adjacent to the support layer. The solute is unable to traverse the active membrane layer easily, resulting in its concentration within the inner structure of the membrane's support layer. The effective driving force in the FO procedure is significantly diminished due to ICP. The results of the study indicated that ECP can be reduced by altering the hydrodynamic conditions surrounding the membrane[17]. Methods to mitigate the impact of ECP encompass gas sparging techniques, mechanical approaches, and flow reversal the impact of fouling and ionic concentration polarization on the performance of forward osmosis water flux by varying the orientation and concentration of the draw solution's membrane. Results indicated that an increase in water flux occurred at higher concentrations of the draw solution; however, ICP was also elevated, particularly when the membrane's activated layer interacted with the feed water. The percentage of surface coverage remained constant until a critical flux, after which it increased significantly with rising water flux. The influence of feed spacers on water flux through the membrane was examined and revealing a significant positive effect on forward osmosis (FO) flux, despite the observation of particle precipitation near the spacer[18]. The performance of forward osmosis (FO) is closely linked to both the draw solution and the membrane; therefore, these factors must be considered in the design of a FO procedure. The draw solution should possess an appropriate molecular size, low viscosity, and high osmotic pressure, while being cost-effective and minimally toxic. Additionally, the FO membrane must exhibit high permeability and a small structural parameter to mitigate the impacts of the ICP phenomenon.

1.3 Fouling of membrane

Membrane fouling presents a significant challenge across numerous applications. The extent of membrane fouling is influenced by the type of membrane and the concentration of contaminants in the feed water. Pretreatment procedures are crucial for eliminating interfering contaminants in desalination processes. The physical and chemical properties of different organic foulants on the FO membrane, concluding that both chemical and hydrodynamic interactions governed FO fouling. The rate of organic fouling can be assessed through intermolecular adhesion forces and interactions between foulants. The proposed forward osmosis (FO) desalination procedure does not depend on mechanical pressure, resulting in membrane pores remaining free of suspended particles. Consequently, fouling during FO is likely to be reversible. Furthermore, due to elevated pressure, membrane compaction leading to flux reduction may be less significant compared to conventional reverse osmosis processes. Flux recovery in the forward osmosis (FO) method was significantly higher than that in the reverse osmosis (RO) method under comparable cleaning conditions, while the flux reduction rates in both FO and RO modes were found to be similar. Furthermore, adhesion sites on the FO membrane significantly contributed to decreased cleaning efficiency and increased fouling[19]. A most important issue in the FO procedure is draw agent selection, which is manifested as the motivation for water flux. A good draw agent has to be easy to regenerate and produce enhanced osmotic pressure. Another important issue in FO is ICP and it results in reduced water flux because of decreased driving force. In the feed solution facing layer method in FO, ICP results in the pressure variation to be much lower across the selective layer compared to the bulk osmotic pressure gradient because of the dilution of draw solute in the membrane support. Membrane optimization for FO has been researched upon only since a decade ago and RO membranes with thin-film composites have mostly been utilized in FO in the meantime. Therefore, much work should be put into optimization of the FO membrane support in addition to enhancing the FO membranes' selective layer.

1.4 FO Membrane

Ideally, a fit for purpose FO membrane should have good mechanical strength, must provide high rejection towards draw and feed solutes, and have an increased water flux. Hence, the key objectives to be considered while designing an FO membrane such as the membrane should possess a permeability of water of >1 $L\ m^{-2}\ h^{-1}\ bar^{-1}$, Maximum reduction in support's structural parameter, and, In order to sustain the variation in osmotic pressure, draw solute rejection of the selective layer has to be increased . The selective and support layers influence mass transport in the forward osmosis (FO) process, with water transport being reduced due to internal concentration polarization (ICP) in the porous support layer. Multiple techniques are employed to produce membranes with selective layers, including layer-by-layer assembly (LbL), interfacial polymerization (IP), inversion of conventional phase for asymmetric membranes, surface grafting, and blending IP is the primary method for preparing FO membranes due to its enhanced selectivity for various solutes, including small-sized solutes such as NaCl F. Esmaeilion (2020), Monjezi, A. A., et al. (2017), Ahmed, M., et al. (2019),[20]. In contrast to pressure-driven techniques, it is important to note that the hydraulic pressure generated by flowing pumps is lower in the FO procedure, thus the membrane support does not require enhanced mechanical strength. The structural parameter (S) of a membrane refers to the thickness of the membrane support, which remains independent of varying operating conditions. Supports with a higher S value yield increased ICP and reduce FO functionality concerning water flux, and vice versa. The structural parameter (Sint) is detailed as follows:

$$Sint=l\tau\varepsilon. \qquad (4)$$

where τ is the tortuosity (-), ε is the support layers's porosity (-), and l is the thickness (m). S indicates the effective diffusion path length that must be travelled by a solute via the support layer of membrane till it attains the selective layer. Various parameters other than porosity, thickness, and tortuosity also influence ICP such as pore morphology support pore diameter, hydrophilicity, and charge. The support's pore size influences the coarseness of the selective layer. Smaller pores cause a smoother selective layer thereby resulting in a lower flux and vice versa[21]. The membrane's hydrophilicity assists in keeping the internal structure of the membrane moist and it also assists in mitigating ICP. Various investigations have shown that there is substantial uncertainty in optimizing the morphology of the support morphology FO applications. In the FO mode, draw counter ions to the support network that is charged, thereby resulting in raised internal osmotic pressure, which consequently leads to an increase of effective driving force.

1.5 Pressure Retarded Osmosis

The developed models that incorporated the combined effects of ICP and ECP on water flux in both FO and PRO modes of FO membranes[22]2010. The models predicted water flux at different temperatures using NaCl as the draw agent. The flux performance improved with rising operating temperature; however, the enhancement was constrained due to the significant impact of ECP and ICP at elevated fluxes. Additionally, flux reduction was observed in both modes due to elevated intracranial pressure according to Masaaki Sekino, 2022 , Piash, K. S., & Sanyal, O. (2023), Gulied, M. Hersi. Ahmed., Alnouri, Sabla., Han, D. S., Stijepović, V., Grujić, A. S., & Stijepović, M. (2025),. Water flux was adversely affected by ECP in the PRO mode, while its impact in the FO mode was minimal. Nevertheless, the models did not account for salt passage in the direction of reverse solute flux and water flux. To predict the water flux in both modes, the developed models are presented as follows:

PRO Mode: $$J_W = A\left[\pi_{Db}\exp(\frac{J_W}{K_D}) - \pi_{Fb}\exp(J_W K)\right] \quad (5)$$

FO Mode: $$J_W = A\left[\pi_{Db}\exp(J_W K) - \pi_{Fb}\exp(\frac{J_w}{K_F})\right] \quad (6)$$

Here, J_w is water flux (cm3/cm2sec) across the semipermeable membrane, parameter A is the coefficient of water permeation (cm3/cm2-sec-atm) and B is the salt permeation coefficient (cm/sec) of a semi-permeable membrane. K is the porous substrate that is resistant to salt diffusion (sec/cm), π_{Fb} is feed solution's bulk osmotic pressure (atm) and π_{Db} is the draw solution's bulk osmotic pressure. K_F and K_D present mass transfer coefficient (m/s) in feed and draw solutions, respectively. The models considered only ECP or ICP effect for predicting water flux as per Nagy, E., Ibrar, I., Braytee, A., & Iván, B. (2022), Nagy, E., & Hegedüs, I. (2021), Xie, P., Cath, T. Y., & Ladner, D. A. (2021). They are presented in the following equations as modelling flux with ECP effect and modelling flux with ICP effect:

Modified with effect of ECP: $$J_W = A\left[\pi_{Db}\, exp(-\frac{Jw}{k_D}) - \pi_{Fb}\, exp(\frac{Jw}{k_F})\right] + 6.54{*}10^{-6}\,(k_F + A\pi_{Fb}) \quad (7)$$

Modified with effect of ICP: $$K = \frac{1}{Jw}\, ln\left[\frac{B + A\pi_{Dm} - Jw}{B + A\pi_{Fb}}\right] + 2.34{*}10^{-4}\,(B + A\pi_{Fb}) \quad (8)$$

In the above equations, A is the coefficient of water permeability (cm3/cm2-sec-atm), B is coefficient of salt permeability (cm/s) of membrane, Jw is the water flux (cm3/cm2-sec) over the membrane. Also, π_{Dm} is osmotic pressure (atm) of draw solution on membrane surface, π_{Db} and π_{Fb} are bulk osmotic pressure (atm) of draw solution and feed solution. K is the resistivity of solute (cm/s) in order to diffuse through the support layer that is porous, kF and kD are mass transfers of feed and draw solutions, respectively. Thus, decreasing K indicated the possibility of higher recovery of feed water as well. Therefore, while designing the membrane, if the support layer is made more porous, the water flux performance will be better, and higher feed water recovery could be achieved in a membrane process that is driven by osmosis Nagy, E., Ibrar, I., Braytee, A., & Iván, B. (2022), Nagy, E., & Hegedüs, I. (2021), Xie, P., Cath, T. Y., & Ladner, D. A. (2021).

1.6 Solute Reverse Diffusion Flux in Modelling Water Flux

For the FO procedure to be effective for treating wastewater and for desalination, minimum reverse permeation of draw agent into feed is required. A model for draw solute flux reversal considering significant ECP and ICP on the two sides of membrane in FO process the effects of reverse solute flux and ECP on predicting the water flux is significant, particularly at high concentration of the feed solution.

2. RESULTS AND DISCUSSION

2.1 Forward Osmosis Desalination with Thermal-Depression Regeneration: Improving Efficiency and Scalability

Desalination has become a critical technology for augmenting water supplies in arid and coastal regions, but conventional processes like reverse osmosis (RO) and thermal distillation are energy-intensive and costly. Improving efficiency and scalability of desalination is an industry priority to meet growing water demand sustainably. Forward osmosis (FO) has emerged as a promising alternative desalination method with the potential for lower energy use and fouling resistance. Recent studies suggest FO-based systems could reduce desalination costs by over 30% in suitable applications. However, to fully realize FO's benefits at scale, innovative approaches are needed to regenerate the drawing solution efficiently. In this context, thermal-depression regeneration – using low-grade heat to recover the draw solute – offers a novel route to improve FO desalination's energy efficiency and scalability. This article provides an overview of FO desalination principles and challenges, explains the thermal-depression regeneration mechanism and its thermodynamic basis, and analyzes its advantages. Forward osmosis (FO) desalination uses a concentrated "draw" solution with high osmotic pressure on one side of a semi-permeable membrane and a feed (e.g. seawater or brine) on the other. This osmotic pressure difference naturally induces water to flow from the dilute feed through the membrane into the drawing solution, while salts and contaminants are retained on the feed side. FO operates without the high hydraulic pressures of RO, giving it an intrinsic resistance to fouling and potentially lower pretreatment requirements. The challenge is that FO does not directly produce pure water – instead it yields a diluted draw solution from which fresh water must be extracted. Regenerating the drawing solution (i.e., separating the extracted water and re-concentrating the drawing solute) is energy-intensive and remains the key hurdle for FO processes. In fact, the energy required to reconcentrate the draw can exceed that of direct desalination by RO unless special strategies are employed. This limitation constrained FO's economic viability to niche applications or cases where low-cost energy (like waste heat) is available. Additionally, FO membranes face internal concentration polarization (accumulation or dilution of solutes within the porous support), which reduces effective osmotic driving force and flux. Despite these challenges, continued advances in membrane design and drawing solution chemistry are gradually improving FO performance. The focus has turned to developing regeneration techniques that can capitalize on FO's low-pressure operation while minimizing energy input which is where thermal-depression regeneration comes in F. Esmaeilion (2020), Monjezi, A. A., et al. (2017), Ahmed, M., et al. (2019),.

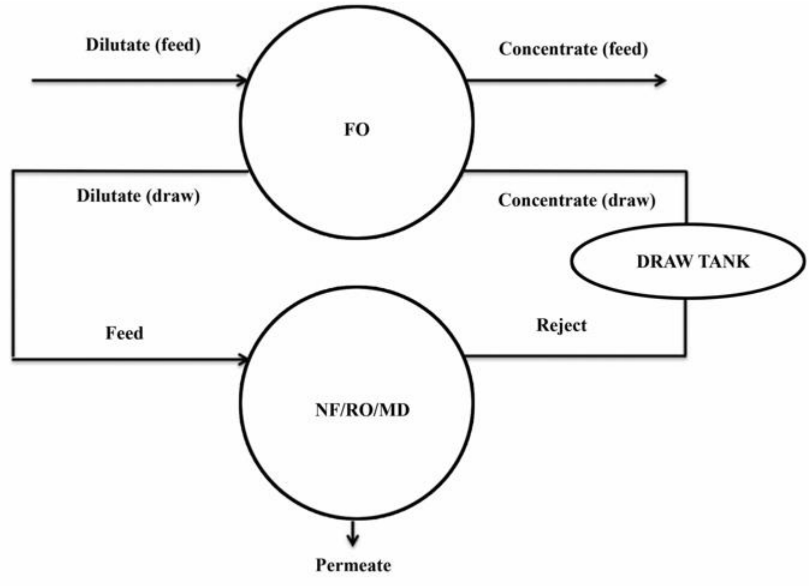


Fig. 13 Block diagram of typical RO, FO, NF and MD

for desalination process H. Asefi, A. Alighardashi, M. Fazeli, and A. Fouladitajar, (2019)

The Thermal-depression regeneration refers to using low-grade heat (i.e. modest temperature heat sources such as waste heat or solar thermal) to recover the draw solute and produce fresh water from the diluted draw solution. The concept leverages thermodynamic triggers like phase changes or solubility shifts that occur with heating (or pressure decrease) to separate the draw solute from water. One approach is to use a volatile or thermolytic draw solute that can be precipitated or vaporized at moderate temperatures, thereby "depressurizing" the osmotic system and releasing clean water. Ammonium bicarbonate draw solutions decompose upon heating to 60–70 °C, releasing ammonia and carbon dioxide gases and leaving behind desalinated water. These gases can then be re-captured and recombined to regenerate the draw solute. Another example is using a gaseous draw agent like dimethyl ether (DME) or ammonia in the FO process. Under ambient conditions DME and ammonia exist as gases, but under moderate pressure they dissolve in water to create a high-osmotic-pressure draw solution. After FO extraction, applying gentle heat or simply reducing the pressure causes the dissolved gas to come out of solution (a phase transition), separating from the water as vapor. The vapor can be condensed or recompressed to regenerate the draw agent for reuse. Thermodynamically, these methods exploit the lower latent heats or specific triggers of the draw solutes compared to vaporizing water itself. Instead of evaporating large quantities of water (as in distillation), the process only needs to supply enough heat to change the state of the draw solute (e.g. driving off a gas or precipitating a salt). This can reduce the energy required if the draw solute is cleverly chosen. Recent advancements include switchable solutes and polymers that respond to temperature changes. For instance, certain draw solutions are designed to undergo liquid–liquid phase separation when heated – one phase becomes almost pure water, which can be drawn off, while the other phase contains the concentrated draw solute. An example is a thermo-responsive polymer draw that, when heated to 80 °C, expels the absorbed water and forms a separate polymer-rich phase[24]. No boiling of water is required in that case, making it extremely energy-efficient. Overall, thermal-depression FO systems are engineered to use low-grade heat sources (e.g. industrial waste heat, geothermal or solar heat) to drive the draw recovery step. This mechanism turns FO into a process that can run predominantly on heat energy rather than electrical energy, distinguishing it from RO which relies entirely on electricity for high-pressure pumps. Using low-grade thermal regeneration for FO draw solutions offers several compelling advantages. First, it can substantially lower the electrical energy consumption of desalination by replacing energy-intensive high-pressure pumps with heat input from inexpensive sources. In FO, electrical demand is for pumping fluid streams (typically only a few kWh per cubic meter), far less than the 3–5 kWh/m³ needed to drive RO's high-pressure pumps. Thermal-depression systems tap into waste heat or solar heat, which often has low or no marginal cost. By doing so, the overall energy cost per unit of water can be reduced. A design study on a DME-draw FO system predicted energy savings on the order of 70–90% in draw regeneration compared to conventional separation methods. Secondly, this approach improves efficiency by operating at lower temperatures than traditional thermal desalination. Using phase-change draw solutes means water is liberated without boiling; Ammonia/carbonate FO regeneration occurred at 60 °C, much lower than multi-stage flash distillation temperatures. Lower temperature operation enables higher utilization of waste heat and easier integration with processes like solar collectors or engine exhaust streams. Third, thermal regeneration can enhance FO scalability and flexibility. FO modules can be added in a modular fashion without proportionally increasing electrical infrastructure, as the heat supply can often be scaled by tapping into larger heat sources or adding solar thermal capacity. This makes FO attractive for co-location with power plants or industrial facilities generating waste heat. In such scenarios, FO acts as a "heat sink" for energy that would otherwise be wasted. Moreover, FO's low-pressure operation and reduced fouling propensity mean that large-scale systems may require less intensive pretreatment and maintenance. This was demonstrated in a pilot treating high-fouling flue gas desulfurization wastewater where FO could concentrate this feed without the softening pretreatment that RO would require. The thermal-depression regeneration in that system allowed handling very saline, scaling-prone brine using low-grade heat instead of electricity. Finally, the ability to use renewable or low-carbon energy sources (solar thermal, geothermal) for draw recovery means FO with thermal regeneration can reduce carbon emissions relative to electrically driven RO. In summary, by smartly exploiting low-grade heat, thermal-depression FO desalination can achieve higher energy efficiency and lower operating costs, while its inherently modular, lower-pressure nature supports scaling up to meet industrial water demands. Researchers and engineers have begun validating these concepts in laboratory and pilot-scale studies. One noteworthy case is the use of thermolytic ammonium salts as FO draw solutes[25]. The FO membrane achieved a water flux of about 6.8 L/m²·h and extracted 99.9% of the water (virtually complete recovery) using the high osmotic pressure of the NH_4HCO_3 draw. To regenerate the draw, the diluted ammonium bicarbonate solution was heated, causing it to dissociate into ammonia and CO2 gas, which were removed. While technically successful in producing pure water, the thermal energy consumption was reported at 265–300 kWh per cubic meter of water higher than that of conventional multi-stage flash (MSF) distillation of 38 kWh/m³ thermal. This underscored the need for efficiency improvements; indeed, without heat recovery the energy demand was prohibitive, explaining why such gaseous draw solutes have seen limited practical use so far . Recent developments have significantly improved on this. A pilot FO system employed a two-phase thermal regeneration using a draw solution of magnesium sulfate $MgSO_4$ coupled with a polymer (UCON) that triggers phase separation. In FO tests, the system concentrated coal power plant wastewater to 5× concentration (80% water recovery) with a stable flux 6 L/m²·h. The diluted draw solution was then mixed with the thermo-responsive polymer and mildly heated 90 °C to induce separation to a polymer-rich phase (containing most $MgSO_4$ and a water-rich phase formed immediately. This allowed recovering fresh water without boiling. The reported thermal energy input was 190 kJ per kg of water , with integrated heat recovery, and only 2.2 kWh/m³ of electricity for pumping. This is a dramatic improvement over the earlier ammonium salt system, cutting thermal energy by roughly 5-fold, into a range comparable with or even lower than some established ZLD (zero liquid discharge) methods. Another case study comes from a solar-powered FO-MD hybrid pilot. A system coupling forward osmosis with membrane distillation (MD), driven by a photovoltaic-thermal (PVT) solar collector[26]. FO was used to extract water from a 10,000 mg/L brackish feed into a 1 M NaCl draw, and the diluted draw then fed an MD unit where low-grade heat evaporated water through a hydrophobic membrane. The pilot, operating under real solar conditions, achieved FO water fluxes of 8.2 L/m²·h and MD fluxes of 2.7–4.3 L/m²·h. It produced about 269 L of desalted water per day using only solar energy (plus minimal pumping power), which extrapolates to 107 m³ per year. While small, the system demonstrated the feasibility of using renewable heat for continuous FO desalination. Economic analysis showed an 11.8% return on investment and a 9-year payback period at that scale, suggesting that larger-scale or optimized systems could be commercially viable. In the Middle East, FO has also been piloted by Modern Water and others; FO-RO hybrid plant in Oman successfully operated using FO as a pretreatment to RO. These case studies collectively illustrate the trajectory of FO with thermal or hybrid regeneration from early high-energy prototypes to increasingly efficient and integrated designs. They highlight performance metrics (fluxes on the order of 5–10 LMH, energy on the order of tens of kWh/m³ of heat) that inform the design of next-generation FO desalination plants. Despite the progress, several challenges must be addressed before thermal-depression FO desalination is widely adopted. Technical challenges include improving FO membrane performance and longevity. Many current FO membranes were originally developed for RO and suffer from internal concentration polarization, which limits water flux . There is ongoing research to fabricate membranes with thinner support layers or novel materials (e.g. aquaporin-integrated membranes) to boost FO flux without sacrificing salt rejection. Membrane fouling, while generally more reversible in FO than RO, can still occur over long operating times and in high-strength wastewaters, so effective fouling control strategies are needed for stable operation. Another technical hurdle is reverse solute flux – some draw solutes can diffuse backward into the feed during FO. Volatile draws like ammonia or DME, or small salts, may leak and contaminate the product or feed if not well-contained, which complicates system design (requiring, for instance, venting and re-capturing stray gases, or using draw solutes that are non-toxic in trace amounts). Ensuring complete recovery of draw agents without losses is vital, especially for expensive or regulated chemicals[27] . From a thermodynamic standpoint, energy efficiency is still a concern. While thermal-depression methods use lower-quality heat, the total energy input can be significant if not recovered. For instance, even 50 kWh/m³ of heat input is a large energy quantity unless waste heat is truly free or abundant. Thus, projects must carefully integrate heat exchangers for energy recovery and seek heat sources that would otherwise be unused. Economic and scalability challenges also remain. The viability of FO with thermal regeneration strongly depends on access to low-cost heat. Not all locations have waste heat streams or cheap thermal energy; some may require investing in a boiler or solar field, impacting cost. The capital cost of FO systems is currently relatively high per volume of water, partly due to the larger membrane area needed (since FO fluxes are lower than RO). Scaling up to produce millions of gallons per day will require cost reductions in membrane manufacturing and module design. Additionally, some advanced draw solutes (polymers, switchable compounds) are not yet produced at industrial scales or may be costly to make and maintain (i.e periodic replacement of degraded polymer). There are also safety and regulatory considerations if volatile or novel chemicals are used in large quantities. Another limitation is that FO by itself cannot achieve very high-water recoveries without a secondary step; if maximal water recovery is needed (as in ZLD applications), FO will likely be one component of a hybrid system (followed by MD, crystallizer, etc.), which adds complexity. In summary, the challenges span materials science (better membranes and draws), process engineering (heat integration, preventing draw losses), and economics (capital and operating cost). Many FO processes today are best suited for niche uses (high-fouling feeds, integration with specific heat sources) rather than drop-in replacement of RO in all scenarios as per M. Pevarnik, M. Schiel, K. Yoshimatsu, I.V. Vlassiouk, J.S. Kwon, K.J. Shea, and Z.S. Siwy, 2018. Continued innovation is required to broaden the technology's applicability. The Forward osmosis desalination with thermal-depression regeneration represents an exciting pathway toward more energy-efficient and scalable desalination. By exploiting low-grade heat to recover draw solutions, this approach can circumvent the heavy electrical demands of conventional RO and capitalize on abundant waste or renewable thermal energy. It is how FO works and its key challenge – draw solution regeneration – and saw that using thermally responsive draw solutes (from ammonium salts to volatile compounds and phase-separating polymers) can improve the energy profile of FO systems. Case studies demonstrate steady progress for early FO prototypes achieved high water recovery but with high heat usage, whereas newer pilot systems have slashed thermal energy requirements and successfully operated using waste heat or solar input. These advancements translate into lower operating costs and make FO more practical at larger scales. Nonetheless, FO with thermal regeneration is not without limitations, and further research is needed to optimize membrane designs, develop even more efficient draw solutes, and integrate systems for minimal energy loss. Industry professionals and researchers are actively tackling these issues so by designing FO membranes specifically to reduce internal concentration polarization and by testing hybrid setups that combine FO with RO, MD, or other processes for complete desalination solutions. Going forward, focus areas should include: developing robust, fouling-resistant FO membranes with higher flux, identifying draw solutes that are inexpensive, safe, and ultra-low-energy to regenerate, and demonstrating FO-thermal systems at larger pilot and commercial scales to validate long-term performance and economics. Collaboration between the desalination industry and the energy sector could also accelerate adoption, by matching FO systems with available waste heat sources in power plants, refineries, or geothermal installations. In conclusion, thermal-depression regenerated FO holds considerable promise for transforming desalination. It aligns with the global pursuit of sustainable water technology by lowering energy consumption and enabling the use of alternative energy inputs. With ongoing innovation addressing current challenges, this approach could play a significant role in the next generation of high-efficiency, scalable desalination plants, contributing to water security with a smaller energy and environmental footprint.

2.2 Introduction to an Integrated Forward Osmosis and Decompression Method

The FO process utilizing DME was characterized by several attributes, including water flux, the final concentration of DME in the drawing solution, temperature, and the effect of cross flow velocity of the draw solution on water flux. In a continuous forward osmosis operation, the osmotic pressure difference between the draw and feed solutions leads to the dilution of the DME draw agent by permeating water from the feed solution, which is then restored through decompression. The regeneration process separates the diluted DME solution into two components as desalinated water and a concentrated draw agent, which is subsequently recycled in the FO unit[29] per M. Arjmandi, M. Peyravi, M.P. Chenar, and M. Jahanshahi,, 2019. The DME solution employed in the FO procedure liquefies at ambient temperature when subjected to pressure generally below 10 bar. Upon exiting the FO unit, the diluted DME draw solution undergoes depressurization and vaporization, resulting in the separation of the extracted clean water.

2.3 Principle of DME Separating Method

DME remains as a gas at atmospheric pressure and room temperature and it liquefies at 5-7 bar pressure, even at normal room temperature. Liquid DME absorbs water. Some of the researchers brought out a dewatering method by using liquefied DME that can extract water efficiently from coal or sewage sludge at room temperature and the procedure is illustrated in Figure 14,15.

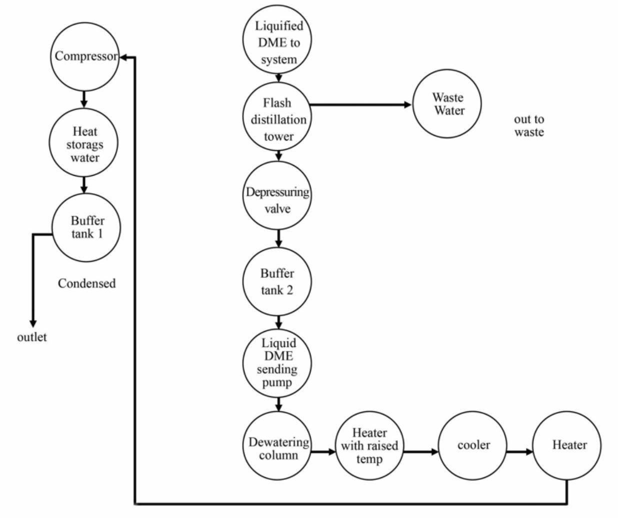


Fig. 14 Coal dewatering equipment by using DME

Y. Wang, M. Zhang, Y. Liu, Q. Xiao, and S. Xu, (2016), V. Parida and H.Y. Ng,, (2013).

In FO desalination using DME draw solution, the method is applied for DME regeneration at downstream of the FO unit. The integrated FO and depression process for DME regeneration is illustrated in Figure 15).

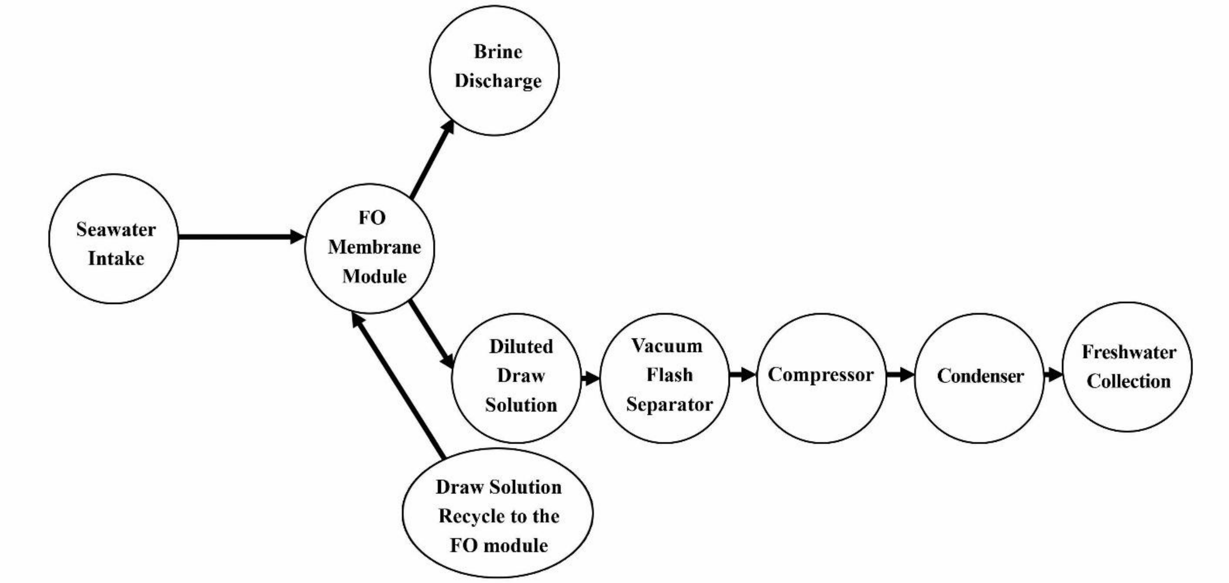


Fig. 15 Flow Diagram of FO-DTR desalination procedure for seawater or brackish water

The proposed FO system comprises a feed chamber and a chamber for the draw agent solution (draw solution), separated by a semipermeable membrane . This method involves the introduction of the feed water line on one side of the membrane via a pump, while the compressed draw solution stream is introduced on the opposite side of the membrane. Water traverses the membrane through natural osmosis, driven by the osmotic pressure of the draw agent, which exceeds that of the feed side. As the diluted draw agent enters the regenerating unit, the concentrated feed solution exits the FO unit. The draw agent exhibits a higher pressure in conjunction with the operating pressure, resulting in the natural flow of water from the feed solution to the draw solution side along a concentration gradient. The feed side maintains a hydrostatic pressure below 1 bar or at minimum atmospheric pressure, while the DME draw solution operates at a hydraulic pressure ranging from 4 to 10 bar. Additional pressure can be applied through a pressure exchanging apparatus to enhance the compression of the separated draw agent via a compressor , or it can be reduced by passing through the regulator. The upper stream in the separation process typically contains concentrated pure DME gas, while the lower stream comprises pure or certain species of the draw agent or residual salt species from the feed solution, such as NaCl or KCl in sea or brackish feed water. The draw agent solution may be separated from water using a stripping or gas depression unit. The extracted water is typically categorized into two portions. The initial segment containing the necessary quantity of clean water can be processed in unit using the vacuum thermal gas stripping method to yield potable water in compliance with WHO standards. The second portion may facilitate the dissolution of the concentrated gas draw agent through the application of a compressor . The upper stream of the separating column is redirected to the separated draw agent stream , while the bottom stream is utilized for the production of drinking water or clean water for irrigation purposes. The regeneration process is modeled using a single flash column at atmospheric pressure to separate the DME draw solution from clean water through a depressurization method Z. Zhou, J.Y. Lee, and T.S. Chung, (2014). The diluted DME-water draw solution is heated before entering the flash tank to ensure complete separation. The separated DME gas will undergo liquefaction via a compressor for recycling within the FO system. The thermal-vacuum flash process may be employed subsequent to the initial depression unit to facilitate the comprehensive separation of DME from purified water.

2.4 DME Separating Process and FO Regenerating Unit Mass Balance Relations

Flash vaporization, both partial and total, takes place when a saturated solution goes through a lowering in pressure when it is passed via a throttling device. Flash evaporation occurs when the throttling tool is placed at the entrance of the pressure vessel. When a liquid made up of multiple components such as a mixture of DME and water is used as the saturated liquid, one segment of it flashes into vapor and the flashed vapor will be enriched with the highly volatile component, DME in this case. Figure (16) illustrates a schematic of a flash evaporation column. In a liquid with multiple components, calculating the amount of residual liquid and flashed vapour in equilibrium involves solving the Rachford-Rice equation at a given pressure and temperature and it requires a solution after trial-and-error iterations**:**

$$\sum_i \frac{z_i(K_i-1)}{1+\beta(K_i-1)} = 0 \qquad (10)$$

$$y_i = K_i x_i \qquad (11)$$

Where β is the vaporized fraction of feed; z_i is the mole fraction of *i* in feed solution; K_i is the equilibrium constant of *i* component, y_i is mole fraction of *i* in gas phase, and x_i is the mole fraction of component *i* in liquid phase. Figure 10 illustrates a flow diagram of these equilibrium streams.

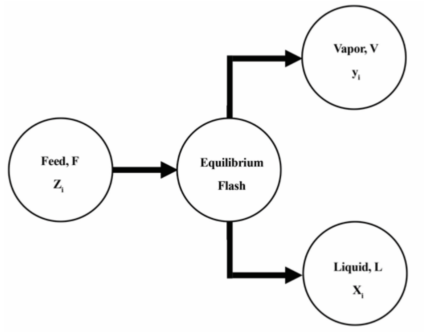


Fig. 16 **Rachford-Rice equation diagram**

The equilibrium constants K_i are generally the functions of various parameters. If Raoult's law holds good for the process, then K_i depends on pressure and temperature only, and can be represented by equation 13 as:

$$K_i = \frac{P_i^{sat}}{P} \tag{13}$$

Where P is the pressure in flash tank and P_i^{sat} is the vapour pressure in gas phase. After solving the Rachford-Rice equation for β, a reverse relation between the equilibrium constant and vaporized feed can be seen as below:

$$\beta = \frac{\frac{z_i}{x_i} - 1}{(K_i - 1)} \tag{14}$$

Zi, Ki, xi and β are the parameters described in equation (1). Therefore, in order to increase the K value and maximize the fraction of vaporized feed β, the flash tank's pressure should be at atmospheric pressure**.** The T-P diagram of DME-water solution is illustrated in Figure 16, 17. Data of vapor pressure vs. temperature of DME-water binary mixture follows the following equation. The T-P of DME obeys the following equation that Temperature °K = -0.6086x^2 + 14.048x + 242.14 (for pressure in bar with a range of 2-12 bar). In the thermal-depression regeneration process of diluted DME-water solution in the atmospheric flash tank, the operating temperature of diluted draw agent was changed from 20-50 °C and the DME concentration in the obtained clean water was recorded to find the optimum operating temperature. It was found that the parameters were varied to produce 1m^3/h clean water from seawater in FO desalination system with 50 % recovery. The diluted draw solution held 0.051 mol/mol of DME-water which resulted as an output stream of FO process is shown in Figure above. Moreover, in order to achieve optimum results, the feed solution's optimum operating temperature and pressure was found to be 30°C and one bar. Operating at the optimized temperature and pressure resulted in lower energy consumption and a decreased solubility of reverse diffused DME to the feed side respectively. The results are shown in Table 2.

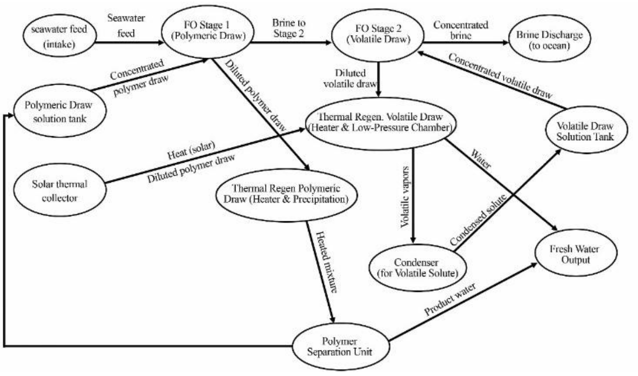


Fig. 17 Flow diagram of DME depression-thermal separation

Table 2 Results for atmospheric thermal - depression regeneration of diluted DME-water draw solution at constant input concentration

	Temperature (°C)	*Pressure (bar)*	*Residual DME in clean water (mol/mol)*	*Recovery %*
Mean	35	6.25	0.0215	75.5
Standard Error	6.4549	0.8539	0.0043	4.7346
Median	35	6.5	0.02	77
Standard Deviation	12.909	1.7078	0.0086	9.4692
Sample Variance	166.66	2.9166	7.57E-05	89.666
Kurtosis	-1.2	0.3428	-0.036	0.1707
Skewness	0	-0.752	0.829	-0.791
Range	30	4	0.02	22
Minimum	20	4	0.013	63
Maximum	50	8	0.033	85
Sum	140	25	0.086	302
Confidence Level(95.0%)	20.542	2.717	0.0138	15.067

It has been shown that a second flash tank working under vacuum should be used for the complete separation of DME from clean water. Hence, the pressure was modified by considering the second vacuum flash vessel at 0.1 bar in the downstream. Table 2 shows the total recovery of the DME separation process.

2.5 Vacuum Depression Regeneration of Diluted DME-Water Draw Solution

VDR is a separation technique used to recover dimethyl ether (DME) from a diluted DME–water draw solution (such as those used in forward osmosis). Applying a vacuum lowers the boiling point of DME, allowing it to vaporize at moderate temperatures and be reclaimed without excessive heat. This method is employed in absorption systems where DME is used to capture compounds like carbon dioxide (CO_2), providing a practical way to regenerate the solvent. In observe, a vacuum is applied to the DME–water mixture, causing the DME to evaporate out of the solution. The DME vapor is then separated from the water, condensed back into liquid, and collected for reuse. The effectiveness of this regeneration process is strongly influenced by the system's design and the composition of the solution[34]according to Foo, Z. H., et al. (2024). The energy consumption of vacuum depression regeneration comes from both maintaining the vacuum and heating the solution for DME evaporation. Vacuum pumps typically require about *0.5–2.5 kWh* of electrical energy per kilogram of DME vaporized, while the thermal energy needed to vaporize DME is *1000–3000 kJ* per kg. Altogether, the total specific energy consumption (SEC) of the process is on the order of *2–5 kWh* per kilogram of DME recovered. This energy demand can be reduced by using efficient vacuum pumps and harnessing waste heat or low-grade heat sources for vaporization, which improves overall performance and lowers environmental impact. An important benefit of the method is its inherently low-temperature operation, which minimizes energy use and avoids thermal degradation of the solution and equipment. However, the system is relatively complex, and there are ongoing operational costs associated with maintaining the vacuum. Typical operating conditions for DME vacuum regeneration are mild, with solution temperatures of 25–50 °C under vacuum pressures of about 0.1–0.5 bar. Under these conditions, the amount of DME remaining in the purified water is kept very low (below about 0.01 mole fraction, roughly 1%), which preserves water quality and minimizes product loss. DME recovery rates are generally high – on the order of 90–99% – achieved through precise vacuum control and effective condensation of the DME vapor. Operating at the higher end of the temperature range (closer to 50 °C) can further improve the purity of the water and enhance DME recovery. This is especially beneficial when the residual DME concentration in the water is extremely low (on the order of 1 ppm or less), as a bit of additional heat helps drive off the last traces of DME. he regenerated DME gas is compressed from near-atmospheric pressure up to its vapor pressure at the operating temperature using a gas compressor. This step prepares the DME for recycling back into the forward osmosis (FO) process as the draw solute as per Z. Zhou, J.Y. Lee, and T.S. Chung, (2014), T. Ruprakobkit, L. Ruprakobkit, and C. Ratanatamskul, (2019), Foo, Z. H., et al. (2024), W.A. Phillip, J.S. Yong and M. Elimelech, (2010). The overall efficiency of the system ultimately cruxes on careful control of key parameters such as temperature, vacuum level, and recovery conditions throughout the process, ensuring that energy consumption is minimized while maintaining a high DME recovery rate. The DME compression unit for FO draw solution regeneration works by separating dimethyl ether (DME) from a diluted draw solution, allowing it to be reused in the process. The solution, after drawing water from the feed, is depressurized (often via a vacuum flash tank), causing DME to vaporize, which is then compressed to about 4–5 bar to return it to a liquid state. This cycle can recover over 99% of DME, enabling continuous operation with minimal loss. The system operates at moderate pressure (4 bar) and ambient to mild temperatures (20-90°C), using low-grade or waste heat to drive the process. The compressor and vacuum pumps require relatively low energy due to DME's low latent heat of vaporization, consuming about 1.5-3 kWh per cubic meter of water produced. This method is energy-efficient compared to traditional desalination methods and has potential for integration with renewable energy sources. The DME system has significant advantages, including low energy consumption, high solvent recovery, and no secondary brine waste, but it requires complex equipment, handling of a flammable substance, and may not be suitable for all applications. Compared to other regeneration methods, such as reverse osmosis (RO), thermal distillation, or novel precipitation draws, DME compression offers a simpler, more efficient solution for water recovery, particularly in scenarios where low-cost heat is available. However, its effectiveness is dependent on proper system integration and the availability of renewable energy. A reciprocating compressor was used to compress DME gas by using a piston that could be moved back and forth within a cylinder[36]. Valves control the flow of low-pressure gas flow into the cylinder and high-pressure gas away from the cylinder. Mechanical work for the compression of gaseous DME is the product of distance and external force that acts on the DME gas, which the force moves. By working, the compressor adds energy to the DME gas. In theory, compression could be performed either adiabatically or at constant temperature. It has to be noted that almost all of the compression procedures are performed near or at isentropic conditions. Equation 15 introduces the work required for an ideal isentropic (adiabatic) compression:

$$W_S = \left(\frac{\gamma}{\gamma-1}\right)\frac{P_{in}V_{in}}{\eta_{IS}}\left[1-\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad (15)$$

here, P_{in} and P_{out} are inlet and outlet pressure in (bar), W is work required for DME gas compression, V_{in} presents inlet gas volume (m3/min), η_{IS} indicates isentropic efficiency and γ is heat capacity ratio C_p/C_v. Ideally, the compression will neither be ideal nor perfectly adiabatic. Therefore, the DME gas compression follows a polytropic compression that is neither isothermal nor adiabatic, but it is particular to the design of the compressor and physical properties of DME gas. The polytropic coefficient, n, is related to the heat capacity ratio γ, isentropic compression efficiency, and inlet-outlet pressure using equation below as:

$$n = \frac{ln\left(\frac{P_{out}}{P_{in}}\right)}{ln\left[\frac{\eta_{IS}\left(\frac{P_{out}}{P_{in}}\right)}{\eta_{IS}-1+\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}}\right]} \qquad (16)$$

$$n = fn(Pout, Pin, \ln\,(\eta_{IS}, (\frac{\gamma-1}{\gamma})) \qquad (16a)$$

Here, η_{IS} is isentropic efficiency of compressor, n is polytropic coefficient, P_{in} and P_{out} are operating pressure (bar) at input output of compressor, and y is heat capacity ratio. Further, the outlet temperature can be calculated in real compression using polytropic compression by using equation 17 which s as follows:

$$T_{out} = T_{in}\left(\frac{P_{out}}{P_{in}}\right)^{\frac{n-1}{n}} \qquad (17)$$

Where, T_{in} and T_{out} are the temperature (K) of stream at input and output of compressor respectively and the rest of the parameters are introduced in the previous equation. So reckoning that the Input Data into Compressor Ratio of specific heats of DME as can be considered as compression ratio to be equal $\gamma = Cp/Cv) = 1.16$, where T_{in} = 20, 30, 40 and 50°C, P_{in} = inlet pressure = 1 bar, P_{out} = outlet pressure = 4, 6, 8 and 10 bars, η_{IS} = isentropic efficiency = 0.85 , V_{in} = inlet gas volume = 3 m^3/min. The output results show that N = polytropic coefficient = 1.19, $T_{out\,=}$ 97, 128, 160 and 192 °C, while W = Energy required for DME gas compression = 5 to 8 kWh/m^3

Table 3. Inlet temperature, Outlet pressure (bar), Polytropic and Compresssion Power (kw)

	Inlet T (°C)	P_{out} (bar)	*Polytropic N^{-}*	*Outlet T_{out} (°C)*	*Compression Power W (kW)*
Mean	35.00	7.00	1.19	143.50	12.77
Standard Error	2.89	0.58	0.00	6.91	0.67
Median	35.00	7.00	1.19	145.90	13.07
Mode	20.00	4.00	1.19	1.02	8.99
Standard Deviation	11.55	2.31	0.00	27.64	2.68
Sample Variance	133.33	5.33	0.00	764.01	7.19
Kurtosis	-1.41	-1.41	-0.56	-0.59	-1.32
Skewness	1.00	1.50	-1.16	-0.08	-0.31
Range	30.00	6.00	0.01	99.40	6.95
Minimum	20.00	4.00	1.18	92.70	8.99
Maximum	50.00	10.00	1.19	192.10	15.94
Sum	560.00	112.00	18.99	2296.00	204.24
Count	16.00	16.00	16.00	16.00	16.00
Confidence Level(95.0%)	6.15	1.23	0.00	14.73	1.43

the polytropic exponent N is about 1.19, with γ=1.16 due to the 85% efficiency (the process is marginally "steeper" than an ideal adiabatic). The outlet temperature T_{out} increases with higher pressure ratio (as expected) and also increases with higher inlet temperature. The required compression power W increases significantly with higher P_{out} i.e. 9 kW at 4 bar vs 16 kW at 10 bar). For a fixed pressure ratio, the power is nearly the same for different inlet temperatures – this is because compressing a given volume flow of ideal gas requires roughly the same work regardless of T_{in} (higher T_{in} gives lower mass flow but higher per-unit enthalpy rise, balancing out). The findings indicate that post-compression, the output temperature of the liquefied DME solution exceeds the operating temperature. Therefore, the heated liquefied DME solution may be employed to elevate the temperature of the diluted DME-water draw solution prior to its entry into the first flash tank and the subsequent vacuum flash tank, thereby enhancing the recovery of DME from clean water. Additionally, concentrated feed water may be heated using liquefied DME to extract any reverse-diffused DME from the feed solution. The implementation of a recovery system in reverse osmosis (RO) desalination can result in energy consumption as 2-4 kWh/m^3. In contrast, the use of a compressor leads to energy consumption 5-8 kWh/m^3, which is significantly greater than that of existing desalination methods, including the RO process. Despite potential advantages, including reduced brine discharge, high feed water recovery, and the ability to separate the DME draw agent at atmospheric pressure, the relatively high energy consumption associated with the DME compression process presents a disadvantage in comparison to existing desalination methods[37] Therefore, to further reduce energy consumption, the thermal-depression process involving a compressor and flash tank is substituted with a distillation column utilizing steam. The procedure and the SEC.. Table 4 presents measured performance of a gas compressor (compressing dimethyl ether, DME) over a range of operating conditions. Inlet temperature (Tin) takes values 20°C, 30°C, 40°C, and 50°C, while the outlet pressure (P_{out}) varies through 4, 6, 8, and 10 bar. For each combination, the table reports the polytropic exponent (N), the outlet temperature (T_{out}), and the compression power (W) in kW. The inlet pressure is 1 bar (atmospheric) and the volumetric intake flow is fixed at 3 m^3/min, with an isentropic efficiency of about 85% for the compressor. Physically, DME has a ratio of specific heats γ is 1.16. The data thus span 16 operating points, enabling analysis of how pressure and inlet temperature influence compressor performance metrics. Overall, the output exhibits very consistent trends. Most notably, the polytropic exponent N remains nearly constant 1.18–1.19 across all conditions. The outlet temperature rises with both higher inlet temperature and higher pressure, whereas compression power depends strongly on outlet pressure but shows almost no change with inlet temperature (at a given pressure). It can be analyzed that of these relationships in detail, highlighting linearity or non-linearity, variation, and implications for Chemical engineering modeling. Outlet Temperature and Polytropic Exponent statistically depend on Polytropic Exponent (N). The polytropic index N in all 16 cases stays close to 1.19, with minimal variation. At 4 bar outlet, N = 1.19 for all four inlet temperatures; at 6 bar, N = 1.18; at 8 bar, Equals 1.18; and at 10 bar, N is 1.188. The range of N (1.18–1.19) corresponds to a <1% variation the mean. In other words, N is effectively constant for this compression process. This consistency implies a uniform thermodynamic process across the tested range. Indeed, N is only slightly higher than the ideal isentropic exponent $\gamma = 1.16$, which is expected since the compressor's 85% isentropic efficiency makes the process marginally "steeper" (more heat retained) than an ideal adiabatic compression. The constancy of N means that the compression follows a very similar polytropic path regardless of inlet temperature or outlet pressure a valuable simplification for modeling. One can treat N is 1.19 as a constant in calculations without significant loss of accuracy, given the negligible variation observed. Outlet Temperature vs. Inlet Temperature: The outlet gas temperature increases with both pressure ratio and inlet temperature. At any fixed outlet pressure, T_{out} rises almost linearly with Tin. Pout = 6 bar, raising the inlet from 20°C to 50°C increases T_{out} from 116.7°C to 156.6°C a +13.3°C change in T_{out} for every +10°C in T_{in}. Similarly, at 4 bar, T_{out} increases by 12.5°C per 10°C rise in T_{in} (from 92.7°C at 20°C to 130.1°C at 50°C). This linear relationship holds at higher pressures (13.9°C/10°C at 8 bar, and +14.4°C/10°C at 10 bar). A plot of outlet vs. inlet temperature yields a straight line, indicating a strong linear trend. The slope of this line grows slightly with pressure, meaning higher pressure ratios amplify the effect of inlet temperature on outlet temperature. This behavior is consistent with the polytropic gas law as it is under a roughly constant exponent N, the outlet temperature in Kelvin is proportional to the inlet temperature ($T_{out} \propto T_{in}\ (P_{out}/P_{in})^{N-1)/N}$. When converted to Celsius, this proportionality manifests as an linear increment. No curvature or unusual deviation is seen in T_{out} vs. T_{in} the process adds a nearly fixed temperature increase (in absolute terms) per degree of inlet heating, somewhat larger at higher compression ratios. Effects of Pressure on T_{out} that cross different outlet pressures, Tout naturally is higher for higher Pout (since the gas is compressed more). At the lowest inlet temperature (20°C), T_{out} goes from 92.7°C at 4 bar up to 148.9°C at 10 bar. Also at 50°C inlet, T_{out} ranges from 130.1°C at 4 bars up to 192.1°C at 10 bar. This shows that both factors – raising the pressure ratio and raising the inlet temperature – independently push the outlet temperature higher. Notably, the influence of pressure is nonlinear that each additional 2 bar of outlet pressure yields a slightly smaller incremental rise in T_{out} (4→6 bar adds 24°C to T_{out} at 20°C inlet, while 8→10 bar adds 14°C). This diminishing return occurs because at higher pressures the gas is already quite hot, and a portion of compression energy goes into further pressure rise rather than proportionally more temperature rise (especially under near-adiabatic conditions). Still, the dominant trend is monotonic: higher P_{out} always results in higher Tout for a given Tin, and higher Tin yields higher T_{out} for a given P_{out}. The absence of any interaction effects underscores a stable, predictable relationship that could be captured with a simple linear model for each pressure level or a polytropic formula. The N and T_{out} behavior as in summary, the polytropic exponent is essentially constant (N to be 1.19). At each pressure level, outlet temperature increases linearly with the inlet temperature. The nearly linear increase (with a slight slope variation by pressure) directs that no phase change or anomalous heat transfer is occurring – the process behaves like an ideal gas compression with consistent polytropic conditions. For system designers, this means the outlet temperature can be easily predicted as a linear function of inlet temperature for a given pressure ratio, using the consistent polytropic factor. It also means that controlling inlet temperature (via precooling) will shift the outlet temperature by a reliably calculable amount (1.3–1.4°C reduction in Tout per 1°C drop in Tin, depending on pressure), which could be useful in thermal management of the compressor and downstream equipment. Compression power requirements rise evidently with increasing outlet pressure. At 4 bar, the required power is about 8.99 kW; at 6 bar it is 11.96 kW; at 8 bar, 14.17 kW; and at 10 bar, 15.94 kW. Thus, increasing the discharge pressure from 4 to 10 bar (a 2.5× pressure ratio increases) raises the power by roughly 77% (from 9 to 16 kW). The relationship is monotonic and nonlinear. Plotting W against P_{out} yields a concave curve (sub-linear growth) where the power increments per additional bar of pressure decrease at higher pressures. Increasing from 4 bar to 6 bar (an extra 2 bar) requires 2.97 kW more, whereas going from 8 bar to 10 bar needs only 1.77 kW more. In terms of marginal power per bar, the first 2 bar increase costs 1.5 kW/bar, whereas the last 2 bar costs 0.9 kW/bar. This suggests diminishing marginal energy costs as pressure increases. A $W \propto P_{ou}$ reveals an exponent b less than 1 (0.63 in this range), rather than a linear b = 1 relationship. In practical terms, compression work does not scale linearly with pressure – it increases at a slower rate. This sub-linearity arises from thermodynamics as the gas is compressed to higher pressures, the specific volume decreases and the incremental work adds more to pressure than to volume reduction, yielding diminishing additional work for equal pressure increments. Engineers should note this nonlinear trend doubling the pressure ratio will not double the power required, it will be less. Simple linear extrapolation beyond the measured range could over-predict power at very high pressures (conservative but not accurate), so using the appropriate polytropic formulas or empirical fit is preferable for design calculations. Power vs. Inlet Temperature where a striking result in Table 4 is that compression power is virtually independent of inlet temperature. At each fixed outlet pressure, the power values for 20°C, 30°C, 40°C, and 50°C inlet are essentially identical. So P_{out} = 8 bar, W = 14.17 kW for all four inlet temperatures from 20° to 50°C. The same holds at 4 bar (always 8.99 kW), 6 bar (11.96 kW across 20–50°C), and 10 bar (15.94 kW in all cases). Any differences are below the measurement/reporting precision. Statistically, the variance of power with respect to inlet temperature is essentially zero for each pressure group meaning no detectable dependence. This result may seem counter-intuitive at first, since a colder inlet (say 20°C vs 50°C) contains denser gas (higher mass flow for the same volume) which one might expect to require more work to compress. However, the demonstrates a compensating effect as when the inlet temperature is lower, although more mass is processed, the per mass is lower because the gas starts colder (the enthalpy rise per kg is smaller). Conversely, a hot inlet means each cubic meter of gas carries less mass, but that gas requires a larger enthalpy increase to reach the final pressure. These two effects mass flow and specific work balance almost entirely, yielding nearly the same total work rate W for the same volumetric throughput. In fact, for an ideal gas under polytropic compression, it can be shown that the work required to compress a fixed volume from Pin to P_{out} is independent of the intake temperature (assuming constant properties and polytropic index). Our results exemplify this principle: compressing 3 m³/min of DME from 1 bar to a given pressure consistently takes the same power whether the gas is at 20°C or 50°C initially. From a statistical standpoint, we observe that outlet pressure accounts for essentially all the variation in compression power, whereas inlet temperature accounts for none. A two-way analysis of variance would find the effect of temperature statistically insignificant (p is 1, F-ratio), and the effect of pressure is highly significant. This uniformity is strikingly illustrated by plotting power data in four separate series (for 20°C, 30°C, 40°C, 50°C) collapse onto one single curve of W vs. Pout. Such reproducibility across temperatures underscores the robustness of the process and simplifies the analysis that the compression power can be treated as a function of pressure ratio alone in this regime.

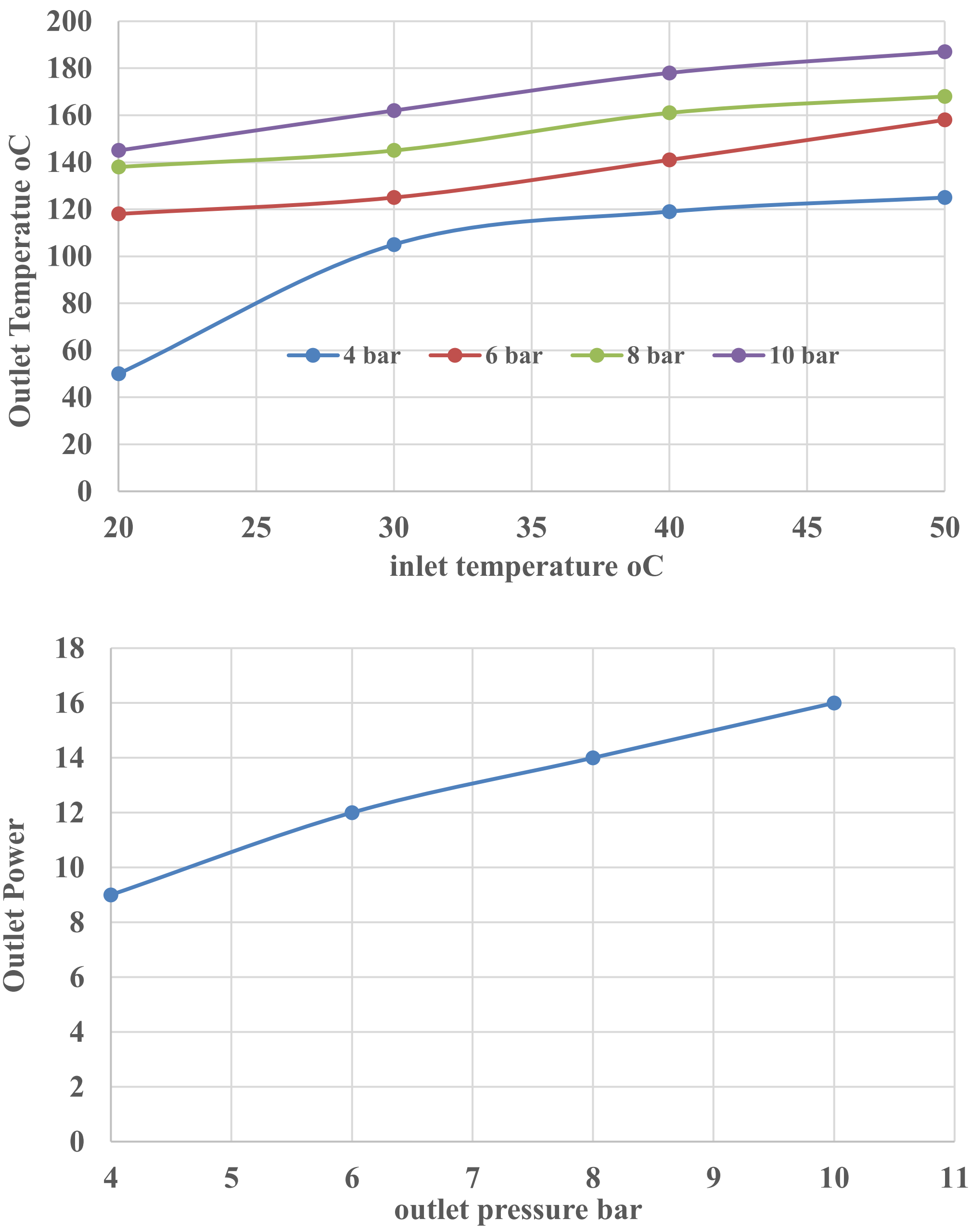


Figure 17b.c: Relationships among variables in the compression process.

The outlet temperature vs. inlet temperature at each outlet pressure. The lines are straight and nearly parallel, indicating a linear increase of T_{out} with T_{in} for each pressure level (slope of 1.3–1.4, increasing with pressure). The Compression power vs. outlet pressure. The polytropic exponent (1.19) is effectively constant across these conditions, leading to consistent behavior. The trends have important implications for how we model the compressor. The near-linear $T_{out} - T_{in}$ relationship means we can employ simple linear models to predict outlet temperature for moderate extrapolations. In contrast, the power requirement should be modeled with a nonlinear function of outlet pressure (Using the polytropic work formula or a fitted curve) rather than assuming proportionality to pressure. Engineers designing compressors or integrating this unit into a larger system should calibrate their models to capture the concave rise of power with pressure. So estimate power at P_{out} = 12 bar by linear interpolation from 4–10 bar, one would over-predict the power demand (since the trend flattens at higher pressures). A polytropic model using N is 1.19 would correctly yield a sub-linear increase in W with pressure, matching the physics observed. Use of Constant Polytropic Exponent Exhibit N is essentially constant (1.19) across the range greatly simplifies thermodynamic calculations. In practice, one can assume a fixed polytropic exponent for DME compression in this regime, rather than having to vary N with operating conditions. This is convenient for simulation and design calculations – a single equation ($T_{out} = T_{in} - P_{out}/P_{in}^{(N-1)/N}$ and the corresponding work equation) will be valid for all cases studied. The slight elevation of N above the ideal γ suggests a small inefficiency or heat input, but it is consistent (likely due to the fixed 85% efficiency of the machine). Designers can use N = 1.18–1.19 for one-step compression of DME with similar equipment, knowing it will predict both temperature rise and work with good accuracy. Thermal Management where the linear increase of outlet temperature with inlet temperature at each pressure means that if the compressor inlet varies, the outlet temperature will vary in a directly proportional way. In design terms, this is a predictable effect for every 1°C higher inlet, expect roughly 1.3–1.4°C higher outlet temperature. Therefore, if high outlet temperatures are a concern (material limits in the compressor or downstream, risk of DME degradation, etc.), controlling the inlet temperature is an effective lever. Substantial cooling of the inlet might not reduce power consumption (as we've seen, power stays the same) but it will lower T_{out}. Often, multi-stage compression systems include inter-cooling precisely to manage temperatures that has an effect on cooling between stages would drop T_{in} to the next stage, thus proportionally dropping T_{out} and keeping temperatures within safe bounds, without affecting the required work of subsequent stages except through the slight change in γ or N. In terms of system efficiency, a key observation is that the compressor's energy usage remains unaffected by inlet air temperature in this instance, provided the volumetric flow rate is maintained at a constant level Operators cannot achieve cost savings through pre-cooling the gas, as the resulting cooling will increase gas density and mass flow rate, effectively erasing any improvements in compression efficiency per unit mass. Warmer inlet temperatures won't provide cost savings, as while each kilogram of gas requires more energy input (due to its higher initial internal energy), the reduction in mass being processed offsets this increased energy demand. The design's significance stems largely from the fact that compression power is predominantly governed by the amount of gas being advanced and the magnitude of the pressure increases that is necessary, rather than by the inlet's thermal state. This simplifies power budgeting. In terms of energy efficiency, investing in after-coolers or recuperators will not reduce the compression work – those are for thermal management but do not change the fundamental work input required by the first law of thermodynamics for a given state change. Design Safety Margin that the compression power increasing from 9 kW at 4 bar to 16 kW at 10 bar. If a compressor is intended to operate across this range, the drive system must accommodate the highest load. However, because the increase is smooth and sub-linear, a machine designed for the 10 bar case (16 kW) will have ample capacity at lower pressures (i.e 56% loading at 4 bar). In fact, the power curve's shape might encourage using a single-stage compressor up to 10 bar in this case, since there is no abrupt jump in required power or efficiency drop-off – the process remains polytropically consistent. The outlet temperatures at 10 bar are high but perhaps manageable; if they were much higher, one might need to split into two stages. A single stage yields an N as valued to be 1.19 throughout, indicating the compressor handles the heat of compression without a large change in polytropic efficiency up to 10 bar. One can model the compressor as a steady component with roughly constant efficiency and performance across these pressures, integration into a larger process (DME recovery or refrigeration cycle). From a statistical analysis outlook, the trends in Table 4 are clear and consistent. The relationships are either linear (T_{out} vs T_{in}) or smoothly nonlinear in a predictable way (W vs P_{out}). The extremely low variation in N and the invariance of W with T_{in} demonstrate a highly regular process – a boon for modeling. We can conclude that in this compressor system, pressure ratio is the primary driver of both temperature rise and power consumption, while inlet temperature shifts the temperature outcome but not the power. These insights allow engineers to create reliable models using a single polytropic exponent and accounting for the slight non-linearity in the pressure-power curve. In a peer-reviewed engineering context, such findings validate that the compression process for DME behaves much like an ideal polytropic compression of an ideal gas with consistent efficiency. Ultimately, this analysis aids in optimizing the compressor and related system components by understanding which variables critically affect performance and which do not.

2.6 Specific Energy Consumption of Distillation Column, Thermal- Depression Regenerating of DME Draw Solution

Relationship between Performance Ratio (PR) and the specific energy consumption of thermal desalination (in kWh per cubic meter of water produced). Higher PR directly corresponds to lower energy required per unit of water, indicating higher efficiency. Increasing PR from 5 to 10 cuts the energy per m³ roughly in half. In terms of accuracy there was a common practice with PR showing proper accuracy and reliability with large project of desalination plant. Here is a graph showing statistically the real output of energy consumption of the plants.

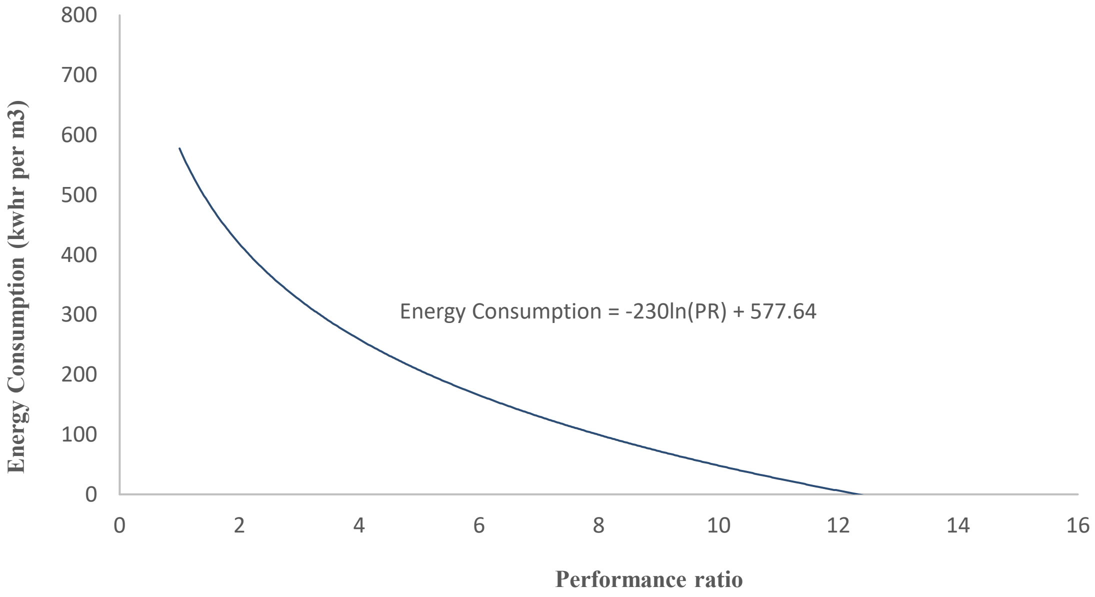


Fig. 18 specific energy consumption of thermal desalination (in kWh per cubic meter of water produced).

This refers to the amount of energy required to regenerate the DME solution by driving the separation of the components using a distillation column. This process typically involves using heat to overcome the vaporization of components and separate them from the draw solution.

$$\text{Specific Energy Consumption (SEC)}= \frac{Enrgy\ Input\ (kj)}{Amount\ of\ Component\ Separated\ or\ Regenerated\ (kg\ or\ mol)} \quad (18)$$

Thermal-Depression Regenerating process for DME in a distillation column, the energy input is typically thermal energy used to heat the column and separate the DME from other components. The depression-heating and stripping of DME gas can be conducted in the distillation column, resulting in the production of clean water, while the reconcentrated DME-water solution may be recycled in the FO process. The product clean water produced through this process contains zero ppm of DME, indicating its potential suitability for drinking water. This process primarily utilizes thermal energy, with a minimal amount of electrical power employed for pump transfer. Figure 12 illustrates the flow diagram of the process designed for DME regeneration utilizing a single distillation column. The distillation column involved the production of 1000 kg/hr of clean water from seawater, achieving a recovery rate of 50%. The dilute draw solution is introduced into the single distillation column. The concentrated drawing solution's operating temperature assumed to range from 20 °C at 4 bars to 50 °C at 8 bars, while the seawater temperature identified as 30 °C. The distillation column expected to operate at a pressure below 4 bars, necessitating the use of a reducing pressure device prior to the column for this purpose.

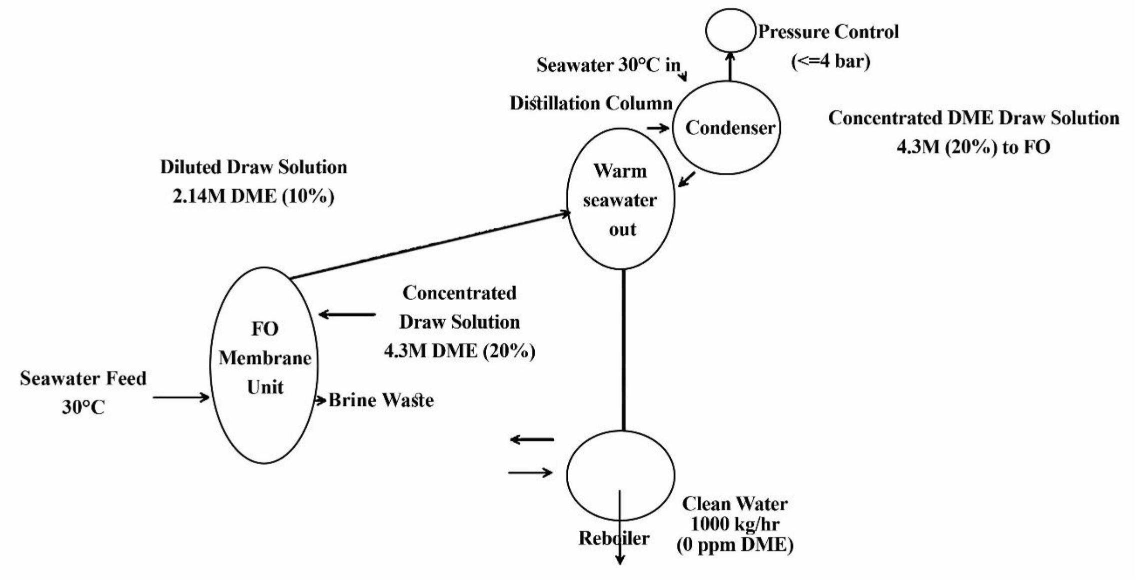


Fig. 19 Single distillation column flow diagram

Z. Zhou, J.Y. Lee, and T.S. Chung, (2014) ,

T. Ruprakobkit, L. Ruprakobkit, and C. Ratanatamskul, (2019),

Foo, Z. H., et al. (2024), W.A. Phillip, J.S. Yong and M. Elimelech, (2010)

The results showed that in order to produce clean water with a DME concentration of zero ppm, the operation temperature and pressure of distillation column has to be set at 131 °C and 3.3 bars, respectively. An important method to estimate the SEC of this thermal separation unit involves the calculation of 'equivalent work'. In this process, thermal energy is preferred over electricity energy based on the capability of generating electricity in a steam turbine and in the process, steam can be supplied to a desalination plant. The equivalent work was using the equation 19 in units of kWh/m3:

$$W_{Eq} = \left(\frac{1000Kg_{waterpproduct} \div (H_{steamused} - H_{steamatcondenser})}{PR}\right) \times E_{Turbine} \times 0.00277 \frac{kWh}{kJ} \qquad (19)$$

Here, H is enthalpy of steam at the mentioned points and PR which is the performance ratio is the total lb per 1000 Btu of water that is produced for each kg of steam that is in the reboiler. The condenser temperature was set at 35 °C based on seawater cooling temperature. The *PR* for FO regeneration process is depicted using the following equation 19 which is as follows:

$$PR = \left(\frac{H_{steamused}\left(\frac{kJ}{Kg}\right)}{Energy.for.FO\left(\frac{MJ}{m^3}\right)} \right) \tag{20}$$

While the unit of Performance Ratio (PR) can be expressed as Kilograms of freshwater produced per unit of thermal energy input. The most specifically, the unit is usually given as kg of freshwater / 2326 kJ. So, the PR of 8 kg/m. It is evidence that PR = kg of distillate produced per 2326 kJ of thermal energy input Steam Properties for given Conditions where is to determine the required values, can be obtain the enthalpy of the steam at the operating condition (131 °C, 3.3 bar) and at the condenser condition 35 °C from steam tables where Enthalpy of steam at 131 °C, 3.3 bar so saturated steam 131 °C has an enthalpy 2725 kJ/kg. This will use 2722 kJ/kg for calculations. The Enthalpy of condensate at 35 °C (H at condenser) – Saturated liquid water at 35 °C has an enthalpy of roughly 145–150 kJ/kg. This will use 146 kJ/kg (interpolated for 35 °C). Using these enthalpy values. This can now calculate the Performance Ratio (PR) and Specific Energy Consumption (SEC). Energy Requirement for FO Regeneration. The energy required for FO draw solution regeneration is on the order of the latent heat of water evaporation. The performance ratio (PR) Calculation that the Performance Ratio (PR) is defined by Equation (20) as the ratio of the steam's enthalpy content to the energy required for FO regeneration of plugging in the values that end to H_{steam} used of 2722 kJ/kg, The Energy for FO is 2326 MJ/m^3 so the Calculating PR founded to be 1.17. The Specific Energy Consumption (SEC) Calculation that gives the Specific Energy Consumption (SEC) for the FO regeneration (in terms work-equivalent terms) is given by Equation 21. This formula computes the equivalent electrical energy (work) required per volume of product water, considering the enthalpy drop of steam and the turbine efficiency where enthalpy drop from steam at 131 °C to condensate at 35 °C, and, PR = 1.17 kJ per m^3 water. So the Specific Energy Consumption (work-equivalent), W is 580 kWh/m^3 of product water. This high value reflects the large thermal energy input required for a single-effect FO regeneration, converted to an equivalent electrical energy loss. The process achieves a performance ratio of 1.17. On an equivalent work basis, the specific energy consumption (SEC) for steam use in the regeneration system is estimated to be 580 kWh per m^3 of freshwater output. The total equivalent work for regeneration of diluted DME draw solution at operating temperature 40 °. For table 4 it is better to think that the heat vs electricity process is heavily dependent on heat-driven while the efficiency can be higher when the total energy input satisfies the need for proper input. Consequently, the depression-thermal regeneration process using distillation column can be compared with flash tank and the advantages of the compression method could be abridged that significant reduction of the SEC while employing the regeneration process, Applying reduced heat for separating DME from clean water, Decreasing the system's maintenance cost by replacing the rotary equipment such as compressor with fixed equipment's such as distillation column, and, Increasing the quality of produced clean water such that it contains no DME as per A. Deshmukh, N.Y. Yip, S. Lin, and M. Elimelech (2014).

Table 4 Energy data of DME regeneration process using single distillation column

	Steam Temp °C	*Steam Presure(psi)*	Diluted DME Conc M	Heat Duty MJ/m^3	Electricity Duty kWh/m^3	PR	Equivalent Work kWh/m^3
Mean	127.85	54	2.51	160.2	0.16	1.172	2.5142
Standard Error	2.8	1.34	0.05	0.68	0	0.003	0.05
Median	125	53	2.5	160	0.16	1.17	2.5

Mode	122	52	2.5	162	0.16	1.17	2.5
Standard Deviation	7.42	3.55	0.13	1.79	0	0.009	0.13
Sample Variance	55.14	12.66	0.018	3.23	0	9.05E -05	0.018
Kurtosis	-0.79	-0.36	-0.3	-1.81	0.16	1.244	-0.3
Skewness	0.76	0.74	-0.35	-0.35	0.16	0.863	-0.353
Range	20	10	0.4	4	0	0.03	0.4
Minimum	120	50	2.3	158	0.16	1.16	2.3
Maximum	140	60	2.7	162	0.16	1.19	2.7
Sum	895	378	17.6	1122	1.12	8.21	17.6
Count	27	27	27	27	27	27	27
Confidence Level(95.0%)	6.86	3.29	0.12	1.66	0	0.008	0.124

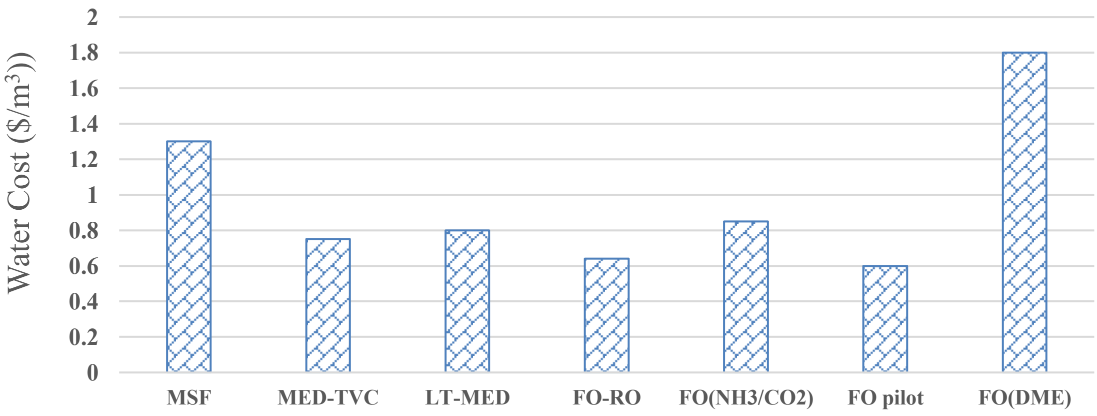
$$PR_{Eq} = \left(\frac{Equivalent\ Work\ \left(\frac{KWh}{m3}\right)}{PR}\right) / (E\left(\frac{kWh}{m3}\right) + Heat\ Duty\ \left(\frac{MJ}{m3}\right) x1/(3.6\eta) \qquad (21)$$

Where η is the efficiency of conversion from heat to electricity (typical values range from 0.3 to 0.4 for steam-based systems; if unspecified, it is assuming a value like 0.35), and, 3.6 converts MJ to kWh. The estimated total equivalent work showed that the SEC could be decreased from 5-8 kWh/m^3 to 2.7 kWh/m^3 using flash-compressing process by using a distillation column. There is a direct relationship between the quantity of energy utilized by FO process and the concentration of dilutive draw agent that is entering the recovery system of the solute. The concentration of diluted DME draw solution is associated with water flux within the membrane and it is directly dependent on the effective osmotic pressure through the active layer.

2.7 Energy requirements of present seawater desalination technologies and FO desalination process with depression regeneration method- A Comparison

Energy consumption of the FO desalination procedure with thermal-depression regeneration method using DME as draw agent is associated with several other current desalination techniques. The equivalent work indicates the required energy for operating the process or SEC in kWh/m^3. Several values of equivalent work (kWh/m^3) are available in literature and are listed in Table 5. The percentage lowering of equivalent work achieved by using the FO procedure, in comparison with other procedures are also shown in the table. Multi-Stage Flash (MSF) is a mature, broadly deployed thermal desalination method but is extremely energy-intensive, consuming on the order of 100 kWh/m^3 of heat plus 3–5 kWh/m^3 of electricity (roughly equivalent to 5.66 kWh/m^3 of mechanical work), with water costs \$1.2–1.5/m^3; all newer methods strive to improve on this baseline. Multi-Effect Distillation with Thermal Vapor Compression (MED-TVC), also fully commercial, uses about 4.05 kWh/m^3 (30% less energy than MSF) and achieves water costs of \$0.6–1.0/m^3. A low-temperature MED variant operates with waste heat or solar heat at similar energy consumption (3.21 kWh/m^3, 40% energy savings vs MSF) and has been proven at pilot scale, enabling costs below \$1.0/m^3 when cheap heat is available. Reverse Osmosis (RO) with energy recovery is the most energy-efficient commercial technology (3.0 kWh/m^3, nearly 50% lower energy use than MSF) and produces water for about \$0.5–1.0/m^3. An FO with RO hybrid (forward osmosis pre-treatment followed by RO) has been shown in pilots to cut RO energy demand by roughly 20–40% (total 4.5 kWh/m^3, 20% less than MSF) and to modestly reduce water cost (by 10–15% compared to RO alone). Emerging forward osmosis (FO) processes promise further gains: FO using an ammonia–carbon dioxide draw solution has shown in lab tests that with a moderate that consume 3.7 kWh/m^3 (about one-third lower energy than MSF), while a more concentrated draw (4.7M) can reduce energy use to roughly 0.8 kWh/m^3 (over 80% energy savings). This NH_3–CO_2 FO approach remains at lab/pilot development but could achieve water costs under $1/$m^3$ given low-grade heat input. A pilot plant using an NH_3–CO_2 draw with high-salinity feed (72 g/L) inveterate the feasibility of this method, using solar thermal energy and only about one-third the electrical energy of RO (an overall significant energy reduction versus MSF) and delivering water for an estimated $0.6–0.8/$m^3$; this system is approaching commercial readiness. Another novel method employs a volatile dimethyl ether (DME) draw in FO, allowing low-temperature thermal regeneration: in the lab it uses only on the order of 1 kWh/m^3 of electricity and this equal to 2.77 kWh/m^3 total equivalent, 20% lesser energy than MSF, but its projected water cost is relatively high ($2.0/$m^3$ and it remains in the experimental stage according to Aryafar, M. (2015), B.D. Coday, B.G.M. Yaffe, P. Xu, and T.Y. Cath (2014) and J. Heikkinen, H. Kyllönen, E. Järvelä, A. Grönroos, and C.Y. Tang (2017). The proposed FO desalination process using DME draw solution with thermal-depression regenerating process offers significant advantages with respect to energy effectiveness and cost compared to current desalination techniques. Also, the electricity consumed in the FO desalination process is further used for pumping draw solution and this is significantly lower than current desalination methods. In comparison to current desalination methods, use of reduced heat source in the FO procedure enhances the quality of clean water that is produced because of vaporizing the draw solution instead of the feed water. The operating basis of the integrated FO and depressurizing-compression method is the production of one m^3/h clean water, recovered from seawater at a rate of recovery of 50 %. A distillation column consuming steam for column reboiler exchanged a flash tank and compressor for thermal-depression process because of high electrical consumption of the compressor when associated with the current desalination methods. A direct relationship exists amongst the temperature of the dilutive draw agent that enters the recovery system of the solute and the amount of DME recovered from the produced clean water through the regeneration process. It was found that when the temperature was raised to 50 °C, DME concentration in the clean water was less than 1 ppm.

Fig. 20 Water Cost Comparison Chart depending on technologies of related desalination



Using the optimized operating conditions, the SEC of the proposed FO desalination procedure was calculated to be 2.7 KWh/m^3 D) Instead of using electricity in the compressor, the available low-grade heat could be used in the distillation column, thereby reducing SEC in the regeneration system. Moreover, maintenance cost of fixed equipments such as columns is usually very less compared to rotary equipment such as compressor. Most importantly, the purity of the clean water obtained in the downstream of the distillation column was found to be 100% whereas it is only 85 % in an atmospheric flash tank downstream. Because of lowering the operating hydraulic pressure and consequently the SEC, the optimum operating temperature of the FO procedure could be between 30-40 °C. F) In the integrated FO-depression procedure, optimum concentration of DME-water draw solution could be 4.3 M between 30 °C to 40 °C draw solution temperature in terms of SEC.

2.8 Thermal-Depression Driven Regeneration for Enhanced Forward Osmosis Desalination

Forward osmosis (FO) desalination has emerged as a promising low-pressure alternative to traditional reverse osmosis (RO), driven by osmotic pressure gradients rather than mechanical force. However, its broader implementation is constrained by the energy-intensive draw solution regeneration step, which often dominates the system's overall energy consumption. Traditional regeneration methods, such as reverse osmosis or thermal distillation, require significant energy inputs and can nullify the low-energy benefits of FO. To address this, research has focused on thermally regenerable draw solutes that respond to moderate heating, leveraging low-grade or waste heat instead of electricity. Ammonium bicarbonate decomposes into ammonia and carbon dioxide gases upon heating, while dimethyl ether (DME) offers a volatile alternative that can be easily evaporated and recovered at relatively low temperatures. Building on these principles, Thermal-Depression Driven Regeneration (TDDR) has been proposed as a generalized and efficient strategy for FO draw solution recovery. TDDR operates by inducing a thermal depression—either in vapor pressure or osmotic pressure through controlled heating or cooling of the diluted draw solution. This thermal planning results in a physical or chemical change, such as solute precipitation or gas evolution, that reduces the osmotic strength of the draw and enables the separation of water with minimal mechanical work[41]Unlike full evaporation processes, TDDR focuses on phase-changing only the draw solute, not the water, thereby drastically lowering the energy required for regeneration. Theoretical models of TDDR systems integrate established thermodynamic relationships, such as van't Hoff and Clausius-Clapeyron equations, to predict osmotic pressures, phase transitions, and energy requirements. These models incorporate both water flux calculations across the FO membrane and energy balances for regeneration, including heat input and work for fluid handling. Case studies of volatile and thermolytic draw solutes demonstrate TDDR's versatility. Dimethyl ether, a volatile organic compound with a low boiling point, can dissolve in water under moderate pressure to create a high osmotic draw. Following the FO step, depressurization or mild heating causes the DME to vaporize, separating from water without significant loss, after which it can be condensed and reused. This process achieves regeneration with low-grade heat and requires minimal electrical input, primarily for compression. In contrast, thermally responsive salts like ammonium bicarbonate demonstrate a different regeneration pathway: a hot, saturated solution exerts high osmotic pressure during FO, and upon cooling, the solute precipitates out, leaving water behind. This precipitative mechanism enables water recovery without full vaporization, and the crystallized solute can be filtered and reused after reheating. TDDR demonstrates superior performance when compared to conventional FO regeneration approaches. Hybrid systems like FO–RO, though capable of reducing fouling and handling high-salinity feeds, still rely on high-pressure RO units, consuming 3–4 kWh per cubic meter or more. FO–MD (forward osmosis–membrane distillation) systems can utilize thermal energy but suffer from low flux and incomplete heat recovery. TDDR, in contrast, avoids the need for boiling water and high-pressure pumping altogether by exploiting temperature-induced solute phase changes, enabling electrical energy consumption to drop below 0.5 kWh per cubic meter, with the remainder supplied by low-grade thermal energy. In optimized designs with effective heat recovery, the energy consumption can approach the thermodynamic minimum for seawater desalination, 0.25 kWh per cubic meter. Beyond energy efficiency, TDDR offers enhanced water recovery potential and environmental advantages. FO systems paired with TDDR can extract water from highly saline feeds more effectively than RO, achieving recoveries exceeding 60%, thus minimizing brine volume and facilitating near-zero liquid discharge (ZLD). The reduced brine output alleviates environmental concerns associated with concentrate disposal. Moreover, TDDR systems can be integrated with renewable heat sources such as solar thermal collectors, geothermal wells, or industrial waste heat streams. These sources provide the necessary thermal input without additional emissions, enabling off-grid or low-carbon desalination in energy-constrained or remote regions Orfi, J., et al. (2025), Ahmed, M., et al. (2019), onjezi, A. A., et al. (2017), Aryafar, M. (2015). Practical considerations such as membrane material resilience under thermal cycling, draw solute containment, and final water polishing steps are being addressed through advances in membrane technology and system integration strategies. The use of benign solutes, such as DME and ammonium bicarbonate, further ensures environmental compatibility, with any residuals in the product water either easily removed or potentially beneficial in applications like agriculture. In summary, TDDR represents a transformative step toward sustainable and scalable forward osmosis desalination. By intelligently combining membrane processes with thermal regeneration driven by phase behavior of draw solutes, the approach significantly reduces electrical energy demand while increasing water recovery and system versatility. Its compatibility with low-grade heat sources and potential for integration with renewable energy systems makes it especially suitable for deployment in arid and resource-limited settings. TDDR bridges the gap between theoretical FO potential and practical implementation, offering an energy-efficient, low-impact, and high-recovery lane for producing fresh water from saline resources.

2.9 Thermal-Depression Driven Regeneration Enhances Forward Osmosis Desalination Efficiency for Large-Scale Applications (TDDREFOELSA)

In FO, water is drawn across a semi-permeable membrane from a saline feed—such as seawater—into a highly concentrated draw solution driven by osmotic pressure. However, the major holdup in FO implementation lies in the regeneration of the diluted draw solution to recover fresh water and reuse the draw agent. Traditional regeneration methods, including reverse osmosis or nanofiltration, introduce energy demands and complexity that counteract FO's potential returns. In contrast, thermal-depression driven regeneration utilizes thermally responsive draw solutes that can be separated from water using low-grade heat or mild thermal cycling. This style opens a new avenue for improving FO efficiency by decoupling water extraction from energy-intensive pressure systems and instead relying on thermal properties for solute recovery. This method is particularly appealing for large-scale operations where low-temperature waste heat or solar energy is readily available. Thermally responsive draw solutes fall into two main categories: volatile compounds and thermo-sensitive polymers. Volatile draw solutes, such as ammonia-carbon dioxide mixtures or dimethyl ether, generate high osmotic pressures capable of drawing water through the membrane[43] T. Alejo, M. Arruebo, V. Carcelen, V.M. Monsalvo, and V. Sebastian (2016). Upon application of moderate heat or a reduction in system pressure, these compounds vaporize, separating from the fresh water. The vaporized draw solute can then be condensed and reused in the FO system. Experimental validations have shown water fluxes up to 10 $L \cdot m^{-2} \cdot h^{-1}$ with seawater feeds, with solute recovery efficiencies exceeding 90%. The energy required for regeneration using this method typically ranges between 2–3 kWh/m^3, which is significantly lower than conventional desalination techniques, especially when low-grade heat is used. Alternatively, thermo-responsive polymers exhibit temperature-sensitive solubility behavior, with a lower critical solution temperature (LCST) at which they evolution from hydrophilic to hydrophobic states. Below the LCST, they are fully dissolved and exert high osmotic pressure; overhead the LCST, they precipitate out of solution, enabling straightforward separation of product water. These polymeric draw solutes offer the advantage of regeneration at temperatures as low as 30–40°C, making them compatible with solar thermal or industrial waste heat sources. In volatile draw systems, closed-loop setups integrating FO membranes with thermal separation units (e.g., low-pressure distillers or membrane contactors) have successfully regenerated draw solutions with minimal loss[44]. In one case study, an FO system using an ammonia-carbon dioxide draw with thermal regeneration achieved over 85% water recovery from seawater and sustained stable fluxes across multiple cycles. Similarly, polymeric draw solutions based on ionic or zwitterionic polymers have been shown to regenerate efficiently through low-temperature heating, achieving over 80% water recovery while maintaining polymer integrity and performance across reuse cycles. These systems require careful thermal control and membrane compatibility but demonstrate potential for sustainable large-scale deployment. Practical implementation requires modular integration of membrane units, thermal regenerators, and the heat exchangers. Systems must also be engineered for chemical containment and environmental safety, particularly when volatile compounds are used, demanding sealed circulation loops, condensers, and ventilation safeguards. Nonetheless, these challenges are conquerable, and several experimental setups have demonstrated effective large-volume operation using solar-heated or waste-heat-powered thermal regeneration T. Alejo, M. Arruebo, V. Carcelen, V.M. Monsalvo, and V. Sebastian (2016). Compared with conventional desalination methods, thermal-depression driven FO systems exhibit distinct advantages in energy efficiency, system modularity, and environmental impact. RO systems, while mature and widespread, require high electrical energy input (typically 3–6 kWh/m³) to overcome seawater osmotic pressure. Furthermore, they are prone to membrane fouling and scaling, particularly at high recovery ratios. Nanofiltration and membrane distillation offer alternative recovery methods but are similarly constrained by energy intensity and brine management issues. In contrast, FO systems with thermally responsive draw solutes bypass the need for high-pressure pumping and achieve water separation at ambient or near-ambient pressures. When coupled with thermal regeneration, especially using solar or waste heat, the total operational energy can be significantly reduced. FO systems often produce a more concentrated brine, which, in some cases, can be processed further or disposed of more efficiently. The decoupling of water extraction from draw solution regeneration allows for flexible system design—membrane modules can be expanded independently of the thermal regeneration unit, facilitating scalable deployment tailored to site-specific resources T. Alejo, M. Arruebo, V. Carcelen, V.M. Monsalvo, and V. Sebastian (2016). In conclusion, thermal depression driven regeneration represents a transformative advancement in FO desalination technology. By exploiting thermally responsive draw solutes and utilizing low-grade or renewable thermal energy, it becomes potential to efficiently regenerate draw solutions at a fraction of the cost and complexity of traditional methods. Both volatile and polymeric draw agents achieves high water flux and regeneration efficiency with seawater feeds. Experience present compatibility with large-scale implementation, especially when designed to utilize industrial waste heat or solar energy sources. When compared with RO, nanofiltration, and membrane distillation, thermally driven FO systems provide a more energy-efficient, modular, and sustainable desalination solution. Continued development in draw solute chemistry, membrane materials, and thermal integration strategies will further enhance system performance and commercial viability. As global water scarcity intensifies, these innovations offer a promising pathway toward scalable, low-energy desalination capable of meeting industrial and municipal demands with minimal environmental impact.

CONCLUSIONS

This study indicates that forward osmosis using dimethyl ether as a draw solution is a undertaking and energy-efficient approximate to desalination. The FO–DME system demonstrated stable membrane performance and effective water extraction from saline feeds, followed by an easy regeneration of the volatile draw solute. DME's unique physical properties, the draw solution preserve be re-concentrated with minimal energy input, chiefly by manipulating pressure and temperature. The screening results suggest that dimethyl ether (DME) is an applicable draw agent. DME transitions to a liquid state at standard temperatures under reasonable pressures below 10 bars. DME exhibits enhanced water solubility and can generate osmotic pressure seven times greater than that of seawater. Consequently, the diluted DME-water draw solution may be depressurized and subsequently vaporized, resulting in the holding of the extracted water. The proposed innovative process demonstrates a capacity to reduce specific energy use, minimize environmental impact, and decrease capital costs in comparison to conventional desalination methods. The ICP and ECP models were utilized to predict the optimal operating conditions of the FO procedure, including temperature, cross flow rate, and pressure, through the calculation of water flux. The physical characteristics of both feed and draw solutions, such as diffusivity, osmotic pressure, dynamic viscosity, and density, were analyzed at different solute concentrations and temperatures ranging from 20 °C to 50 °C. The practicality of the combined FO with thermal-depressurizing technique for seawater desalination is modeled to evaluate the SEC. The SEC estimation is based on a production rate of 1 m³/h of clean water extracted from seawater, with a recovery rate of 50% in optimal operating conditions. The side containing the DME draw agent should be kept at a pressure of 4 bar and a surrounding temperature of 30 °C to 40 °C to attain optimal DME solubility in water. The ideal operating pressure on the feed side should be kept under 1 bar. When the draw agent interacts with the active layer of the membrane, this configuration is referred to as PRO mode. Research results indicate that a crossflow rate of 0.222 m^3/s for both the draw and feed solutions is crucial in the turbulent zone to mitigate the effects of concentration polarization and osmotic pressure on the membrane. The optimal conditions for the feed solution are a temperature of 30 °C and a pressure below 1 bar. The study reached several suppositions: like the proposed forward osmosis (FO) desalination process, which employs DME-water as the draw solution, proves to be an efficient membrane-based method for seawater desalination, largely due to the low capital investment required for the FO unit, which means at pressures under 10 bars. The yield from the FO process shows that the reduction in water flux across the membrane caused by internal concentration polarization (ICP) is 80%, while the effect of external concentration polarization (ECP) accounts for about 50%. The forward osmosis process, the water flux across the membrane was measured to be between 10 and 15 l/m^2hr at a temperature of 20 °C. This is analogous to accessible desalination systems, such as reverse osmosis (RO) systems, which typically exhibit an average permeate flux of 11-15 l/m^2hr. The performance of forward osmosis as a utility of water flux improves when the forward osmosis unit operates in a transitional space between turbulent and laminar flow in both the draw and feed streams.

The operating pressure on the feeding wall should be maintained below 1 bar, while the DME draw solution must be kept at a pressure exceeding 4 bars. The solubility of DME in water diminishes as operating pressure decreases; consequently, any DME that reverses diffuse into the feed solution from the draw side can be separated and regenerated on the draw solution's side. The draw solution must be positioned against the membrane's active layer in PRO mode, as maintaining pressure on the draw solution side is essential for maximizing the dissolution of liquefied DME in water at the optimized temperature. At an operating temperature of 30 °C, a DME-water draw solution was necessary to minimize the specific energy consumption (SEC). To moderate the solubility of DME in the solution and improve the quality of clean water, the temperature of the diluted DME-water draw solution should be raised before the depression regeneration process. Improving the operating temperature to 50 °C may lead to a freshwater quality with DME concentration below 1 ppm. The benefits of utilizing a distillation column in the thermal-depression regeneration method consist of functioning at moderate temperature ranges, resulting in substantial energy savings, making high-quality purified water, and efficiently separating DME from water. Upkeep expenses are degraded in comparison to rotary machinery such as compressors. The estimated specific energy consumption (SEC) for the proposed forward osmosis (FO) desalination system is 2.7 kWh/m^3, which container be decreased to 0.5 kWh/m^3 with the application of a heat recovery process.

CREDIT AUTHORSHIP:

Mohammed Saleh Al Ansari: contribution statement and Conceptualization, Data Collection, proposed work formulation related work framework.

Chamandeep Kaur: Implementation and validation, Additional Validation, Data Collection, Overall Supervision. Declaration of competing interest the authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Data availability No data was used for the research described in the article.

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