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Membrane based desalination systems for seawater

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ABSTRACT

Desalination is a necessary supplement for the already existing natural resources to meet the growing demand of fresh water. It requires energy to separate the vast resources of seawater which contains around 3.5% of dissolved salts. Several technologies have been developed in recent years, besides the century old thermal desalination processes. This article provides an overview of the membrane technologies, particularly focusing on the most used Reverse Osmosis for seawater desalination.

INTRODUCTION

Ocean is the repository of many life-sustaining requirements available tangibly or intangibly. Energy can be obtained from the ocean in many ways; from within as waves, or outside as the wind. The ocean water is spread over about two-thirds of the earth's surface (Wang and Huo, 2022) and contains virtually all the mineral salts and valuable metals albeit in a very low concentrations. With increasing population, the demand for the fresh water has increased manifold to meet the needs of several life support systems including domestic, agriculture, food processing, pharmaceuticals, power generation, metallurgical industries, refinery operations etc. Only about 3.5% of annual precipitation is available for human use in rivers, ground water and lakes. Even in this, a significant fraction is rendered unfit due to anthropogenic contaminants. With reference to India, the per capita availability of fresh water has dwindled to about 1500 m^3/annum at present, down from 5000 m^3 in 1950, indicating water stress conditions. Being aware of these constraints, already a few desalination plants have been installed in parts of Gujarat and Tamil Nadu in late nineties. Since India is blessed with a long coastline of about 7,516.6 kilometers including about 5,422.6 kilometers in mainland and 2,094 kilometers in island territories, stretching across nine states and four union territories, Government of India has established the 'Desalination Mission' to adopt desalination in larger scales towards enhancing water security (Dhakal et al., 2022). Nature has illustrated the basic concepts of desalination processes; thermal and membrane based as seen from the evaporation – condensation–precipitation cycle using the thermal energy of the sun, while the plants separate the excess water through cell membranes for its removal through transpiration. In a similar manner the desalination technologies currently in vogue are either thermal, or membrane based.

Many variations of thermal energy-based desalination processes are in practice, in tune with capacity required, and locational logistics, exhibiting varying specific energy consumptions. Based on the form of energy the specific energy for seawater desalination varies from about 3 kWh/m^3 for reverse osmosis to about 15 kWh/m^3 for electro-dialysis, with the thermal processes in the middle depending on the type. However, the selection of an appropriate desalination technology is site specific, depending on the end use, economics, opportunity and logistic costs, thus accounting for the variety of desalination technologies in use.

Among the technologies available today, reverse osmosis is the most popular, as it operates under ambient temperatures with low specific energy consumption, and has a major share, dominating over hitherto popular, century old thermal desalination. The overall cost of water is also lower per m^3 and the modularity allow variable operating capacities. Constant development in the technologies, constituting the front-end and back-end components to provide sustainable performance, have made the process more attractive. This article provides an overview of the membrane-based electro-driven, concentration-driven, thermal- driven desalination processes, with particular focus on reverse osmosis with reference to seawater desalination including design philosophy, operational characteristics, limitations, and possible opportunities.

DESALINATION PROCESSES

Desalination means separation of pure water from its solution and can be achieved either by preferentially (which form the minor constituent ~ 3.5% in seawater and still lesser in most of the other saline waters) or water from the solution. The process requires energy to achieve the separation, which can be imposed externally as in thermal desalination, and the membrane based reverse osmosis (RO), or use the internally available energy in the system as in forward osmosis (FO) and membrane distillation. Unlike thermal desalination processes, membrane processes do not involve phase change, except membrane distillation, for the purpose of desalination.

MEMBRANE PROCESSES

Membrane processes are versatile as they can be used for desalination under different energy gradients such as reverse osmosis with mechanical energy (pressure), electro-dialysis with electrical energy (electric-potential), forward osmosis with chemical potential energy (concentration), and membrane distillation with thermal energy (thermal), but with different types of membranes. Among these processes, only reverse osmosis and the electro-dialysis have been found to be suitable for large scale deployment. Reverse osmosis has become the most preferred desalination process, particularly for seawater,

due to its low specific energy consumption, flexible operation, quick start-up and shutdown and the suitability of the product with minor post treatment for providing safe drinking water. On the other hand, due to higher specific energy consumption for seawater concentration, and the operational constraints in producing product water with salinities suitable for potable water supply, electro-dialysis is not a favored alternative. Improved version of ED, viz. the electro-deionization (EDI), is suitable only for low salinity water, particularly for last mile purification to produce high purity water.

Reverse osmosis

Osmosis is a natural phenomenon, which describes the flow of solvent (water) from dilute solution (lower solute concentration) to higher concentration through a semi permeable membrane. Consequent to the phenomenon, a hydraulic pressure builds up on the concentrated solution side till the attainment of equilibrium. The value of pressure at equilibrium is termed as '*Osmotic Pressure*'. When hydraulic pressure greater than the osmotic pressure is applied, pure water from the higher solute concentration side can be separated through the membrane and the process is called '*Reverse Osmosis*' as indicated in Figure 1.

One may consider the osmotic pressure as the energy required to separate pure water molecules overcoming their interactions with the solutes. Osmotic pressure is a colligative property and is a linear function of molar concentration of the species in water for dilute ideal solutions. The technology is based on the semi-permeable membrane's ability to separate pure water from its solution and transport it through the capillaries with as less a resistance as possible, providing a good water flux at reasonably low pressures (over the osmotic pressure).

Membranes

Membranes used in the reverse osmosis process are porous having pore-sizes in the order of two to five tenths of a nanometer (2–5 Angstroms). After the initial discovery of the reverse osmosis membrane in 1959, many developments have taken place leading to better separation efficiency and higher water flux at reasonably lower pressures (about 30 bar above the osmotic pressure of seawater). The membrane extensively used in desalination and water treatment applications are known as *Thin Film Composite (TFC)* membranes, which consist of a polymer formed of a diamine (m-phenylene diamine) and an acid chloride (tri-mesoyl chloride) on a porous substrate by in situ polymerization as indicated in Figure 2, which results in polymer containing neighboring groups of hydrophobic and hydrophilic substrates increasing the selectivity.

The porous substrate provides a smooth passage of water with less resistance to flow, while the top surface ensures very high selectivity (providing more than 99.4% + solute removal). Since the pores are not uniform, the membranes exhibit a distribution of pore-sizes, with some of them larger, allowing the passage of some of the solutes through the pores preventing absolute separation. Narrowing the pore-size distribution leads to better separation efficiency. Reverse osmosis phenomenon is a surface driven process and hence requires high surface area for large capacity desalination. Out of the different configurations, hollow fiber is the most compact. However, due to operating constraints related to hydrodynamic considerations, spiral wound configuration is preferred and is considered the work horse of the large capacity seawater desalination plants.

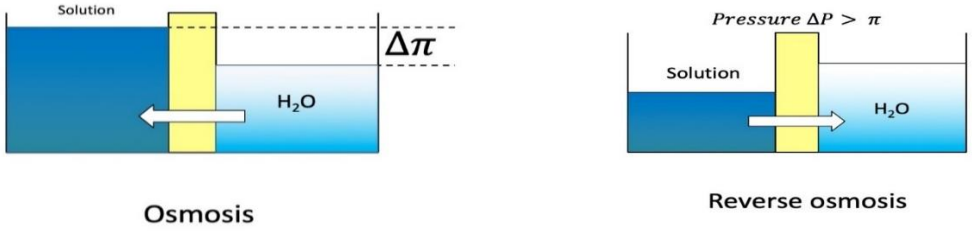

Figure 1. Principle of osmosis and reverse osmosis

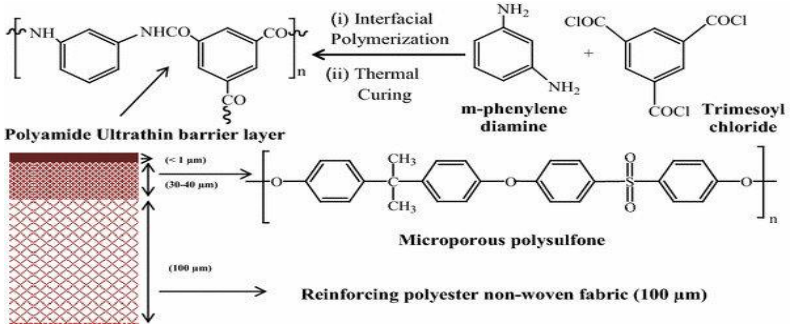

Figure 2. TFC membrane synthesis by in situ polymerization of m-phenylene- diamine and tri-mesoyl chloride over a porous support

Seawater reverse osmosis desalination plant

Typical flow diagram is shown in Figure 3. Accordingly, the feed from the source, enters the pre-treatment section. The purpose of the pre-treatment section is to ensure long service life of the membrane surface by minimizing fouling, scaling, and preventing oxidative chemical degradation. The particulate matter and micro-organisms are removed by a series of filters including ultra-filters at the end of the filtration system. Anti-scalants, and sodium-bisulfite are dosed to minimize scaling and to provide a reducing environment, to minimize the oxidative damage of the membrane surface. After monitoring the performance of the foulant removal efficiency by silt density index (SDI) and ensuring positive oxidation reduction potential (ORP) value, the feed is pressurized through high pressure pumps, and sent through a set of membrane modules arranged in parallel to meet the design capacity. Initially multi-stage centrifugal pumps were preferred, while at present positive displacement pumps compatible with the energy recovery devices are used. Each module would contain a few elements (6-8) connected in series depending on the design recovery (defined as percentage of feed recovered as product). A number of such modules are arranged in parallel to meet the design capacity. The unused pressurized feed (reject stream), is passed through the energy recovery device to recover unspent energy. Over a period, the energy recovery devices (Schunke et al., 2020) have evolved starting from a recovery efficiency of 70% in Pelton wheels to the presently popular work exchangers operating at 98%+ efficiency.

The product water is corrosive as it contains more monovalent ionic species. The product can be passivated by passing through a lime column, for domestic use and through de-ionisation using mixed-bed ion exchangers for industrial uses (boiler feed or for electronic industries) requiring high puritywater.

Seawater reverse osmosis (SWRO) plants require periodic maintenance to chemically clean the membranes. The operators have to be alert in monitoring the functioning of pre-treatment system, lest the chances of membrane failure could be high. To minimise undue damage to the membrane, the product water from the plant is allowed to flow through a (suck back) tank located at a higher elevation compared to the top module. This helps in the product water passing through the product channel of the modules, in case of sudden or temporary stoppage of the plant to avoid drying of the membrane surface. Further, osmosis will set in helping to remove the scale formed on the feed side. During planned shut down, membranes need to be protected by maintaing a reducing environment (by periodically filling them with sodium bi-sulfite solutions), to prevent oxidation of the membrane through air in leakage.

Unlike thermal desalination plants, where the product water will have a few ppm of dissolved salts (<10 ppm), the SWRO product will have a few hundreds of ppm . In order to reduce the dissolved solids content, if required, one may have to use one more reverse osmosis system, using the product water as the feed, but without any pre-treatment step and using cheaper tap water/brackish water membranes. With the use of the positive displacement pumps and the work exchangers as energy recovery device, the specific energy consumption has been found to be less than 3 kWh/m^3 (Ruiz Garcia et al., 2023).

Electrodialysis

Membrane Characteristics

Electrodialysis (ED) uses charged non-porous membranes, aiming at specifically removing the ionic solutes for producing desalinated water from the saline or seawater under an electric-potential gradient. The membranes have mobile anion and cation moieties. These membranes are akin to ion exchange resins, made of functionalized polymers with pendent groups containing replaceable sodium Na^+ or Cl^- ions such as [$SO_3^-Na^+$] or [$R_3N^+Cl^-$], known as cation exchange and anion exchange membranes, respectively.

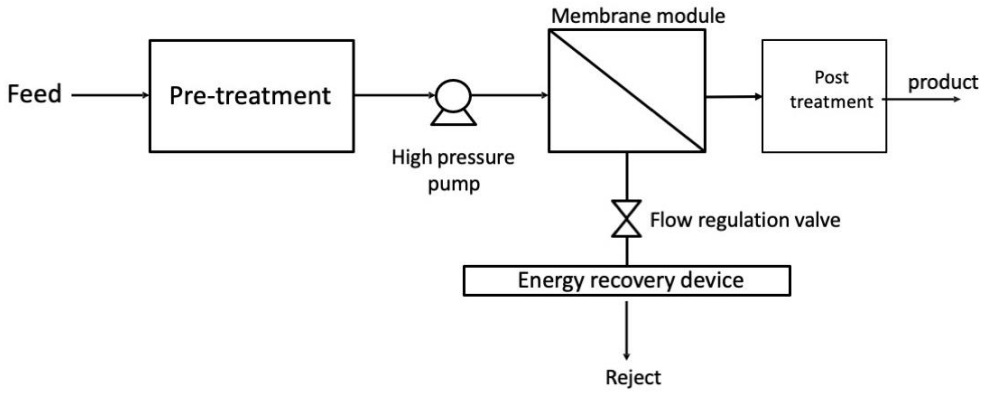

Figure 3. Flow sheet for seawater reverse osmosis desalination plant

Process description

A '*cell pair*' refers to a set of anion and a cation membranes**.** In an electrodialysis unit (Al-Amshawee et al., 2020), as shown in Figure 4, a number of cell pairs are arranged together between the electrodes (anode and cathode) such that cation and anion exchange membranes are alternately placed. Feed, after pre-treatment of the source water, is passed through all the compartments. Electrode rinse solutions are circulated around the electrodes to remove the gases (hydrogen at the cathode, and oxygen /chlorine at the anode). The pre-treatment involves the removal of scale forming ions such as calcium and magnesium and foulants using softeners or nanofiltration. This helps to improve the efficiency of the desalination process and prolong the life of the ED membranes.

When the electrical potential is imposed, the ions in the solution move towards their counter electrodes i.e., anions towards the cathode and the cations towards anode. The direction of the movement is fixed, due to the polarity of the electrodes. As the ions move, cations can pass through cation exchange membrane, but not through anion exchange membrane encountered in their path, and vice-versa for anions. Consequently, as the movement of ions progress, alternate compartments become depleted and concentrated with respect to the solutes, resulting in diluted water and concentrated stream. The depleted (dilute) water is collected as desalinated water, while the concentrated solutions, separately.

The operational challenge in the process, is the accumulation of ions near the membrane surface resulting in concentration polarization, attributable to the lesser diffusivity of the ions in the membrane phase compared to the solution phase, resulting in reduced current utilization efficiency. Since the energy consumption depends on the number of ions and their charge, the energy consumption for seawater desalination is high due to a higher concentration of the feed (about 35000 ppm), with significant presence of bivalent ions and the consequent concentration polarization. For brackish water with less TDS (<5000 ppm), electrodialysis, is energy efficient. ED is better suited in removing ionic components with low molecular weight, but not for neutral, high molecular weight and less mobile ionic species. At very low solute concentrations, the transport rate and the current utilization efficiency decreases. Consequently, it is difficult to obtain low concentration of product water, using electro-dialysis.

To reduce energy consumption in sea water desalination using ED, and to increase the energy utilization by circumventing the concentration polarization phenomenon, the concept of '*Electro-Dialysis Reversal* (EDR)' was introduced, by which the electrode polarities are frequently reversed to change the direction of ionic movement and hence to minimize the effect of concentration polarization. However, this concept resulted in the reversal of product and concentrate compartments resulting in contamination of the product water leading to poor product quality.

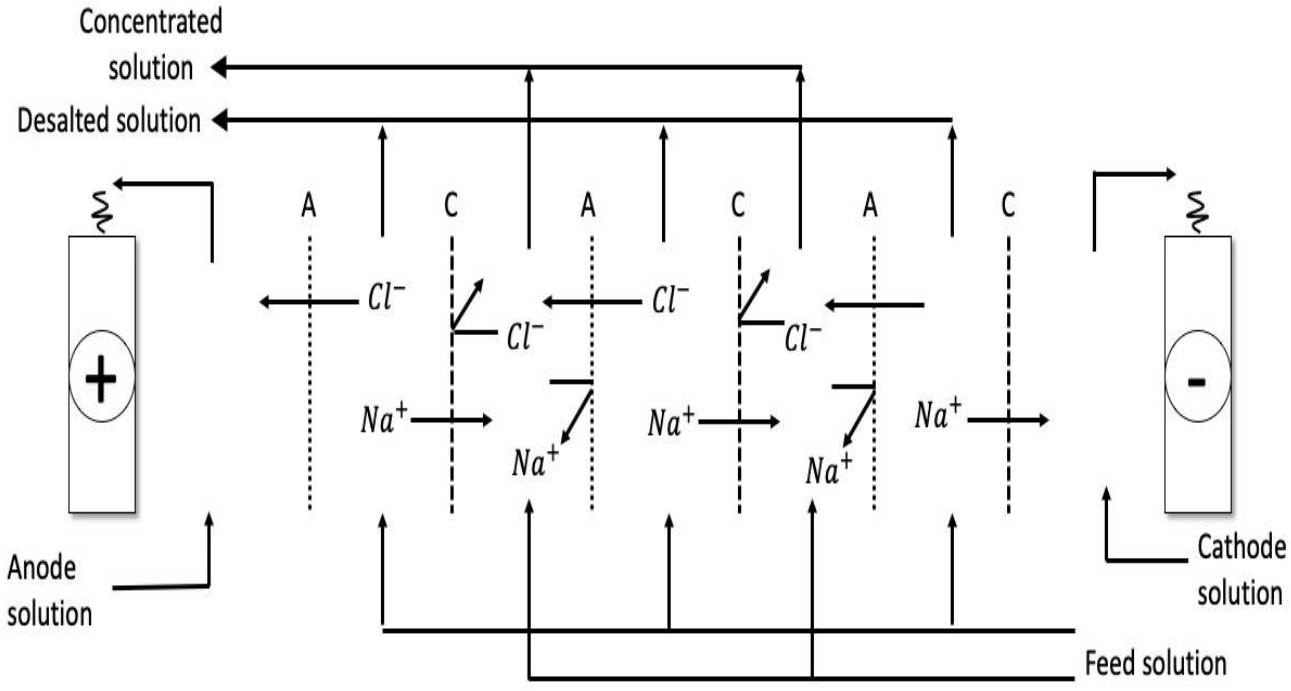

Figure 4. Working philosophy of electro-dialysis process

DEVELOPING MEMBRANE PROCESSES

Besides, reverse osmosis and electro-dialysis, a few more membrane processes have been developed for desalination operating under different energy gradients; temperature, concentration, and electric potential viz., Forward Osmosis (FO), Membrane Distillation (MD), and Electro-Deionization (EDI) respectively.

Forward Osmosis

The operating philosophy of forward osmosis (Cai and Hu, 2016) is same as osmosis i.e., water permeates through the semi permeable membrane from its higher concentration (water) to its lower concentration. In practice, a concentration difference with reference to water is imposed using a synthetic draw solution with a higher osmotic pressure than the feed stream to osmotically draw water from the feed stream. Consequently the draw solution is diluted (Mehta et al., 2014). Fresh water is then separated from the draw solution by a downstream process, using some form of energy: thermal or mechanical (pressure) as shown in Figure 5. A Variety of membranes such as thin film composites, cellulose acetate, and bio-membranes such as aquaporin etc. and draw solutes including several inorganic solutes such as ammonium bicarbonate, chlorides of magnesium, calcium and sodium, organic compounds including glycerol and high molecular weight compounds, have been investigated to decrease the reverse solute flux, improve the water flux, and the ease of recovering fresh water from downstream process. Another interesting consequence of forward osmosis namely pressure retarded osmosis, can lead to power generation, from the hydraulic pressure being developed in the draw solution side.

Membrane Distillation

Membrane distillation (Parani and Oluwafemi, 2021) uses porous membranes which are hydrophobic in nature. Unlike liquid water which exists in an associated state, water vapor does not exhibit association amongst them and behaves as hydrophobic moieties. Thus, using hydrophobic membrane, the water vapor is preferentially transported by maintaining a vapor pressure gradient created by temperature differential. Depending on the method of condensation, four different methodologies were developed as indicated in Figure 6. In direct contact membrane distillation (DCMD), the water vapor permeating through the membrane is condensed by circulating cold water in the permeate side. In vacuum membrane distillation (VMD), an appropriate vacuum is maintained on the permeate side to enable the condensation of the vapor. In the air gap membrane distillation (AGMD), the vapor is condensed on the wall of the shell, accommodating the membrane, by maintaining a cooler wall temperature by external cooling. In sweep gas membrane distillation (SGMD), the water vapor gets humidified by the gas (nitrogen or air) and recovered outside the unit. Studies on membrane distillation for seawater have been carried out using solar energy as a thermal source using vacuum for condensing the vapors (Mericq et al., 2011).

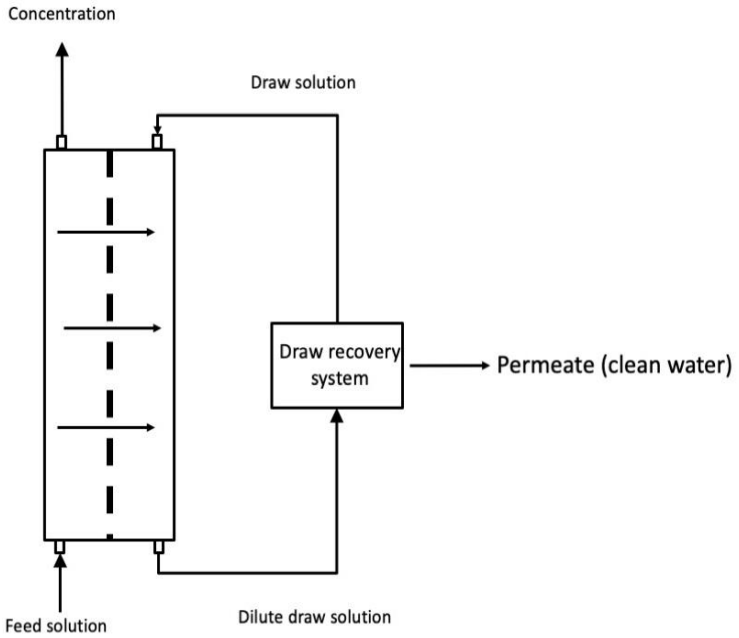

Figure 5. Working principle of forward osmosis. Feed and draw solutions are circulated on either side of the membrane during which draw solution gets diluted because of osmotic flow and clean or product water is recovered using thermal or mechanical energy.

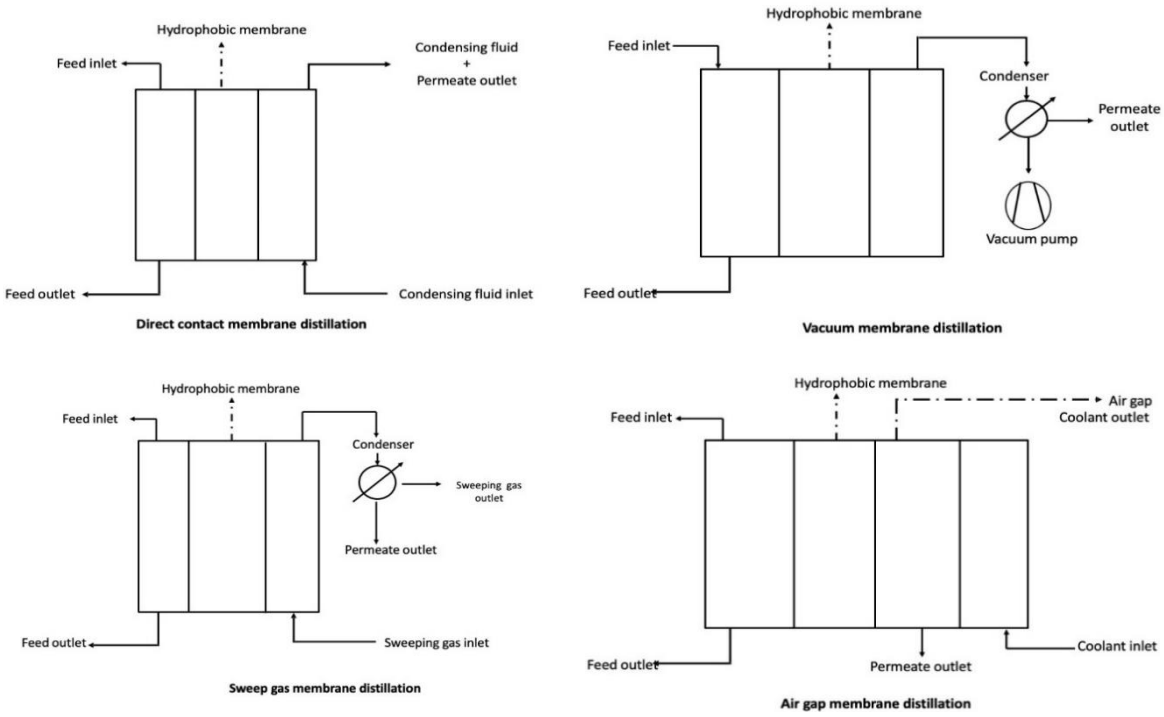

Figure 6. Different methodologies adopted for condensation of the product in membrane distillation (direct, vacuum, sweep gas and air gap).

Electro-Deionization

Electro-Deionization (EDI), like an electro-dialysis unit, consists of a number of cell pairs (a set of anion and cation exchange membrane), and is a membrane process which can be used as last mile purification process to produce de-ionized water, from the product water obtainable from any of the major desalination technologies, be it thermal, electro or pressure driven process, replacing the hitherto used mixed bed ion exchange resins. Use of the mixed bed exchangers, involve frequent regeneration following tortuous procedures and the consequent management of regenerant waste. EDI can be considered as an ion exchange bed with continuous regeneration with electrical energy. The basic difference is the presence of mixed bed exchange resins in the dilute compartment. Feed water with only a few dissolved ionic solutes, is passed through the cells under an applied electrical field. As in ED, the ions start migrating, resulting in concentrate and dilute streams in two adjacent compartments. The ions are initially bound to the resin. With the production of hydrogen and hydroxyl ions due to the high resistance of the dilute stream and consequent electrolysis of water, the resin gets regenerated, and the ions move to the adjacent concentrate compartment.

The limitations of EDI differ from conventional ion exchange, where the purity of the product is limited by the saturation of the resins, while in EDI, the purity is limited by the feed rate. However, high ionic load will overload the module. Hence mixed bed ion exchangers as well as EDI are suitable only for low concentrations of ionic solutes, except that the latter does the removal and regeneration in situ, making it ideal for last mile deionization of product water from conventional desalination processes.

CONCLUSIONS

Seawater desalination is necessary to meet the growing demand of freshwater across the globe. Amongst the commercially developed processes, reverse osmosis is a sustainable and affordable means of providing safe drinking water with many advantages such as operational flexibility because of its modular construction, with respect to capacity, availability of energy source (easily available at any location). ED has limitations in terms of feed salinity and specific energy consumption and product salinity for seawater desalination. In contrast, thermal plants barring vapor compression evaporation (VCE), requires both thermal and electrical energy and produces product with very less concentration of dissolved solids making it imperative and to have elaborate post treatment to make it potable. The basic challenge in any membrane process is the concentration polarization leading to scaling and consequent loss in productivity. The concept of EDR, which sought to alleviate the problem of polarization, resulted in poor product quality due to frequent change of

product and concentrate compartments. All the membrane processes require good pretreatment to minimize scaling and fouling. Since RO is a high pressure system, the pre-treatment requirements are rigorous, while ED systems require feed pretreatment to remove hardness and species that may cause fouling and scaling on to the ion-exchange membranes (Kadhim et al., 2023), which decreases the efficiency. However, electro-dialysis can support higher concentrations of those foulants than reverse osmosis. Electro-dialysis membranes, are normally assembled in plate and frame configuration, allowing the removal of membranes and cleaning them directly. In the case of reverse osmosis, where spiral configurations are used, cleaning must be done online chemically, which has the risk of deterioration of the membrane performance. Even otherwise, the membranes deteriorate with time needing periodic replacements and considered part of operating cost rather than being a capital cost.

The greatest challenge of the membrane processes is the ultimate disposal of spent membrane elements in reverse osmosis and the charged membranes in ED, as the membranes are not bio-degradable. In the case of SWRO, the membrane elements are prepared to withstand high operating pressures and shredding them for disposal through incineration is energy intensive. Probably one may investigate the possibility using them for construction purposes. The concentrate solutions of disposed normally into the sea by slow dispersion along the coast.

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Author Credit Statement

Dr. Prabhakar has conceived the contents of the paper, based on the presentation made at a conference held at Hyderabad. Dr. E. Poonguzhali, has written the text based on the contents of the presentation and mutual discussions.

Data Availability

As such there is no data (experimental or otherwise) to share, but will be pleased to answer any queries.

Compliance with Ethical Standards

There is no conflict of interest and the contents are compliant with the ethics. Authors adhere to copyright norms

References

Al-Amshawee, S., Mohd Yunus, M. Y. B., Mohd Azoddein, A. A., Hassell, D. G., Dakhil, I. H. And Hasan, H.A., 2020. Electrodialysis desalination for water and wastewater: A review. Chem. Engineering J., 380, Article: 122231. DOI: 10.1016/j.cej.2019.122231

Cai, Y. and Hu, X. M., 2016. A critical review on draw solutes development for forward osmosis. Desalination, 391(16–29). DOI: 10.1016/ j.desal. 2016.03.021

Dhakal, N., Salinas-Rodriguez, S. G., Hamdani, J., Abushaban, A., Sawalha, H. et al., 2022.

Is desalination a solution to freshwater scarcity in developing countries? Membranes,12 (4), 381. DOI: 10.3390/ membranes 12040381

Kadhim, R., Khudhair, B. H. and Jaafar, M. S., 2023. Comparative study of water desalination

using reverse osmosis (RO) and electro-dialysis systems (ED). J. Engineering, 29,(4), 61–77. DOI: 10.31026/j.eng.2023.04.05

Mehta, D., Gupta, L. and Dhingra, R., 2014. Forward osmosis in India: Status and comparison with other desalination technologies. Int. Scholarly Research Notices,175464. DOI: 10.1155/2014/175464

Mericq, J., Laborie, S. and Cabassud, C., 2011. Evaluation of systems coupling vacuum

membrane distillation and solar energy for seawater desalination. Chem. Engineering J., 166(2), 596–606.

Parani, S. and Oluwafemi, O. S., 2021. Membrane distillation: Recent configurations, membrane surface engineering, and applications.Membranes,11(12), 934. DOI: 10.3390/ membranes11120934

Ruiz-García, A., Nuez, I. and Khayet, M., 2023. Performance assessment and modeling of an SWRO pilot plant with an energy recovery device under variable operating conditions. Desalination, 555, 116523. DOI: 10.1016/j.desal.2023.116523

Schunke, J. A., Herrera, G. A., Padhye, L. and Berry, T. A., 2020. Energy recovery in SWRO

desalination:Current status and new possibilities. Frontiers in Sustainable Cities, 2, Article 9. DOI: 10.3389/frsc.2020.00009

Wang, J. and Huo, E., 2022. Opportunities and challenges of seawater desalination technology.

Front. Energy Res., 10, https://doi.org/10.3389/fenrg.2022.960537

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