Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.892837

54 (2015) 1526–1541
May

Taylor & Francis
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A review on energy consumption of desalination processes

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Received 7 July 2013; Accepted 24 January 2014

ABSTRACT

The technologies that are used mainly in the seawater desalination industry are reviewed and evaluated in this article. The utilization principles, applications, and problems of these processes are summarized and discussed. The desalination methods are compared with each other for performance ratio (PR), gain output ratio (GOR), unit energy consumption (kWh/m^3), or unit operating cost (\$/m^3) and afterward the preferred method is identified.

Keywords: Desalination processes; Gain output ratio; Performance ratio; Energy consumption

1. Introduction

The increase in world population, accompaniment with increase in industrial and agricultural activities in the recent decade, has led to excessive exploitation of available water resources and freshwater resources pollution. Therefore, adopting various methods for converting polluted water or salty water into potable water is necessary.

In general, water is divided into five main categories:

- Freshwater (0.5 g/L and less salinity)
- Brackish water (0.5–30 g/L salinity)
- Saline water (30–50 g/L salinity)
- Sea water (35 g/L salinity)
- Brine water (50 g/L and more salinity)

One of the most popular methods to produce potable water is “Desalination”, in which the salty water is converted into potable water by the removal of salt content. All desalination methods can be classified into four categories:

(1) Thermal
(2) Crystallization
(3) Membrane
(4) Other

Fig. 1 illustrates an overview on desalination methods.

In this article, the above methods are described with respect to their subsets, features, applications, and problems.

1.1. Thermal desalination methods

In this category, the required energy for desalination is supplied by a heating source such as natural gas, steam, electricity, renewable energy, etc. In these systems, gain output ratio (GOR) or performance ratio (PR) is defined as efficiency. GOR is defined as: the ratio of the mass of water produced through a desalination process over a fixed quantity of energy consumed. In many practical cases, steam may not be the medium of heat transfer, so the PR is most commonly defined as the mass, in pounds, of water produced by desalination per 1,000 BTU of heat

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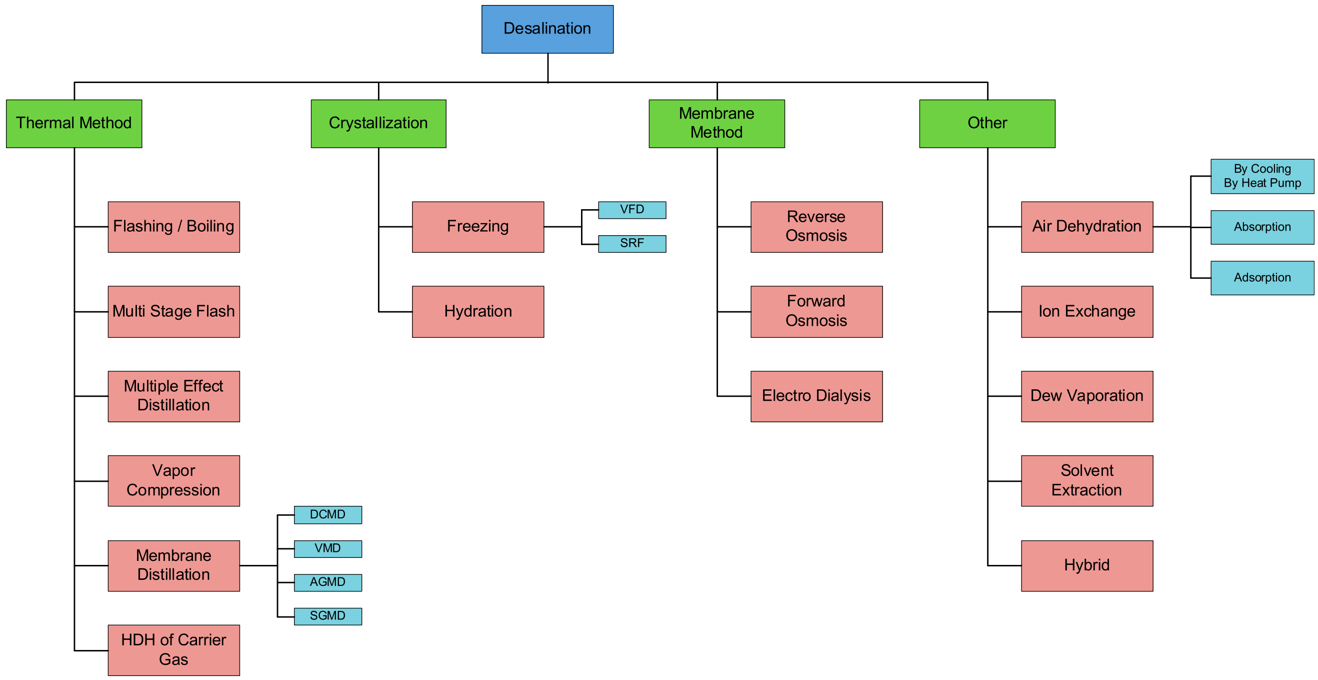

Fig. 1. Desalination methods tree.

provided to the process. The SI equivalent of this formulation is the number of kg of water produced per 2,326 kJ of heat [1].

1.2. Simple boiling

Boiling is the rapid vaporization of liquid occurring when it is heated to its boiling point (100˚C in atmospheric pressure), the temperature at which the vapor pressure of the liquid is equal to the pressure exerted on the liquid by the surrounding atmosphere (below the boiling point liquid evaporates from its surface). Boiling process can be used as a method of water disinfection and desalination but is only advocated as an emergency water treatment method because this method consumes a high amount of energy (since there is no internal energy recovery, GOR for this process is always less than one). Today, this method is mostly applied in producing steam with the least application in desalination. Fig. 2 illustrates a scheme for this method.

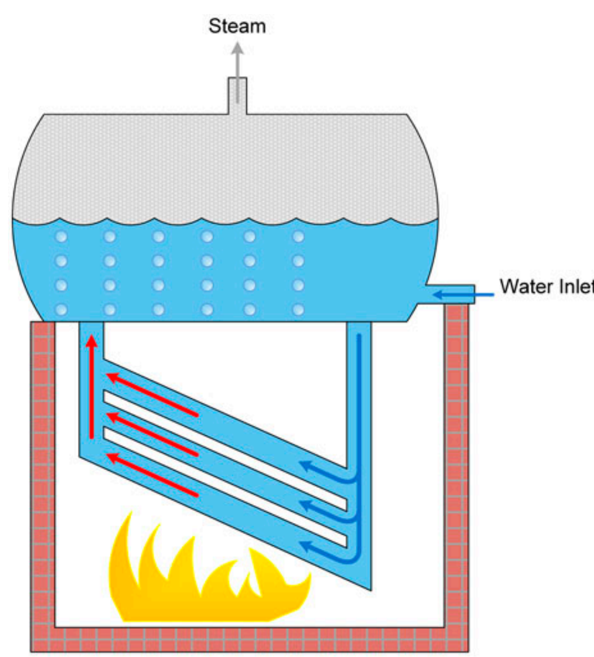

Fig. 2. A simple boiling evaporator.

1.3. Multi-stage flash

Multi-stage flash (MSF) is the main process for the desalination industry with a market share close to 60% of the total world production capacity until the late twentieth century. MSF still has a sizeable market share in the beginning of twenty-first century [2]. This method contains 90% of the thermal desalination methods [3]. There are many new articles on this method in the field of modeling, simulation, energy analysis, optimization, thermodynamic, etc [4–10]. Fig. 3 shows a schematic diagram of the MSF system.

This system consist of several flashing stages (increasing the flashing stages can increase internal energy recovery), a brine heater, pumping units, venting system, and a cooling water control loop. Incoming sea water passes through the heat exchanger where its temperature increases. Next, it is passed to the brine heater where the steam from an external source supplies the energy for the process and heats the sea water in the heat exchanger to the maximum process temperature (80–90˚C). Then it is released into the first vacuum chamber, the water vapor condenses into freshwater product by the cooling water control loop and this operation is repeated for other stages. These are the special and distinguishing features of the MSF process. A small number of connection tubes are installed in the MSF process construction which restricts leakage problems and simplifies the maintenance work. Evaporation and condensation could be performed in several stages, hence an increase in efficiency. Despite the development and progress in the MSF process, the performance ratio has shown a value of 8 [2], while in the latest studies, the reported value is 14 [12].

Some important features of MSF desalination method are as follows:

- Suitable for the region with cold salty water such as Middle East
- Ability for combination with renewable energy sources such as solar
- Simple design and construction
- Process reliability
- Extensive experience for operation and maintenance
- Suitable for normal and high desalination capacities
- GOR: 8–14

1.4. Multiple effect distillation

This method is similar to MSF. In multi-effect distillation plant, the column pressures are adjusted such that the cooling (energy removal) in one column functions as the heating source (energy input) in another column. To accomplish this, each column must be operated at a different pressure. In the conventional multiple effect distillation (MED) plant, the sea water enters the first effect and is raised to the boiling point. Both the water feed and heating vapor to the evaporators flow in the same direction. The remaining water is pumped to the second effect, where it is once more applied to a tube bundle. This process continues for several effects, about 4–21 effects in a typical big plant [13,14] (an increase in flashing stages can increase the internal energy recovery). In the new designed plants, which are shown in Fig. 4, the sea water (feed) is divided into several parts before entering the flash drums. The produced vapor from the salty water is

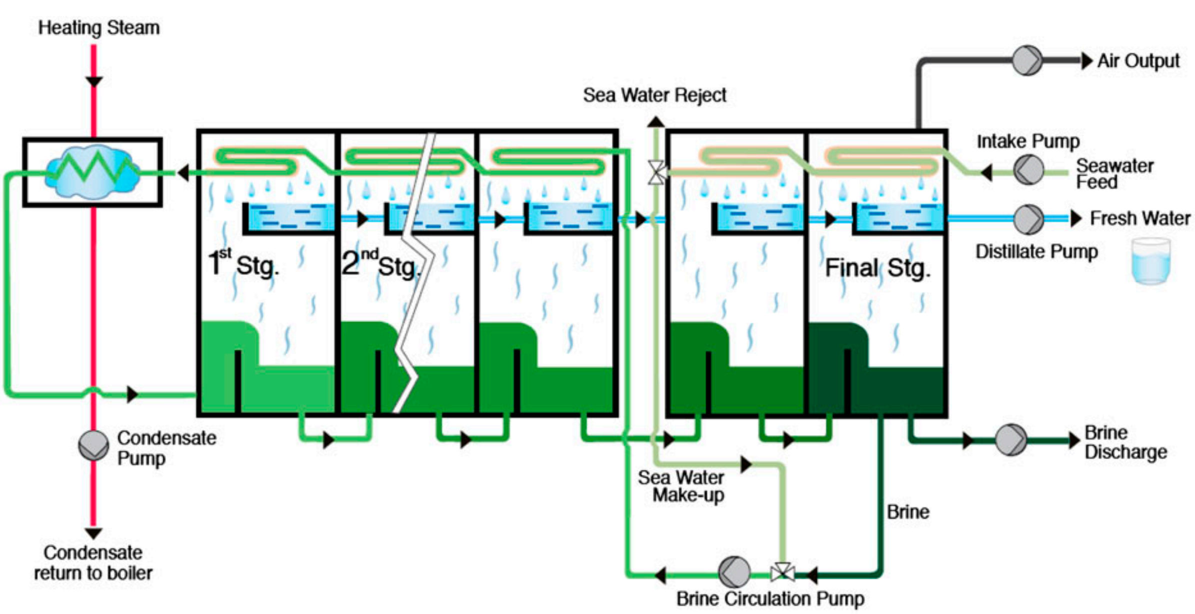

Fig. 3. A scheme for MSF desalination [11].

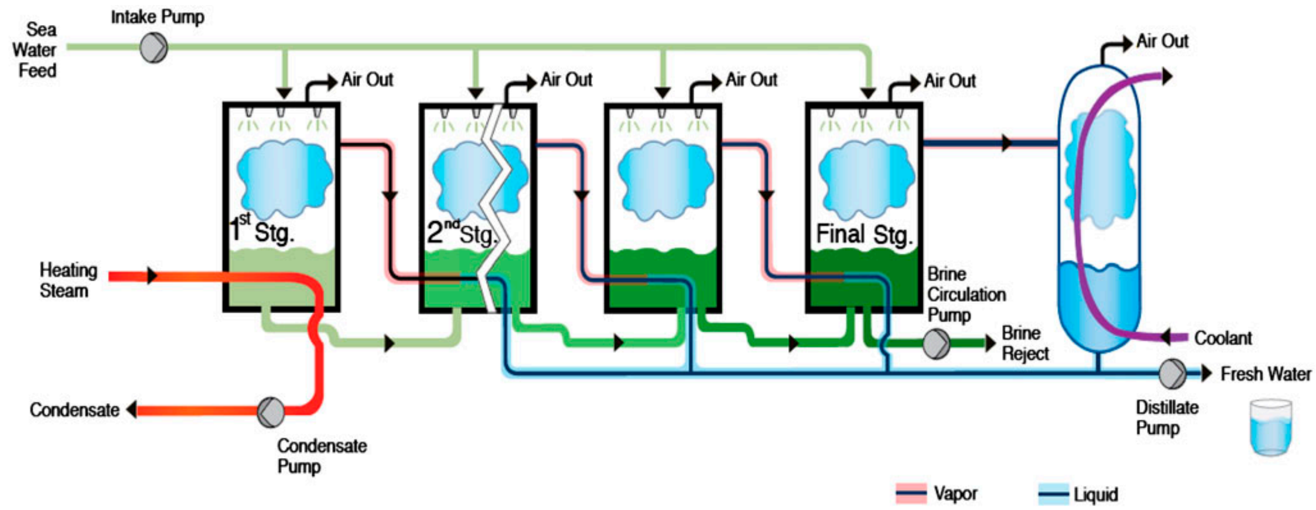

Fig. 4. A scheme for MED desalination [11].

sent to the next stage for heating the next stage feed where it is condensed through the next stage and freshwater is obtained. Finally, the residue water is discharged from the system and returned to the sea.

Some important features about MED desalination method are mentioned in previous works [14–22] as follows:

- Suitable for the region with hot salty water
- Combination with renewable energy
- Simple design and construction
- Process reliability
- Extensive experience for operation and maintenance
- Suitable for normal and high desalination capacities
- GOR: 9–18

1.5. Vapor compression

In the vapor compression (VC) process, the heat for evaporating the sea water is generated through VC [23]. Two methods are used to condense the water vapor and to produce the amount of sufficient heat to evaporate the incoming sea water: a mechanical compressor and a steam jet. In this method, sea water is evaporated and the vapor is passed through a compressor. Here, the vapor is compressed, which leads to an increase in vapor dew point (in this condition the compressed vapor dew point is higher than sea water boiling point), so vapor can be condensed by sea water indirect contact (it can save a lot of energy) and cause to evaporate sea water. In order to reduce the energy consumption of the compressor, compression ratio should be selected close to one. In this process, the sea water temperature is held at 100˚C.

VC units are built in a variety of configurations in order to promote sea water evaporation. The compressor creates a vacuum in the evaporator and then compresses the vapor taken from the evaporator and condenses it in a tube bundle. A simple scheme for VC method is illustrated in Fig. 5.

The power consumption of this method is high (because of compressor usage) but it becomes economically feasible when energized by solar cell [24].

Some features about this method are as follows:

- High energy consumption
- Low occupied space in comparison with MSF and MED

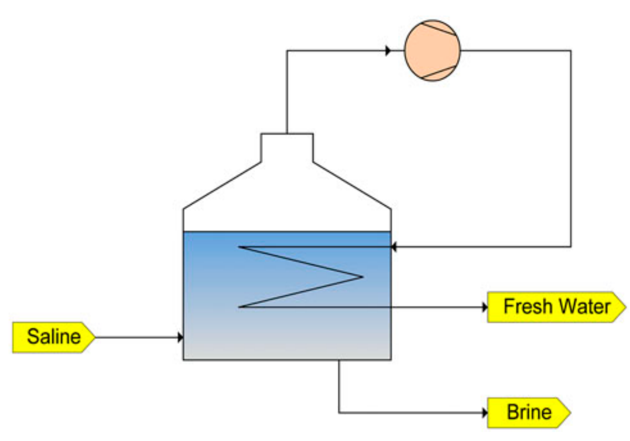

Fig. 5. A scheme for VC desalination.

- Suitable for low desalination capacity
- Less popular in comparison with other thermal methods
- GOR: 12–14

1.6. Membrane distillation

Here, the hot saline solution flows in direct contact with hydrophobic micro-porous membranes, and the cold solution flows on the cold side of the membrane. The temperature difference between the hot and cold faces of the membrane causes the vapor pressure of the concentrated solution to be higher than that of the cold fluid; as a result, water starts to evaporate at the hot side of the membrane, penetrates through the membrane pores, and then is transferred and condensed on the cold fluid or condensed in a film on a cooling plate [25]. A scheme of membrane distillation (MD) desalination is illustrated in Fig. 6.

MD systems can be classified into four configurations, according to the nature of the cold side of the membrane:

(1) The direct contact membrane distillation, where the membrane is only in direct contact only with liquid phases [27–29]. In this configuration, a thin membrane is located between hot brackish water and cold freshwater; in the hot side, water is evaporated and passed through the membrane and finally condensed in the cold side of the membrane.

(2) The vacuum membrane distillation (VMD), where the vapor phase is evacuated from the liquid through the membrane and condensed in a separate device, if needed [30,31]. In this configuration, the membrane is installed between the hot brackish water and a vacuum chamber in order to increase the chemical potential between two sides of the membrane. After water vaporization, water is evacuated to another membrane side and moved to condensation section.

(3) The air gap membrane distillation, where an air gap is interposed between the membrane and the condensation surface [32]. In this configuration, vapor is penetrated through the membrane and an air gap; finally, it is cooled by a cold plate and freshwater is produced.

(4) The sweeping gas membrane distillation, where a stripping gas is used for carrying of the produced vapor, instead of vacuum as in VMD [33–37]. When it is needed to condense vapor in another place, this configuration can be useful. In this condition, after the water is vaporized and passed through the membrane, vapor is carried by sweeping gas (air or nitrogen). Through this method, the freshwater is produced in condensation place.

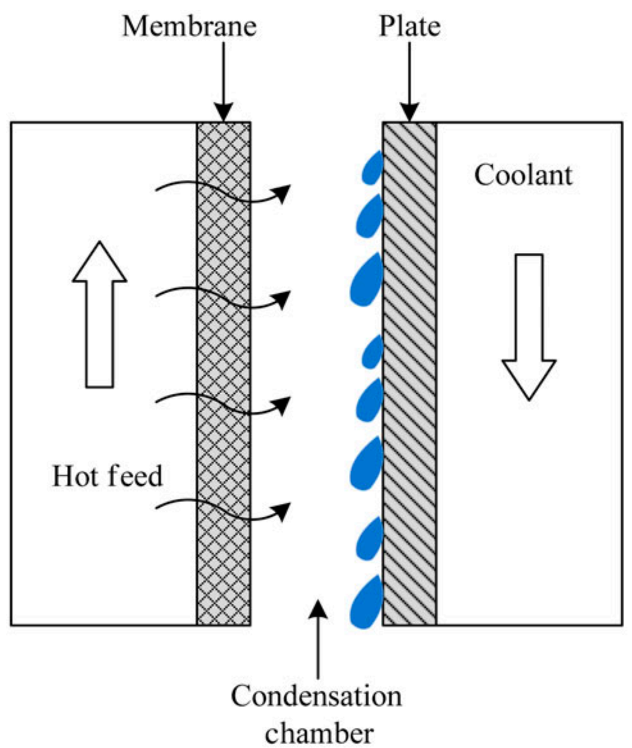

Fig. 6. A scheme for membrane distillation [26].

Some features of the MD method are as follows:

- No pressure is necessary to operate the system
- It could be combined with renewable energy sources
- Operable at low and high temperatures (45–90 °C)
- Suitable for low and normal desalination capacities

1.7. Humidification de-humidification

The humidification de-humidification (HDH) process is based on the fact that air can carry big quantities of water vapor. The vapor-carrying capability of air increases with temperature: 1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature rises from 30 to 80 °C. When the salt water is exposed to the flowing air, a certain quantity of vapor is extracted by air, which provokes cooling. Distilled water, on the other hand, may be recovered by bringing the humid air in contact with a cold surface, which causes the condensation of part of the vapor in the air [38]. Generally, the condensation occurs in a heat exchanger where the salt water is preheated by the latent heat of condensation. An external heat source is therefore necessary to compensate heat loss. A scheme for HDH system is illustrated in Fig. 7.

The HDH technique is especially suited for sea water desalination in arid region when the demand for water is decentralized [40,41]. Solar desalination based on the HDH cycle presents the best method of solar desalination due to overall high energy efficiency [42]. The advantages of this technique are:

- Flexibility in capacity (low, normal and high)
- Flexibility in arrangement
- Moderate insulation
- Moderate operating cost
- Using low-grade thermal energy such as solar and geothermal
- High performance ratio (GOR up to 16.7) [43]
- Low corrosion of the facilities
- High ability for combination with other methods
- Ability for operation in one or several stages

The HDH systems are classified under three main broad categories [44–49] (Fig. 8). Operating conditions relate to the category of the system while the operating temperature is usually between 50 and 90˚C. Water close loop or air close loop can increase the internal energy recovery and decrease the total energy consumption.

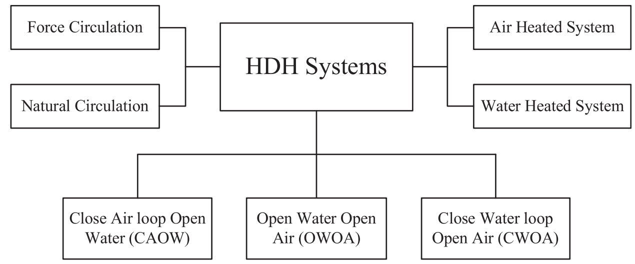

Fig. 8. HDH classification.

1.8. Dew-vaporation

This method is similar to HDH process but in this process, the evaporator and condenser are the same. Here, a flat plate gets energy from produced vapor and transfers it to the sea water in order to vaporize part of the water. An increase in the plate condensation can increase the internal energy recovery. The mechanism in this process is same as that of the HDH process [50]. A scheme for this process is illustrated in Fig. 9.

Some of the important features of this process are:

- Usable for low desalination capacity
- Moderate insulation
- Moderate operating cost
- Using low-grade thermal energy such as solar and geothermal
- Less mass transfer surface in comparison with HDH
- Less space occupation in comparison with HDH
- GOR: up to 11 (in multi-stage systems) [52]

The thermal desalination methods are summarized in Table 1.

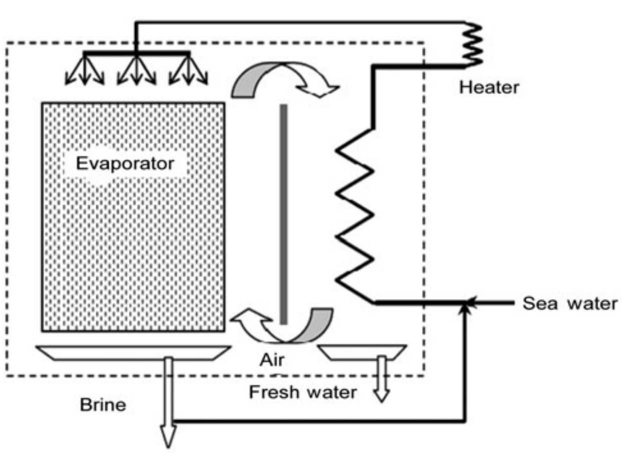

Fig. 7. A HDH desalination apparatus [39].

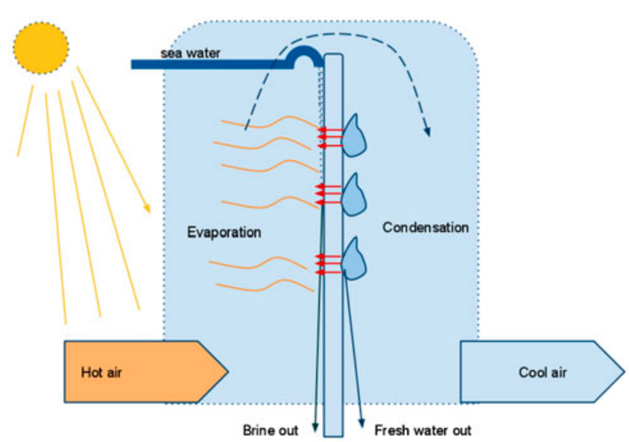

Fig. 9. A scheme for Dew-vaporation desalination [51].

Table 1
Thermal desalination summary

Method	GOR	Capacity	Operating temperature
Boiling	< 1	Not applicable	About 100˚C
MSF	8–14	Normal & high	40–90˚C
MED	9–18	Normal & high	40–90˚C
VC	12–14	Low	About 100˚C
MD	–	Low & normal	45–90˚C
HDH	Up to 16.7	Low & normal	50–90˚C
Dew-vaporation	Up to 11	Low	50–90˚C

2. Crystallization desalination methods

When water molecules become crystallized, the ice crystals formed are salt free. During this process, dissolved salt is excluded. This concept is applied in desalination process to remove salt from water and make it freshwater. There are two main desalination processes based on crystallization: freezing and hydration.

2.1. Freezing

During the process of freezing, the dissolved salt is excluded during the formation of ice crystals. Under controlled conditions, the sea water can be desalinated by freezing to form the ice crystals. Before the entire mass of water is frozen, the mixture is washed and rinsed to remove the salts in the remaining water or adhering to the ice. The ice is then melted down to produce freshwater. Therefore, the freezing process consists of cooling the sea water feed, partial crystallization of ice, separation of ice from sea water, melting of ice, refrigeration, and heat rejection [14]. There are two main processes for freezing desalination: vacuum freezing desalination (VFD) and secondary refrigerant fluid (SRF).

2.1.1. Vacuum freezing desalination

In this method, cooled saline water is sprayed into a vacuum chamber (4 mbara); some of the water flashes off as vapor removing more heat from water and causing ice to form. The ice floats on the brine and is washed with freshwater, melted and the freshwater which is less dense than the brine flows out of the washer-melter (Fig. 10). Theoretically, freezing desalination has a lower energy requirement than other thermal processes but a few small freezing plants were built in the last 40 years and this process is not commercially developed [53].

2.1.2. Secondary refrigerant fluid

In this type of freezing desalination, a liquid hydrocarbon refrigerant such as propane or butane is vaporized in direct contact with the saline water (refrigerant temperature is related to the type of

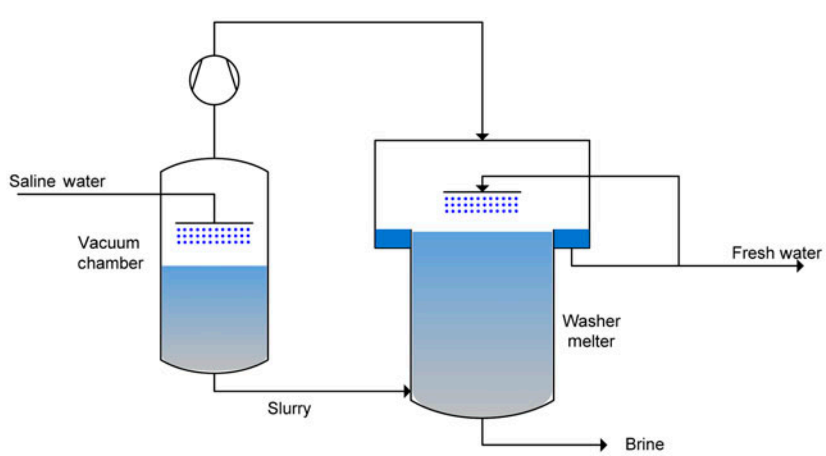

Fig. 10. A scheme for VFD desalination.

refrigerant); thus, slurry of ice is produced in brine. The vaporized refrigerant is compressed and after cooling is recycled to the freezer chamber. The slurry of ice is taken off, washed, and transferred to the melter where freshwater is produced. The advantage of SRF method is its low susceptibility to scaling and corrosion. A scheme for this method is shown in Fig. 11.

Some important features of the freezing desalination process are mentioned as follows:

- Lower theoretical energy consumption
- Minimal potential corrosion
- Little scaling or precipitation
- Hardship for producing vacuum (for VFD)
- Handling the ice and water mixtures which are mechanically complicated to move and process

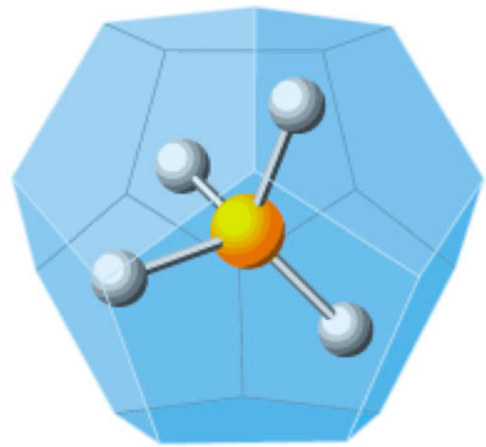

Fig. 12. A hydrate crystal [54].

2.2. Hydration

In this process, the saline water is mixed with a hydrocarbon which forms hydrates or clathrates. In a hydrate, a hydrocarbon molecule is enclosed in a molecular cage of water molecules forming a solid ice-like phase as shown in Fig. 12. The cage or hydrate forms ice-like crystals which contain none of the salts present in the sea water in which the hydrate forms; in the next stage, the hydrocarbon shall be removed from water and freshwater is produced [54].

This technology is still under development but when applicable at larger scale, it could be a cheap alternative to the traditional thermal and membrane desalination processes. A scheme for hydration desalination process which is proposed by Javanmardi and Moshfeghian is shown in Fig. 13. They showed that the investment and operating cost for this process are more than other conventional methods such as MSF and RO [55].

There are some methods for water deionization in crystallization category such as fluidized bed crystallization [56]; but these methods are widely used for removing of water hardness not for salt (specially Na^+ and Cl^-) removal.

3. Membrane desalination methods

In this category, the main element for salt separation from water is membrane. There are four

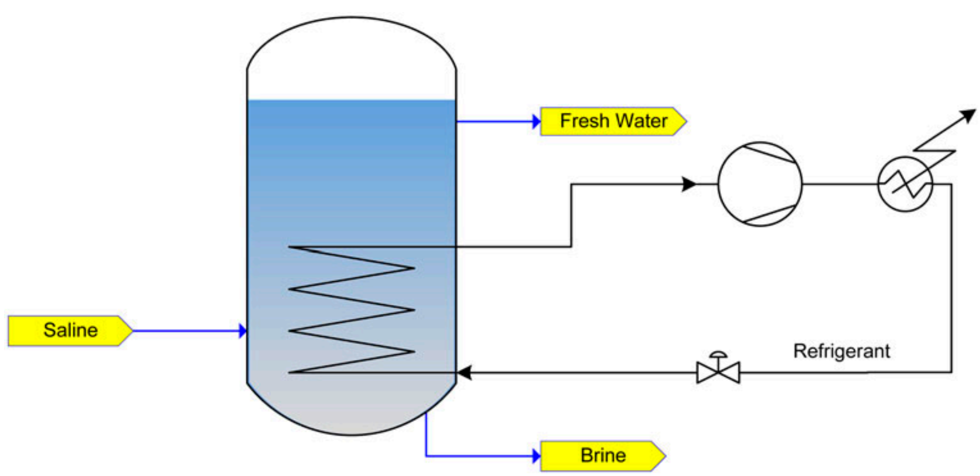

Fig. 11. SRF desalination.

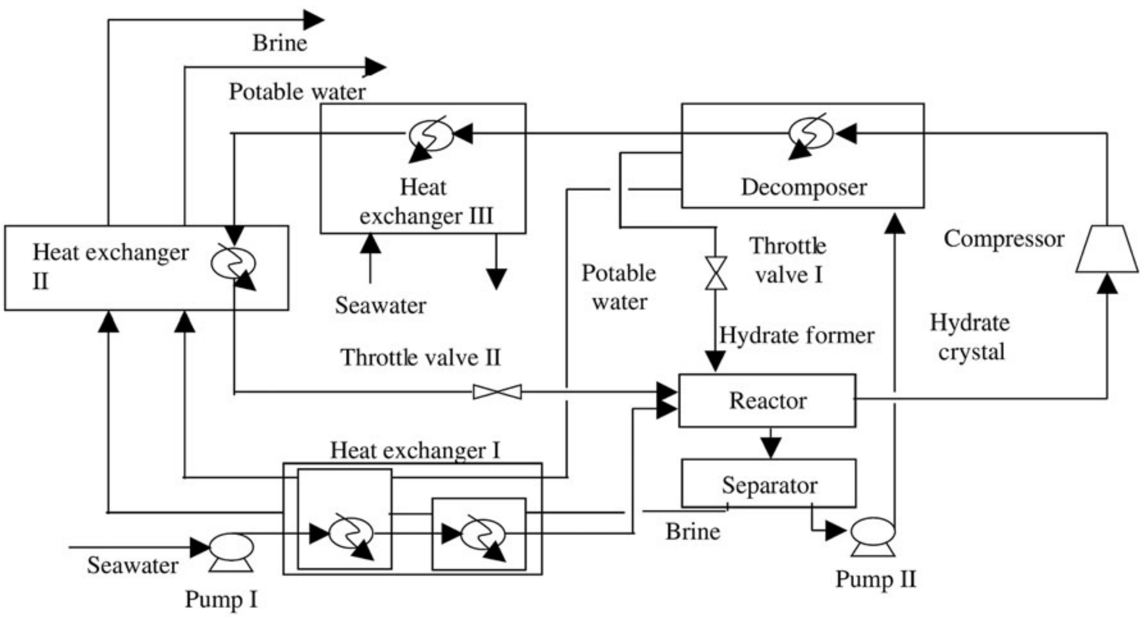

Fig. 13. A scheme for hydration desalination process [55].

methods for membrane desalination: RO, FO, ED, and microbial cell.

3.1. Reverse osmosis

Reverse osmosis (RO) is the main technology applied in membrane desalination. The RO process is based on separation rather than distillation, although MD can be performed. This method contains 80% of membrane desalination methods [3].

In this process, the osmotic pressure is overcome by applying an external pressure higher than the osmotic pressure on the sea water; thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind the membrane with an increase in salt concentration. No heating or phase separation change is necessary. The major part of energy required for desalting is for pressurizing the sea water feed. In this process, a great amount of energy is consumed for pumping (because of high pressure gradient). The typical operation cost in a RO process is illustrated in Fig. 14.

A typical large sea water RO plant consists of four major components: feed water pretreatment, high pressure pumping, membrane separation, and permeate post-treatment [58]. Major design considerations for sea water RO plants are the flux, conversion

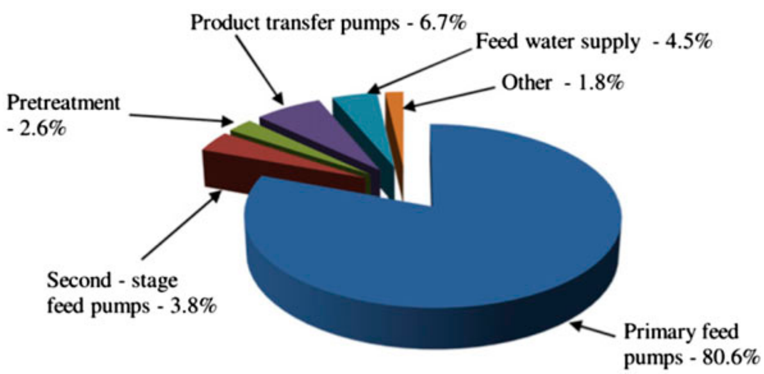

Fig. 14. Operation cost in a RO desalination process [57].

or recovery ratio, permeate salinity, membrane life, power consumption, and feed water temperature.

Some of the RO process features are [59–63]:

- Recovery rate: up to 60%
- 2–5 kWh/m^3 power consumption
- Need to high pretreatment area
- High fixed capital investment (in Middle East)
- May fouling or concentration polarization
- Using high feed pressure for separation
- Applicable for low salt concentration
- High salt rejection

3.2. Forward osmosis

Forward osmosis (FO) is a membrane-based separation process, like RO, which relies on the semi-permeable character of a membrane in salt removal. However, unlike RO, the driving force here for separation is osmotic pressure, not hydraulic pressure. By using a concentrated solution of high osmotic pressure called the draw solution, water can be induced to flow from saline water across the membrane, rejecting the salt. The (now diluted) draw solution must be re-concentrated, yielding potable water and recycling the draw solute [64]. The general process diagram is illustrated in Fig. 15.

Since the recovery or utility of the draw solute is critical in successful implementation of the FO process, depending on the intended use of the desalinated water, various draw solutes may be used. Some current versions of FO use an edible solute, such as concentrated glucose or ammonium salts. These salts (a mixture of ammonium bicarbonate, ammonium carbonate, and ammonium carbamate) are formed when ammonia and carbon dioxide gasses are mixed in an aqueous solution. The salt is rejected by the semi-permeable membrane used in FO and is highly soluble, leading to the reliable generation of high osmotic pressures.

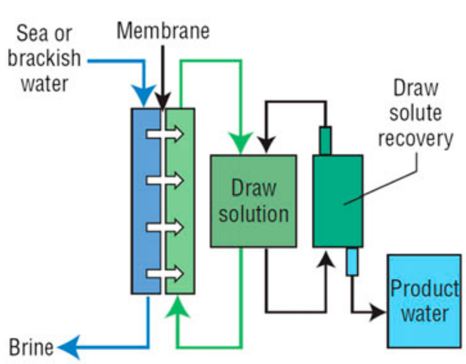

Fig. 15. A scheme for FO desalination process [64].

Once the concentrated draw solution is applied in separating water from the saline feed source, the subsequent diluted draw solution may be treated thermally to remove its ammonium salt solutes, producing freshwater as the primary product of the FO process. This thermal separation of draw solutes is based on the useful characteristic of these salts to decompose into ammonia and carbon dioxide gasses when the solution is heated. The temperature at which this occurs depends on the pressure of the solution [65].

FO has two main advantages in comparison with RO: more desalination flux [64,66] and less pumping energy consumption [67]. These advantages are presented in Figs. 16 and 17.

Some important features of FO desalination process are:

- Usable for low and moderate salt content
- High desalination flux in comparison with RO

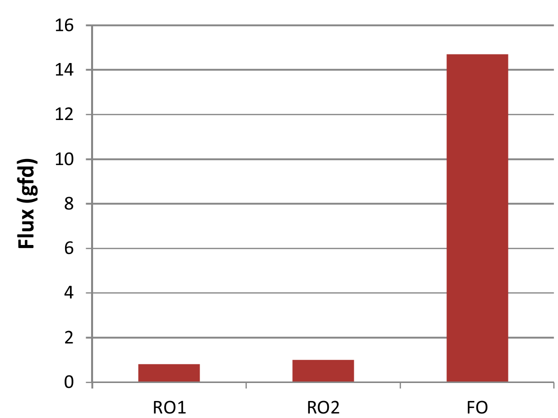

Fig. 16. Flux comparison between FO and RO [66].

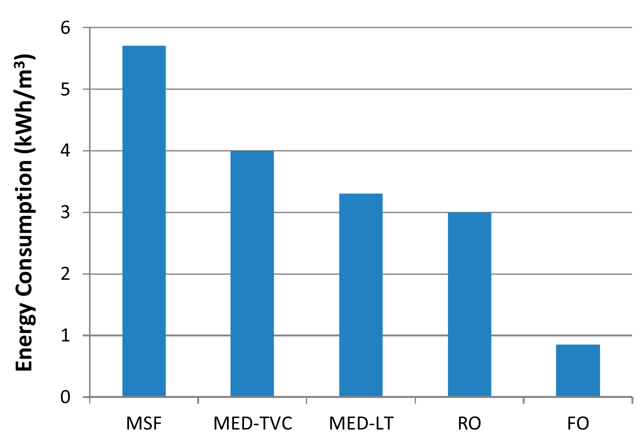

Fig. 17. Energy consumption comparison between FO and other process [67].

- Low energy consumption in comparison with RO (less than 1 kWh/m^3)
- Using osmosis pressure, not hydraulic pressure for separation
- Higher fixed capital investment in comparison with RO
- May fouling or concentration polarization (lesser than RO)

3.3. Electro-dialysis

In an electro-dialysis (ED) system, the anionic and cationic membranes are formed into a multi-cell arrangement built based on the plate-and-frame principle to form up to 100 cell pairs in a stack. The cation and anion exchange membranes are arranged in an alternating pattern between the anode and cathode. Each set of anion and cation membranes forms a cell pair as shown in Fig. 18. Salt solution is pumped through the cells while an electrical potential is maintained across the electrodes. The positively charged cations in the solution migrate toward the cathode and the negatively charged anions migrate toward the anode. Cations pass through the negatively charged cation exchange membrane but are retained by the positively charged anion exchange membrane. Similarly, anions pass through the anion exchange membrane but are retained by the cation exchange membrane. The outcome of this process is that one cell of the pair becomes depleted of ions while the next cell becomes enriched in ions [68]. This process is widely used to remove dissolved ions from water specially Na^+ and Cl^-.

Brackish water desalination is the vastest application of ED. The competitive technologies apply ion exchange for very dilute saline solutions, below 500 ppm [69]. In the 500–2000 ppm range, ED is often a low-cost process. One advantage of ED applied to brackish water desalination is that a big portion, about 80–95%, of the brackish feed is recovered as product water. However, these high recoveries mean that the concentration of brine stream is 5–20 times more than the feed [70].

3.4. Microbial cell

Current water desalination techniques are energy intensive and some of them operate at high pressures. One of the newest desalination methods which operate without energy or high pressure is microbial cell. A microbial fuel cell is modified by placing two membranes between the anode and cathode, creating a middle chamber. An anion exchange membrane is placed next to the anode, and a cation exchange

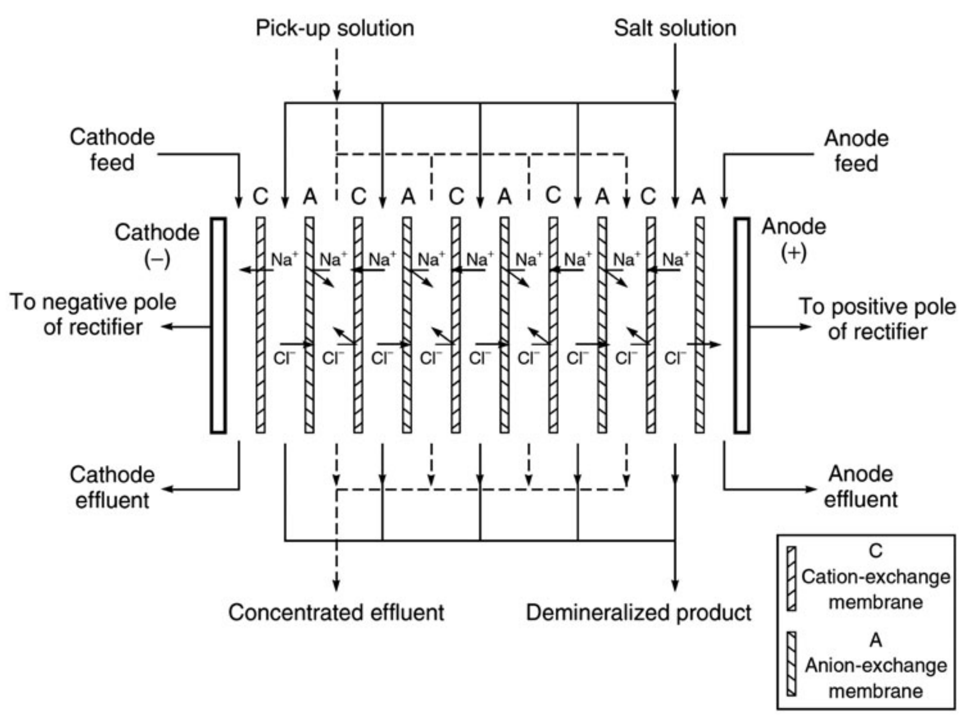

Fig. 18. A scheme for ED desalination method [68].

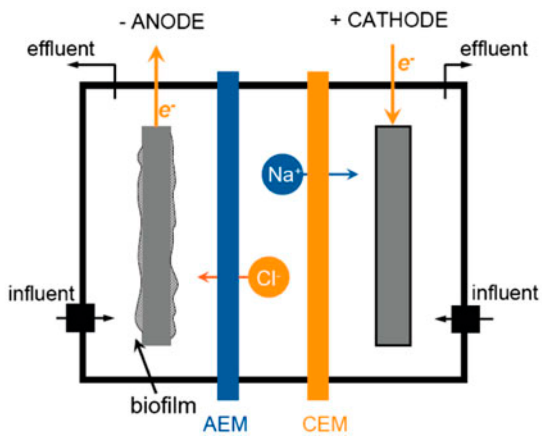

Fig. 19. A scheme for microbial cell desalination [72].

membrane is positioned next to the cathode as shown in Fig. 19. When electrical current is produced by bacteria on the anode, ionic species in the middle chamber are transferred into the two electrode chambers, desalinating the water in the middle chamber [71–75].

Some important features of microbial cell process are mentioned as follows:

- Usable as one to several pair of membrane modules
- No need for electrical energy
- Producing electrical energy during the process
- Applicable for low-capacity plants
- Having 90% salt rejection

This technology is still under development.

It should be mentioned that usually all membrane desalination methods operate at ambient temperature.

4. Other desalination methods

Some processes are developed to desalinate sea water which have not reached the level of commercial success that MSF, MED, and RO have and they are not included in the previous three categories. There are three important methods which are not put in the previous three categories: Air Dehydration, Ion Exchange, and Hybrid.

4.1. Air dehydration

This method is usually used in humid area; in this process, the humid air enters into the system and the air moisture is extracted from the air as desalinated water. These processors are machines that extract water molecules from the atmospheric air, ultimately causing a phase change from vapor to liquid. Three classes of machines are proposed which cool a surface below the dew point of the ambient air, concentrate water vapor through use of solid or liquid desiccants, or induce and control convection in a tower structure. Patented devices vary in scale and potable water output from small units suitable for one person's daily needs to structures as big as multi-story office buildings in coastal region and humid region [76]. This process is not commercialized yet and is only used for small capacity plants with a high operating cost.

4.2. Ion exchange

The ion exchange technologies are often used for water softening among other applications. The ion exchange system can best be described as the interchange of ions between a solid phase and a liquid phase that surrounds the solid. Chemical resins (solid phase) are designed to exchange their ions with liquid phase (feed water) ions, which purify the water. Resins can be made of naturally occurring inorganic materials (such as zeolites) or synthetic materials. Modern ion exchange materials are prepared from synthetic polymers customized for different applications. Ion exchange technologies applied to desalination are rather complex. In brief, saltwater (feed water) is passed through the resin beads where salt ions from the saltwater are replaced for other ions. No heat is required for this process, it operates at ambient temperature. The process removes Na^+ and Cl^- ions from feed water, thus producing potable water. Ion exchange can be applied in combination with RO process such as blending water treated by ion exchange with RO product potable water to increase water production [77].

Ion exchange technology demonstrates significant advantages in removing boron in a desalination application. Due to its high selectivity, ion exchange resin performance is not influenced by operating conditions

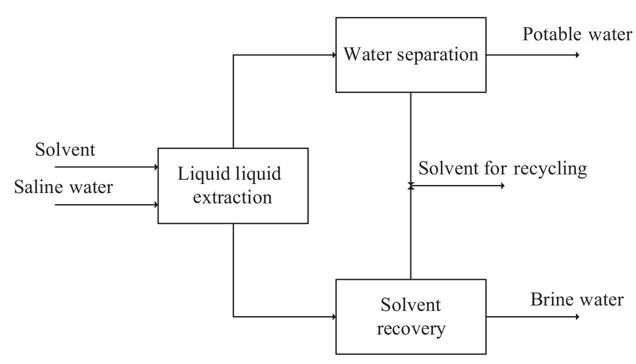

Fig. 20. Solvent extraction desalination schematic [80].

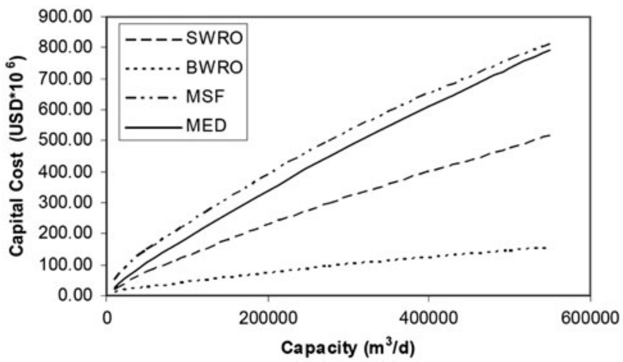

Fig. 21. A typical capital cost for desalination plants [88].

such as temperature, pH, or salinity. Its high water yield makes it an ideal technology when retrofitting an existing plant for boron removal, with minimum capacity loss [78].

4.3. Solvent extraction

In this method, a saline solution (e.g. sea water) is brought into contact with a directional solvent (edible oil). The saline solution and solvent are heated before or after contact to enhance the directional dissolution of water into the solvent, thereby producing distinct phases; a first phase containing the solvent and water from the saline solution and a second phase containing a highly concentrated residue of the saline solution. The first phase is extracted from the second. Alternatively, the second phase can be extracted from the first phase. After extraction, the first phase is cooled to precipitate the water from the solvent and the precipitated water is removed from the solvent. The extracted water can be in the form of substantially pure water (e.g. suitable for industrial or agricultural use or even meeting drinking water standards of purity, such as 99.95% purity) [79]. A scheme of solvent extraction desalination method is illustrated in Fig. 20.

This method can use low-quality heat, generated from terrestrial heat sources, the ocean, the sun, or as waste heat from other processes. These desalination methods can also be easily applied and can offer significant energy and economic savings in comparison with present desalination methods.

4.4. Hybrid systems

Desalination plants require significant amounts of energy in the form of heat and/or electricity. So,

Table 2
Economic Parameters for MSF, MED, and RO [2,12–14,43,52,67,88,89]

	Capacity (m^3/d)	UPC (US\$/m^3)	GOR (kg/kg)	UPE (kWh/m^3)	Reference
SWRO	10,000	0.95	–	5.1–7.45	[88]
	50,000	0.70	–		[88]
	275,000	0.50	–		[88]
	500,000	0.45	–		[88]
BWRO	10,000	0.38	–	2–5	[88]
	50,000	0.25	–		[88]
	275,000	0.16	–		[88]
	500,000	0.14	–		[88]
MSF	10,000	1.97	8–14	5–6	[2,12,67,88]
	50,000	1.23			[2,12,67,88]
	275,000	0.74			[2,12,67,88]
	500,000	0.62			[2,12,67,88]
MED	10,000	1.17	9–18	3–4	[13,14,67,88]
	50,000	0.89			[13,14,67,88]
	275,000	0.67			[13,14,67,88]
	500,000	0.60			[13,14,67,88]
FO	–	–	–	<1	[67]
HDH	–	–	16.7	–	[43]
Solar HDH	–	0.67	–	–	[43]
Dew-vaporation	–	–	11	–	[52]
Solar dew-vaporation	–	0.34	–	–	[43]
VC	–	–	12–14	11–14.56	[89]
ED	–	–	–	2.6–5.5	[89]

hybrid systems which combine the thermal and membrane processes or other utilities are being studied as promising options for improving the economics aspect of the issue [81]. The hybridization of RO and MSF plants is being investigated by many researchers [82]. The hybrid RO-MSF plants have potential advantages of a low power demand, improved water quality, and lower running and maintenance costs compared to stand-alone RO or MSF plants.

In industrial scale, ED-RO hybrid processes are used for high recovery of product water from brackish water without compromising on water quality. In this hybrid process, ED unit is operated in high TDS region (low system resistance and thus high efficiency), and RO system is operated in low TDS region, to reduce salinity load on membrane [83]. In another industrial application for producing demineralized (DM) water, RO and ion exchange methods are combined as a hybrid system. In this system, a high proportion of hardness is removed by RO and other ions are removed by ion exchange system to reach DM water with TDS < 1 [84].

Also hybrid system can include dual-purpose plants. In these plants, two or three systems are usually combined with each other to increase energy efficiency of the system as a whole, for example combination of MSF or RO desalination system with nuclear plant to absorb heat loss and increase energy efficiency [85]. Combination of a HDH system and an air conditioning unit or a HDH system and a cooling tower can increase water production rate and decrease energy consumption for the combined system [86]. A combination of Ro and power plant can increase fuel efficiency up to 70% [87].

5. Conclusion

In this article, the technologies mainly used in sea water desalination industry are presented together with a review of technologies applicable in sea water desalination systems erected in various parts of the world. The most important parameter in the design of each plant is the energy consumption or operating cost. In desalination system, this parameter is mentioned as PR, GOR, unit energy consumption (kWh/m^3), or unit operating cost ($/$m^3$). All of these parameters are applied to obtain the performance of a desalination system; for example, GOR or PR is usually applied in thermal methods and unit energy consumption is applied in membrane methods.

The typical capital cost and energy comparison between the most applicable desalination methods (MSF, MED, RO, etc.) are illustrated in Fig. 21 and Table 2.

Here, it could be suggested that the FO desalination method [especially because of high flux and low power consumption (according to Figs. 16 and 17)] is the best choice in this category and could be developed in future years.

References

[1] Committee on Advancing Desalination Technology, Desalination: A National Perspective, The National Academies Press, Washington, DC, 2008.

[2] H.T. El-Dessouky, H.M. Ettouney, Y. Al-Roumi, Multi-stage flash desalination: Present and future outlook, Chem. Eng. J. 73 (1999) 173–190.

[3] F.F. Alshareff, Investment Opportunities in the Desalination Sector of the Kingdom of Saudi Arabia Resulting from Privatization and Restructuring, Saudi Water and Power Forum, Jeddah, 2008.

[4] M. Abduljawad, U. Ezzeghni, Optimization of tajoura MSF desalination plant, Desalination 254 (2010) 23–28.

[5] H. Al-Fulaij, A. Cipollina, H. Ettouney, D. Bogle, Simulation of stability and dynamics of multistage flash desalination, Desalination 281 (2011) 404–412.

[6] M.M. Alhazmy, Multi stage flash desalination plant with brine-feed mixing and cooling, Energy 36 (2011) 5225–5232.

[7] H. Baig, M.A. Antar, S.M. Zubair, Performance evaluation of a once-through multi-stage flash distillation system: Impact of brine heater fouling, Energy Convers. Manage. 52 (2011) 1414–1425.

[8] H. Ettouney, Brine entrainment in multistage flash desalination, Desalination 182 (2005) 87–97.

[9] S.R. Hosseini, M. Amidpour, A. Behbahaninia, Thermoeconomic analysis with reliability consideration of a combined power and multi stage flash desalination plant, Desalination 278 (2011) 424–433.

[10] M. Mazzotti, M. Rosso, A. Beltramini, M. Morbidelli, Dynamic modeling of multistage flash desalination plants, Desalination 127 (2000) 207–218.

[11] Ruhrpumpen brochure, Desalination: Reverse Osmosis, Multi-Stage Flash and Multi-Effect Distillation, Ruhrpumpen Corporation, Witten, 2011.

[12] Y. Junjie, S. Shufeng, W. Jinhua, L. Jiping, Improvement of a multi-stage flash seawater desalination system for cogeneration power plants, Desalination 217 (2007) 191–202.

[13] T.-X. He, L.-J. Yan, Application of alternative energy integration technology in seawater desalination, Desalination 249 (2009) 104–108.

[14] A.D. Khawaji, I.K. Kutubkhanah, J.-M. Wie, Advances in seawater desalination technologies, Desalination 221 (2008) 47–69.

[15] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: A solar desalination case study, Desalination 262 (2010) 11–14.

[16] P. Fernández-Izquierdo, L. García-Rodríguez, D.-C. Alarcón-Padilla, P. Palenzuela, I. Martín-Mateos,

Experimental analysis of a multi-effect distillation unit operated out of nominal conditions, Desalination 284 (2012) 233–237.
[17] H. Raach, J. Mitrovic, Simulation of heat and mass transfer in a multi-effect distillation plant for seawater desalination, Desalination 204 (2007) 416–422.
[18] H. Sayyaadi, A. Saffari, Thermoeconomic optimization of multi effect distillation desalination systems, Appl. Energy 87 (2010) 1122–1133.
[19] H. Sayyaadi, A. Saffari, A. Mahmoodian, Various approaches in optimization of multi effects distillation desalination systems using a hybrid meta-heuristic optimization tool, Desalination 254 (2010) 138–148.
[20] M.A. Sharaf, A.S. Nafey, L. García-Rodríguez, Exergy and thermo-economic analyses of a combined solar organic cycle with multi effect distillation (MED) desalination process, Desalination 272 (2011) 135–147.
[21] C. Sommariva, H. Hogg, K. Callister, Environmental impact of seawater desalination: Relations between improvement in efficiency and environmental impact, Desalination 167 (2004) 439–444.
[22] D. Zhao, J. Xue, S. Li, H. Sun, Q.-D. Zhang, Theoretical analyses of thermal and economical aspects of multi-effect distillation desalination dealing with high-salinity wastewater, Desalination 273 (2011) 292–298.
[23] A. Porteous, Desalination Technology, Applied Science Publishers, London, 1983.
[24] D. Zejli, A. Ouammi, R. Sacile, H. Dagdougui, A. Elmidaoui, An optimization model for a mechanical vapor compression desalination plant driven by a wind/PV hybrid system, Appl. Energy 88 (2011) 4042–4054.
[25] A.M. Alklaibi, N. Lior, Membrane-distillation desalination: Status and potential, Desalination 171 (2004) 111–131.
[26] C. Charcosset, A review of membrane processes and renewable energies for desalination, Desalination 245 (2009) 214–231.
[27] K.W. Lawson, D.R. Lloyd, Membrane distillation. II. direct contact MD, J. Membr. Sci. 120 (1996) 123–133.
[28] L. Martínez, F.J. Florido-Díaz, Theoretical and experimental studies on desalination using membrane distillation, Desalination 139 (2001) 373–379.
[29] J. Phattaranawik, R. Jiraratananon, Direct contact membrane distillation: Effect of mass transfer on heat transfer, J. Membr. Sci. 188 (2001) 137–143.
[30] S. Bandini, C. Gostoli, G.C. Sarti, Separation efficiency in vacuum membrane distillation, J. Membr. Sci. 73 (1992) 217–229.
[31] G.C. Sarti, C. Gostoli, S. Bandini, Extraction of organic components from aqueous streams by vacuum membrane distillation, J. Membr. Sci. 80 (1993) 21–33.
[32] A.S. Jönsson, R. Wimmerstedt, A.C. Harrysson, Membrane distillation—A theoretical study of evaporation through microporous membranes, Desalination 56 (1985) 237–249.
[33] L. Basini, G. D'Angelo, M. Gobbi, G.C. Sarti, C. Gostoli, A desalination process through sweeping gas membrane distillation, Desalination 64 (1987) 245–257.
[34] M.C. García-Payo, C.A. Rivier, I.W. Marison, U.V. von Stockar, Separation of binary mixtures by thermostatic sweeping gas membrane distillation, J. Membr. Sci. 198 (2002) 197–210.
[35] M. Khayet, P. Godino, J.I. Mengual, Theory and experiments on sweeping gas membrane distillation, J. Membr. Sci. 165 (2000) 261–272.
[36] M. Khayet, P. Godino, J.I. Mengual, Nature of flow on sweeping gas membrane distillation, J. Membr. Sci. 170 (2000) 243–255.
[37] C.A. Rivier, M.C. Garcia-Payo, I.W. Marison, U.V. Stocker, Separation of binary mixtures by thermostatic sweeping gas membrane distillation I. theory and simulations, J. Membr. Sci. 201 (2002) 1–16.
[38] K. Bourouni, M.T. Chaibi, L. Tadrist, Water desalination by humidification and dehumidification of air: State of the art, Desalination 137 (2001) 167–176.
[39] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: Review and state-of-the-art, Desalination 203 (2007) 346–365.
[40] A. Eslamimanesh, M.S. Hatamipour, Mathematical modeling of a direct contact humidification–dehumidification desalination process, Desalination 237 (2009) 296–304.
[41] A. Eslamimanesh, M.S. Hatamipour, Economical study of a small-scale direct contact humidification–dehumidification desalination plant, Desalination 250 (2010) 203–207.
[42] S. Parekh, M.M. Farid, J.R. Selman, S. Al-Hallaj, Solar desalination with a humidification–dehumidification technique—A comprehensive technical review, Desalination 160 (2004) 167–186.
[43] S. Al-Hallaj, S. Parekh, M.M. Farid, J.R. Selman, Solar desalination with humidification–dehumidification cycle: Review of economics, Desalination 195 (2006) 169–186.
[44] M. Khedr, Techno-economic investigation of an air humidification–dehumidification desalination process, Chem. Eng. Technol. 16 (1993) 270–274.
[45] H. Ben-Bacha, T. Damak, M. Bouzguenda, Experimental validation of the distillation module of a desalination station using the SMCEC principle, Renewable Energy 28 (2003) 2335–2354.
[46] E. Chafik, A new type of seawater desalination plants using solar energy, Desalination 156 (2003) 333–348.
[47] M. Ben Amara, I. Houcine, A. Guizani, M. Mâalej, Experimental study of a multiple-effect humidification solar desalination technique, Desalination 170 (2004) 209–221.
[48] E. Chafik, Design of plants for solar desalination using the multi-stag heating/humidifying technique, Desalination 168 (2004) 55–71.
[49] G.P. Narayan, M.H. Sharqawy, E.K. Summers, J.H. Lienhard, S.M. Zubair, M.A. Antar, The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production, Renew. Sustainable Energy Rev. 14 (2010) 1187–1201.
[50] J. Beckmann, Method and Apparatus for Simultaneous Heat and Mass Transfer Utilizing a Carrier Gas, patent no. US 6,911,121, 2005.
[51] Wikipedia, Dewvaporation, 2013, Available from: http://en.wikipedia.org/wiki/Dewvaporation.
[52] B.M. Hamieh, J.R. Beckman, Seawater desalination using dewvaporation technique: Theoretical development and design evolution, Desalination 195 (2006) 1–13.

[53] URS Australia, Introduction to Desalination Technologies in Australia, Fisheries and Forestry, Canberra, No. mql, 2637, 2002.
[54] R. Clayton, A review of current knowledge desalination for water supply, Foundation for Water Research, No: FR/R0013, 2011.
[55] J. Javanmardi, M. Moshfeghian, Energy consumption and economic evaluation of water desalination by hydrate phenomenon, Appl. Therm. Eng. 23 (2003) 845–857.
[56] R. Segev, D. Hasson, R. Semiat, Improved high recovery brackish water desalination process based on fluidized bed air stripping, Desalination 281 (2011) 75–79.
[57] A. Subramani, M. Badruzzaman, J. Oppenheimer, J.G. Jacangelo, Energy minimization strategies and renewable energy utilization for desalination: A review, Water Res. 45 (2011) 1907–1920.
[58] M.B. Baig, A.A. Al Kutbi, Design features of a 20 migd SWRO desalination plant, Al Jubail, Saudi Arabia, Desalination 118 (1998) 5–12.
[59] M. Kihara, H. Yamamura, S. Jinno, M. Kurihara. Operation and reliability of very high recovery seawater desalination technologies by brine conversion two stage RO desalination system, Proceedings of the IDA World Congress on Desalination and Water Reuse, Manama, 2002.
[60] I. Moch. A 21st century study of global seawater reverse osmosis operating and capital costs, Proceedings of the IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, 2002.
[61] J.M. Rovel. Current and future trends in SWRO, Proceedings of the IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, 2002.
[62] A.B. Hamida, I. Moch, Controlling biological fouling in open sea intake RO plants without continuous chlorination, Desalin. Water Reuse 6 (1996) 40–45.
[63] M.G. Khedr, Membrane fouling problems in reverse osmosis desalination applications, Desalin. Water Reuse 10 (2000) 8–17.
[64] T.Y. Cath, A.E. Childress, M. Elimelech, Forward osmosis: Principles, applications, and recent developments, J. Membr. Sci. 281 (2006) 70–87.
[65] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, A novel ammonia—Carbon dioxide forward (direct) osmosis desalination process, Desalination 174 (2005) 1–11.
[66] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, Desalination by ammonia–carbon dioxide forward osmosis: Influence of draw and feed solution concentrations on process performance, J. Membr. Sci. 278 (2006) 114–123.
[67] R.L. McGinnis, M. Elimelech, Energy requirements of ammonia–carbon dioxide forward osmosis desalination, Desalination 207 (2007) 370–382.
[68] R.W. Baker, Membrane Technology and Applications, 2nd ed., Wiley, Menlo Park, CA, 2004.
[69] M.P. Grotheer, Electrochemical processing (inorganic), in: J.I. Kroschwitz, A. Seidel (Eds.), Kirk Othmer Encyclopedia of Chemical Technology, Wiley Interscience, New York, NY, 1992.
[70] M. Hamada, Brackish water desalination by electrodialysis, Desalin. Water Reuse 2 (1992) 8–20.
[71] P. Clauwaert, P. Aelterman, T. Pham, L. De Schamphelaire, M. Carballa, K. Rabaey, W. Verstraete, Minimizing losses in bio-electrochemical systems: The road to applications, Appl. Microbiol. Biotechnol. 79 (2008) 901–913.
[72] X. Cao, X. Huang, P. Liang, K. Xiao, Y. Zhou, X. Zhang, B.E. Logan, A new method for water desalination using microbial desalination cells, Environ. Sci. Technol. 43 (2009) 7148–7152.
[73] S. Cheng, D. Xing, D.F. Call, B.E. Logan, Direct biological conversion of electrical current into methane by electromethanogenesis, Environ. Sci. Technol. 43 (2009) 3953–3958.
[74] B.E. Logan, D. Call, S. Cheng, H.V.M. Hamelers, T.H.J.A. Sleutels, A.W. Jeremiasse, R. Rozendal, Microbial electrolysis cells for high yield hydrogen gas production from organic matter, Environ. Sci. Technol. 42 (2008) 8630–8640.
[75] B.E. Logan, J.M. Regan, Microbial Fuel Cells—Challenges and Applications, Environ. Sci. Technol. 40 (2006) 5172–5180.
[76] R.V. Wahlgren, Atmospheric water vapour processor designs for potable water production: A review, Water Res. 35 (2001) 1–22.
[77] Y. Tamim, E.T. Kimberly, Overview of desalination techniques, J. Contemp. Water Res. Edu. 132 (2005) 3–10.
[78] C. Jacob, Seawater desalination: boron removal by ion exchange technology, Desalination 205 (2007) 47–52.
[79] D. Kraemer, B.B. Mikic, A. Bajpayee, G. Chen, J.H. Lienhard, A.J. Muto, Water Desalination Using Directional Solvent Extraction, Massachusetts Institute of Technology, No: 8119007 B2, Cambridge, MA, 2010.
[80] K. Holum, Proceeding of the First International Symposium on Water Desalination, US Department of Interior, Washington, DC, 1965.
[81] M.G. Marcovecchio, S.F. Mussati, P.A. Aguirre, N.J. Nicolás, Optimization of hybrid desalination processes including multi stage flash and reverse osmosis systems, Desalination 182 (2005) 111–122.
[82] Osman A. Hamed, Overview of hybrid desalination systems—Current status and future prospects, Desalination 186 (2005) 207–214.
[83] S. Thampy, G.R. Desale, V.K. Shahi, B.S. Makwana, P.K. Ghosh, Development of hybrid electrodialysis-reverse osmosis domestic desalination unit for high recovery of product water, Desalination 282 (2011) 104–108.
[84] H.A. Abdulgader, V. Kochkodan, N. Hilal, Hybrid ion exchange—Pressure driven membrane processes in water treatment: A review, Sep. Purif. Technol. 116 (2013) 253–264.
[85] I.I. Kutbi, Z.A. Sabri, A.A. Hussein, Selection for desalination processes for dual-purpose nuclear plants, Desalination 58 (1986) 113–134.
[86] H. Marmouch, J. Orfi, S.B. Nasrallah, Effect of a cooling tower on a solar desalination system, Desalination 238 (2009) 281–289.
[87] I. Kamal, Integration of seawater desalination with power generation, Desalination 180 (2005) 217–229.
[88] M.K. Wittholz, B.K. O'Neill, C.B. Colby, D. Lewis, Estimating the cost of desalination plants using a cost database, Desalination 229 (2008) 10–20.
[89] A.-J. Mahmoud, Energy Sources for Coupling with Desalination Plants in the GCC Countries, ESCWA, 2001.