A Concise Review of Major Desalination Techniques: Features and Limitations

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Abstract. This paper provides a succinct and simplified account of desalination techniques. The techniques are categorized as membrane-based, thermal-based, combined membrane/thermal-based and miscellaneous techniques. Essential features of membrane-based, thermal-based and combined membrane/thermal-based techniques are presented, while their associated limitations are equally highlighted. Reverse Osmosis (RO) remains the state-of-the-art technology in seawater desalination with the highest installed capacity of 65% globally. Whereas, solar desalination potentially shows as a cost and energy-effective means of ensuring steady supply of potable water in off-grid arid-coastal environments, where freshwater reserves are non-existing. In general, if the world is to aim for global freshwater sustainability, seawater desalination must be considered crucial, and a good understanding of its techniques will further drive the vision closer to reality.

Keywords: Desalination · Desalination techniques · Membrane-based techniques · Thermal-based techniques · Solar-thermal desalination · Reverse osmosis · Solar still

1 Introduction

Desalination, from its root word ‘desalt’, is the removal of salt from saline water. By convention, seawater desalination is the use of specialized techniques to recover freshwater from seawater by eliminating the dissolved salt and mineral contents [1]. Several techniques have been adopted for the extraction of freshwater from seawater. They are generally classified under membrane-based, thermal-based and chemical-based

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technologies. Prominent among membrane-based technologies are Reverse Osmosis (RO), Nanofiltration (NF) and Electrodialysis (ED). Thermal-based technology involves conventional thermal distillation, which uses heat to evaporate seawater, after which the vapour is collected as distillate. The chemical-based options—involving ion-exchange, have not been found very practical to treat water with high level of dissolved solids [2]. Overall, RO excels as the most installed and most effective desalination technology with 65% total installation capacity globally (Fig. 1). Thus, it remains the state-of-the-art in seawater desalination [3].

Categorizations from literature furbish overlapping details that make recognition of the fundamental principles on which specific desalination techniques function to be tedious. This unfolds a research gap of a summarized and simplified approach to classifying these techniques. Therefore, the aim of this review paper was to give more exhaustive synopsis of the desalination technologies from the literature and examine each of them on account of its characteristic features and associated limitations.

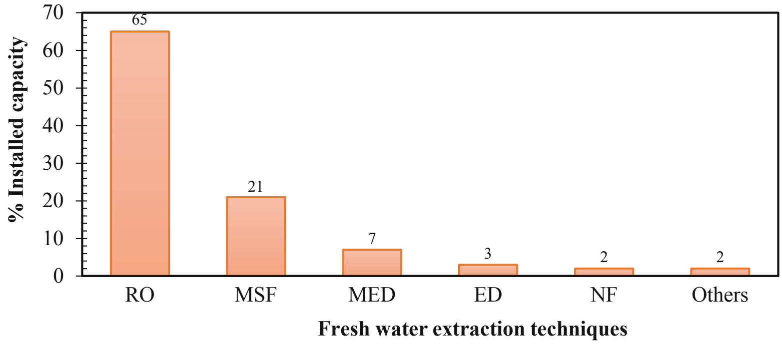

Fig. 1. Overall global installed desalination capacity by techniques. RO: Reverse Osmosis, MSF: Multi-Stage Flash Distillation, MED: Multi-Effect Distillation, ED: Electrodialysis, NF: Nanofiltration, Others: comprise Freezing/Hydrate-based desalination, Membrane Distillation (MD), Forward Osmosis (FO) and Solar Still Distillation (SSD) [4].

2 Desalination Techniques

The major desalination techniques can be categorized into four broad categories: Membrane-based, Thermal-based, Combined membrane/thermal-based, and Miscellaneous techniques, as presented in Fig. 2.

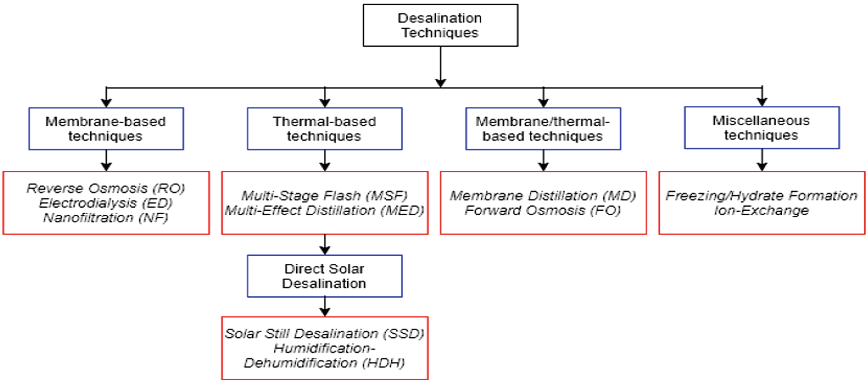

Fig. 2. Categorization of major desalination techniques

2.1 Membrane-Based Techniques

The membrane-based techniques are gaining attention, nowadays, with the advent of high permeability membranes. They involve the use of polymeric membranes to separate salt solutes from seawater. In practice, by using either hydraulic pressure, osmotic pressure or electrical potential, feed saline water is driven across a semi-permeable membrane. The membrane selectively permits freshwater to permeate, while retaining the solutes [1]. The overall effectiveness of the membrane techniques is, however, hindered by the high energy requirements to drive seawater across the membrane [3, 5]. The minimum theoretical energy required to desalinate typical seawater of 35,000 mg/L salt concentration at 50% recovery is 1.06kWh/m^3, which is regardless of the type of system used, nor the energy inputs for seawater supply, pre and post treatments, and brine disposal [5]. This figure translates to the energy, in form of applied pressure, required to overcome the osmotic pressure of seawater for cross-boundary flow of water through the membrane. Apparently, a higher value should be expected for waters with higher concentrations, such as found in the Arabian Gulf with 45,000 mg/L characteristic concentration.

In addition to the energy demand of the membrane technology, fouling, internal concentration polarization, membrane effectiveness in the low pH range (for cellulose acetate and cellulose triacetate membranes) and susceptibility to chlorine attack (in polyamide-polysulfone thin-film composite membranes) are known performance indices in saline water membrane applications [6, 7]. For RO, the actual energy consumption for the best-in-class of seawater, being the one with the lowest salt concentration is between 2.5–2.8 kWh/m^3, translating to a cost range of about 0.5–0.8 USD/m^3 of produced water [8]. But for the most conventional plants, operational energy consumptions ranges between 3–5 kWh/m^3 [9].

2.2 Thermal-Based Techniques

Differently, the thermal-based techniques use heat energy obtained mostly from the combustion of fossil fuels to separate freshwater in the form of vapour-to-condensate from saline water. These techniques are energy intensive, except where waste heat is reused. Multi-Stage Flash distillation (MSF) and Multi-Effect Distillation (MED) are entirely thermal processes of seawater desalination [4]. While the thermal technology appears less cumbersome compare to the membrane-based processes, its operation suffers low thermal-to-vapour conversion efficiency and greenhouse gasses emission from the combustion of fossil fuel, except where clean renewable energy sources are employed.

2.3 Combined Membrane-Thermal Techniques

Some other desalination technologies combine both the membrane and the thermal applications, making it a two-stage process. Membrane Distillation (MD) [10] and Forward Osmosis (FO) [11] are typical examples. In MD, thermal energy is needed to vaporize seawater, while a vapour-permeable membrane is used to separate the resultant vapour from the water bulk, which is later condensed to recover freshwater condensate. In FO, membrane process precedes the thermal application stage. A thermolytic hypersaline solution, such as ammonium carbonate $(NH_4)_2CO_3$, is applied as a draw solution against the seawater feed solution—the former draws water molecules from the later and becomes diluted. The process is then completed by applying heat to the diluted thermolytic draw solution to disintegrate the ammonium ion (NH_4^+) and carbonate ion (CO_3^{2-}) and recover freshwater, as represented in Eq. (1). Besides the fact that MD and FO exploitations are still vying for acceptance beyond the R&D quadrant, the overall success of the duo techniques hopes to leverage the availability of low-grade or recycled heat for its thermal process stages.

$$(NH_4)_2CO_3\ (aqeuos) \text{—}\ (heat) \text{—}\!\!\rightarrow\ 2NH_3 + CO_2 + H_2O \tag{1}$$

2.4 Miscellaneous Techniques

A few other desalination techniques are less popular and have, thus, received a fairly modest recognition in literature. One of them is freezing or hydrate formation, where water molecules are frozen and cleansed of salt contents, then de-frozen to regain pure water [12]. Another is ion-exchange technique, whose efficiency is only limited to low-salinity water sources [13, 14]. However, in all the desalination techniques mentioned, high energy requirements, huge costs of plant installations, operations and maintenance, as well as operational technical expertise are stupendous challenges. These challenges preclude the techniques as potential solutions in remote settlements with potable water supply challenges. This further justifies the need to develop viable alternatives to the much-praised RO technology.

Solar-Thermal Desalination. Solar-thermal desalination (STD) offers a potentially cost-effective and technologically sustainable approach to seawater desalination, especially for remote arid-coastal environments, where access to the grid is totally non-existing or extremely inadequate [15]. STD is not only cheap, but it also benefits from the abundance of solar energy potential typical of most arid environments, to produce potable water. The energy renewability and its ecofriendly inclination puts STD ahead of other possible sustainable solutions. As a thermal-based technology, it relies on solar radiation to heat up seawater to produce vapour, which is then collected as condensate for onward usage. Thus, STD functionality is measured by the specific water productivity (SWP)—which pivots, as illustrated in Fig. 3, around three metrics: 1) solar absorptivity $(\propto)$, which is a measure of the percentage of solar radiation that is converted to heat; 2) thermal efficiency (η_t) of the solar absorbing surface, which is a measure of the heat that is required to convert water to vapour via evaporation; 3) gain output ratio (GOR), a measure of the percentage of the resultant vapour that is condensed as distilled water. Fundamentally, GOR gives an indication of how much the latent heat of condensation is reused for further distillation [15]. Prominent seawater desalination techniques that leverage direct solar radiation are solar still desalination (SSD) [16] and humidification-dehumidification (HDH) [17], both working with the same principle and along a common desalination pathway.

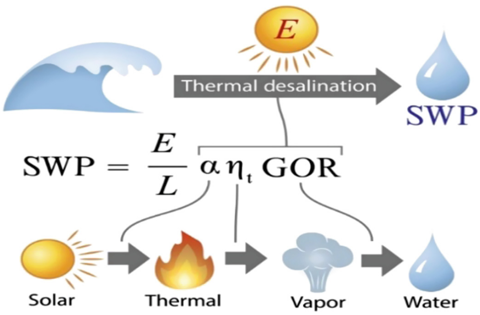

Fig. 3. Direct solar-thermal desalination pathway. E is the solar radiation (kW/m^2) and L is the latent heat of evaporation $(kWh/litre)$ [15].

Solar Still Desalination (SSD). Basically, solar-thermal desalination (STD) can be categorized into direct and indirect solar desalination [18, 19]. SSD—a typical representative of the direct solar desalination techniques, is a simple assembly, comprising a basin, a transparent inclined cover, distillate collection channels and collectors, seawater inlet compartment, and a host of pipe connections. It uses direct solar radiation to heat up seawater in the basin. The water evaporates to the ambient enclosed atmosphere created between the contents of the basin and the transparent inclined cover. The water vapour condenses on the cover and rolls down the inclined plane into the distillate channel and collected as potable water [20–25]. For the indirect STD, on the other hand, solar energy is collected via a collector or a photovoltaic (PV) modules and stored as electrical energy in batteries, which can be coupled directly to a solar still to enhance the thermal input through a heating device [26], or used as a hybrid with other forms of desalination techniques as the energy source [27].

Table 1 gives an overall comparison between the conventional desalination techniques discussed in the preceding sessions and solar-thermal desalination via solar still desalination. Considerations such as energy concerns, economics and costs, and technological sophistications and technical expertise favour the adoption of STD for low-income communities.

Table 1. Summary of special issues concerning conventional desalination techniques in comparison with solar-thermal desalination via solar still desalination

Special issues	Conventional desalination techniques	Solar-thermal desalination
Energy and environmental concerns	• Non-renewable and environmentally impairing, as GHG emission is typical • Reliance on steady supply of refined energy or fossil fuel burning, if otherwise	• Renewable, eco-friendly and potentially cost-effective • Inconsistent availability and spatial variation of solar radiation
Technology and technical expertise	• Installation requires high technological sophistications, as plants components are huge • Sound technical expertise (though varies from a technique to another) is needed for operation and maintenance	• Installation requires moderate technological sophistications • Modest technical expertise is sufficient for its operation and maintenance
Economics and costs	• High start-up and installation capitals, as plant sizes are usually large • High operation and maintenance costs are inevitable, and operation could stop for days during repair or maintenance	• Low start-up/installation costs, making it suitable for low-income communities • Almost insignificant operation and maintenance costs
Productivity and water quality	• Productivity is usually high, depending on plant capacity, while specific output depends on techniques • Good water qualities that meet acceptable standards. However, the suitability to desalinate high-salinity water varies with technique	• Low productivity, typically below 10 L per square meter per day. • Water quality meets acceptable standards. However, occasional contamination is not unlikely because of low system sophistication. It can desalinate high-salinity water
Development and commercial status	• Some techniques (such as RO, NF, MSF & MED) are commercially functional globally, while many others still domicile within the R&D domain	• It is still within the R&D domain. But a number of functional units has been installed to serve households and small communities

3 Conclusions

Desalination techniques have been categorized in this study into membrane-based, thermal-based, combined membrane/thermal-based and miscellaneous techniques. Each of the techniques has been sufficiently entrenched in literature, but their main features and limitations were brought to focus in this review to serve as an easy and quick reference for ongoing and future studies. The membrane-based techniques are gaining rising-attentions in the desalination industry globally due to the advent of high-permeability membranes. However, their overall efficiency is hindered by fouling, concentration polarization, susceptibility to chlorine-attack and effectiveness over a low range of pH, which are distinctive characteristics of polymeric membrane and saline water interactions. The thermal-based techniques, on the other hand, are promising, as they are free from limitations associated with the membrane techniques. However, their popularity is hindered by low thermal-to-vapour conversion efficiency and the inherent green-house gas (GHG) emission when powered by fossil fuels. While the combined membrane/thermal-based techniques present great potential to desalinate seawater at fairly low costs, their success seeks to leverage the uninterrupted availability of low-grade/waste heat for the affiliated thermal process. Some other techniques are, however, less common and use approaches different from the ones previously mentioned—they are classified as miscellaneous techniques. Finally, solar-thermal desalination (STD) is a thermal-based technique that benefits directly from the energy from the sun to desalinate seawater. Although the eco-friendliness and renewability of its energy source and its low installation, operation, and maintenance costs are some of the considerations that have earned STD preference over other techniques, it would need extensive research attentions to productively compete with them for commercial acceptance.

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