Chapter 16

Desalination of Water

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Abstract

Water is very essential for all living beings. It covers nearly 70% of earth's surface. Even though the major portion of earth is covered by water, there is severe shortage of drinking water in most of the countries across the world. Safe drinking water is vital for all forms of life though it does not provide any calories. Desalination of sea water appears as a solution for this problem. Advanced desalination technologies that are applied to seawater and brackish water prove to be effective alternatives in a variety of situations. This study mainly focuses on upcoming trends in modern desalination technologies and emphasizing the options offered by them. Desalination is a technique where the excess salts are removed from sea water or brackish water converting it into safe potable or usable water. Desalination methods are categorized into thermal processes and membrane processes. In this chapter we discuss about different thermal processes like multistage flash distillation, multiple effect distillation, vapour compression evaporation, cogeneration and solar water desalination. We also discuss about various categories of membrane processes like reverse osmosis, electro dialysis and membrane distillation methods. This chapter also concentrates on advantages and disadvantages and economical parameters involved in each of these methods.

Keywords: desalination, sea water, potable water, desalination techniques

1. Introduction

Water is very essential for life. It is one of the most abundant resources of the earth, covering about 3/4th of earth's surface. Though it covers earth's major portion yet there is severe shortage of potable water in many countries around the world mainly developing countries and middle east region countries. The reason for this situation is that nearly 97.5% of earth's water is salt water present in oceans and remaining 2.5% is fresh water which is in the form of ground water, ice-mountains, lakes and rivers, which serves most human and animal needs [1, 2].

According to UNEP (United Nations Environment Programme) 1/3rd of the world's population lives in countries with insufficient freshwater resources [3]. Hence enormous efforts are required to make new water resources available and minimize water deficiency in countries with shortage of fresh water [4]. World Health Organization guidelines state that the permissible limits of salinity in drinking water are 500 ppm and in few cases it may extend up to 1000 ppm [5]. Most of the water on earth has salinity ranging upto 10,000 ppm and for sea water it may be in the range of 35,000–45,000 ppm due to its dissolved salts [6].

For every 20 years, the consumption rate of water is doubling exceeding by two times the rate of population growth. The potable water resources are on the decline and water demand is high. In recent times various industrial and developmental activities have resulted in increasing pollution and deteriorating the quality of water. Thus water shortages and unreliable quality of water are considered to be major hindrances for sustainable development of society.

The existing water resources are decreasing

- Due to unbalanced distribution of rain water and drought
- Extreme exploitation of ground water resources and its un sufficient recharge
- Degradation of water quality due to the discharge of domestic and industrial wastes without sufficient treatment

Since the fresh water resources are very limited to serve the major population needs and salt water is unsuitable for many applications, desalination of salt water (sea water) emerges as a boon to most of the population to serve their needs [6]. This chapter gives detailed information on different desalination techniques used across the world. It also highlights the merits and demerits involved in these processes.

2. Desalination

It can be defined as any process which removes excess salts and minerals from water (or) the chemical process of changing seawater into potable water are called desalination. These processes may be used for municipal, industrial or any commercial uses. In major desalination methods the feed water is treated and two streams of water are obtained

- Treated potable fresh water that has less amounts of salt and minerals(treated water or product water)
- Concentrate or brine that has salt and mineral concentrations higher than that of original feed water or saltwater [7, 8].

Salt water or feed water sources may include sea water, brackish, wells, surface (rivers and streams), wastewater, and industrial feed and process waters. With advancements in technology, desalination processes are becoming cost effective compared to other methods of producing usable water to meet the growing demands. The water that is obtained after desalination should be remineralised to be fit for human consumption. The concentrated brine obtained in desalination process must be disposed of in a proper manner.

3. Desalination technologies

Different desalination processes have been developed, some of them are at present under research and development. The two major technologies that are mainly used for desalination are

- Thermal desalination technology
- Membrane desalination technology

Both the technologies include a number of different processes, a part from these there are alternative technologies like freezing and ion exchange which are not generally used. All these technologies need energy to operate. Conventional energy or renewable energy is generally used in these methods (**Figure 1**).

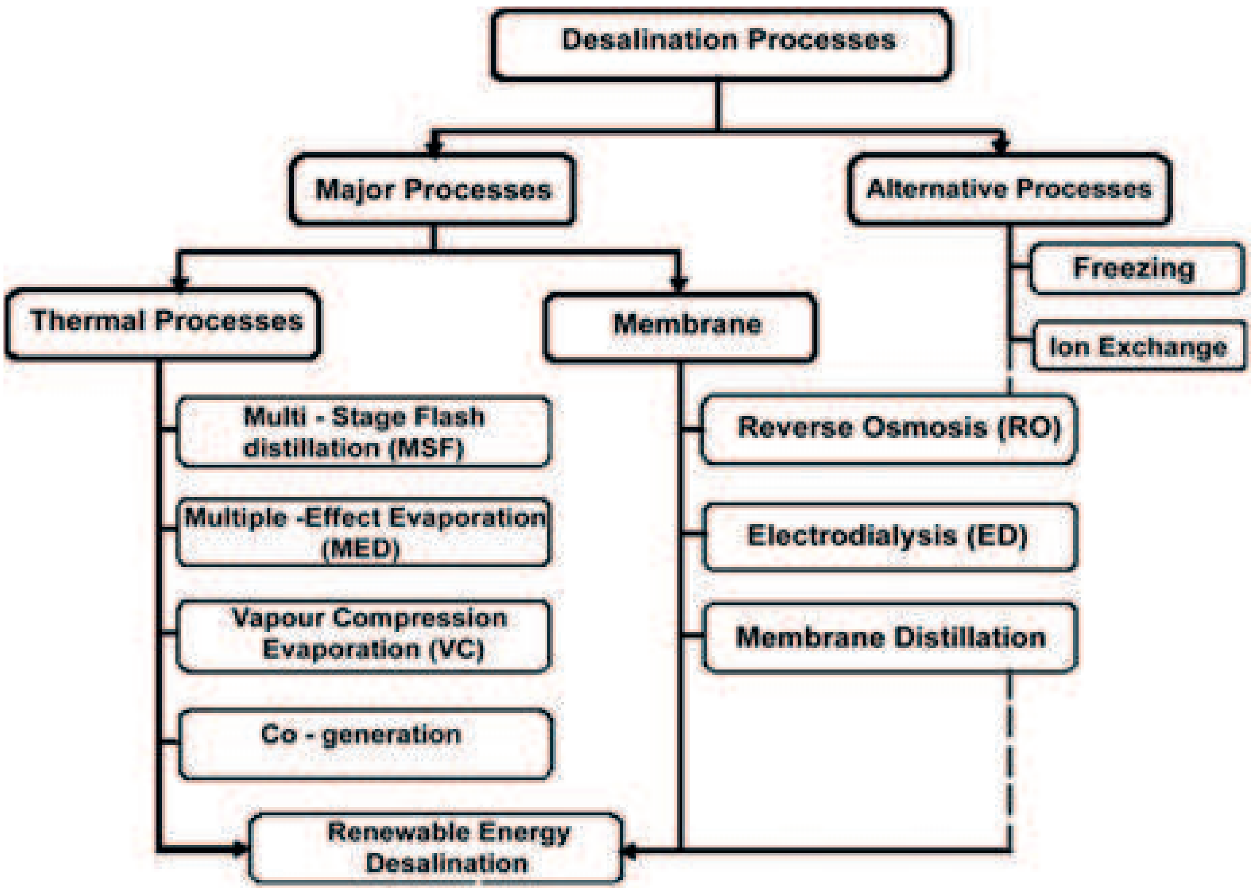

Figure 1. Classification of water desalination processes. Source: [2].

3.1. Thermal desalination processes

It is generally known as distillation. It is one of the most ancient ways of desalinating sea water and converting them to drinking water. This technology is rarely used for desalinating brackish water since it is expensive.

This technology is based on principles of boiling the saline water and evaporating it and then collecting the condensed vapour to obtain pure water. The salt is left behind and the distillate is collected, [9].

The thermal desalination processes are subdivided into the following types

- Multi-stage flash distillation (MSF)
- Multi-effect distillation (MED)
- Vapour compression evaporation (VC)
- Cogeneration
- Solar water desalination

3.1.1. Multi-stage flash distillation (MSF)

Multistage flash distillation process principle involves the distillation through many (multi-stage) chambers (**Figure 2**). Here each successive stage of the plant runs at progressively low pressures. The feed water is initially heated under high pressure and is passed into the first flash chamber. In first flash chamber the pressure is released causing the water to boil rapidly resulting in quick evaporation or flashing. This process continues in each successive stage because the pressure in the next stage is less than the previous stage. The vapour that is

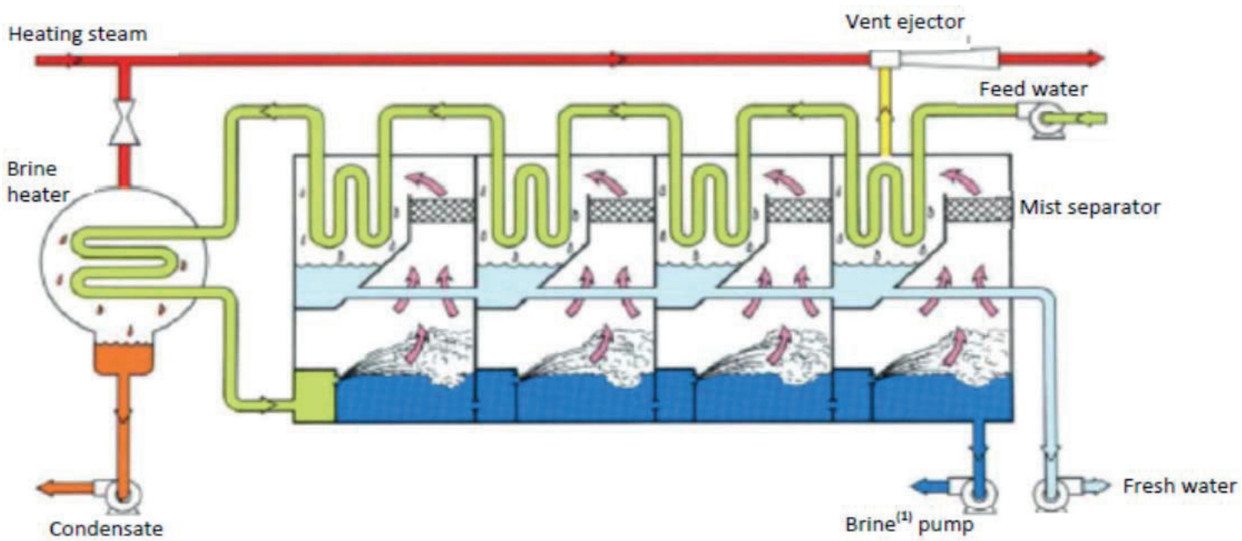

Figure 2. Multi-stage flash distillation. Source: [10].

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produced by flashing is converted into fresh water by condensing it on heat exchanger tubing present in each stage. The tubes are then cooled by incoming cooler feed water.

In the MSF process as shown in Figure, the feed water (saline water) is heated in a vessel known as the brine heater until it reaches a temperature below the saturation boiling temperature.

The heated seawater then flows through a series of vessels, in sequence, where the lower atmospheric pressure causes the water to boil quickly and get vaporized. This sudden introduction of hot water into the reduced-pressure chamber is referred to as the 'flashing effect' because the water nearly flashes into steam [11]. A small percentage of this water is converted into water vapour and this percentage is mainly dependent on the pressure inside the stage. The vapour that is generated by flashing is converted to fresh water by getting condensed on the tubes of heat exchangers (condenser) that pass through each stage. The incoming feed water going to the brine heater cools the tubes. This, in return, heats up the feed water and thus increases the thermal efficiency by reducing the amount of thermal energy required by the brine heater to raise the temperature of the seawater.

Building of MSF distillation plants started in late1950s. Some of these MSF plants can comprise 15–25 stages [12]. These distillation plants can possess either

- Once- through or
- Recycled process
- In once- through design, the feed water or saline water is passed through the heater and flash chambers only once and then it is disposed of
- In recycled design, the feed water used for cooling purpose is also recycled.

All of these processes can be structured as a long tube or cross tube design. In case of long tube design the tubing is parallel to the concentrate flow and in case of cross tube design, the tubing is perpendicular to concentrate flow.

MSF is producing around 64% of the total world desalinated water at present. Though this process is the most reliable source for the production of potable water from seawater, yet it is considered as an energy demanding process that requires both thermal and mechanical energy [12].

MSF plants are prone to corrosion unless stainless steel is used. In addition to corrosion, MSF plants are also subjected to erosion and impingement attack. This erosion is generally caused by the turbulence of the feed water in the flash chamber, when it passes from one stage to another.

3.1.1.1. Advantages and disadvantages of MSF

- MSF plants are relatively simple to construct and easy to operate [11]
- They have no moving parts, other than conventional pumps, and contains only some amount of connection tubing [11]

- The quality of effluent water contains 2–10 ppm of dissolved solids which means a high level of purification. So it is re-mineralized in the post-treatment process to make it palatable and fit for consumption [13].
- Though operating plants at higher temperatures (over 115°C) improves their efficiency but causes scaling problems because the salts such as calcium sulphate precipitate on the tubes surfaces and cause thermal and mechanical problems like tube clogging.
- It is considered as an energy intensive process, which requires both thermal and mechanical energy, but it can be overcome by the cogeneration system.
- Adding more stages in MSF improves its efficiency and increases water production, but it increases the capital cost and causes operational complexity [14] (**Figure 3**).

3.1.2. Multiple effect distillation

The multi-effect distillation process has been used since the late 1950s and early 1960s. Multi-effect distillation employs the same principles of multi-stage flash distillation but contrary to it, it occurs in a series of vessels (effects) and uses the principles of evaporation and condensation at reduced ambient pressure [17].

In Multi- effect distillation process, a series of evaporator effects produce water at progressively lower pressures. As pressure decreases successively water boils at lower temperatures and the water vapour of the first vessel serves as the heating medium for the second, and so on. The more the vessels or effects, the higher the performance ratio. The water vapour which

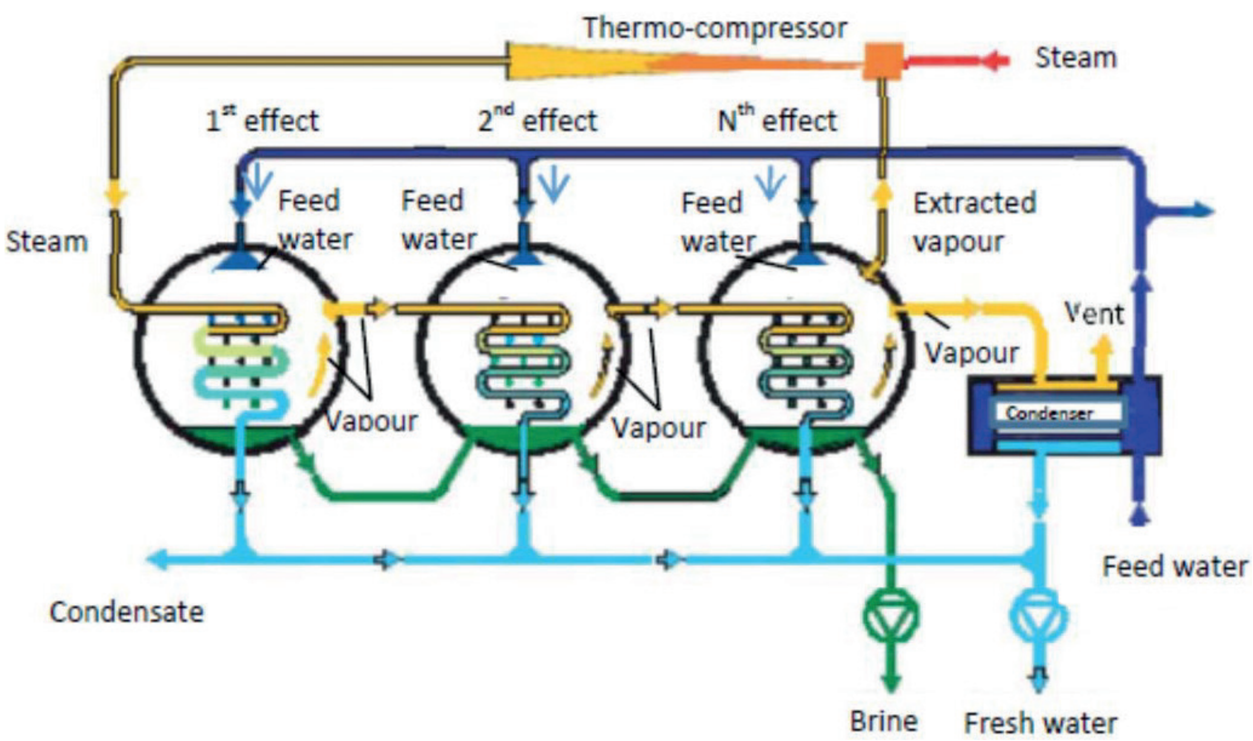

Figure 3. Multiple effect distillation. Sources: [15, 16].

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is formed during boiling of water is condensed and collected. The use of multiple effects makes this process more efficient.

Multi-effect distillation is known to be the oldest large scale distillation method for desalinating sea water. Its major characteristics are high quality distilled water, high unit capacity and high heat efficiency.

3.1.2.1. Advantages and disadvantages of multi-effect distillation

- The multi-effect distillation process is designed to operate at lower temperatures of 70°C. This lessens tube corrosion and the scale formation on the tube surfaces.
- The quality of the feed water is not as important as that in Reverse Osmosis system technology. Hence the cost of pre-treatment and operation of this technology is low.
- The power consumption in this technology is lower than that of the MSF and performance is higher than MSF plants. Hence MED technology can be considered to be cost effective and more efficient than MSF technology in terms of potable water production [11] (**Figure 4**).

3.1.3. Vapour compression evaporation

The vapour compression distillation (VCD) or vapour compression evaporation process is operated individually or used along with other processes like MED and single-effect vapour compression. In this method the heat for evaporating the feed water comes from the compression of vapour and not by the direct exchange of heat from steam produced in a boiler [7].

Two devices are generally used in this process to condense the water vapour to generate adequate heat to evaporate the seawater. Among them one is a mechanical compressor (mechanical vapour compression) and the other a steam jet (thermal vapour compression), Vapour compression (VC) units are built in different configurations. Mechanical compressor is

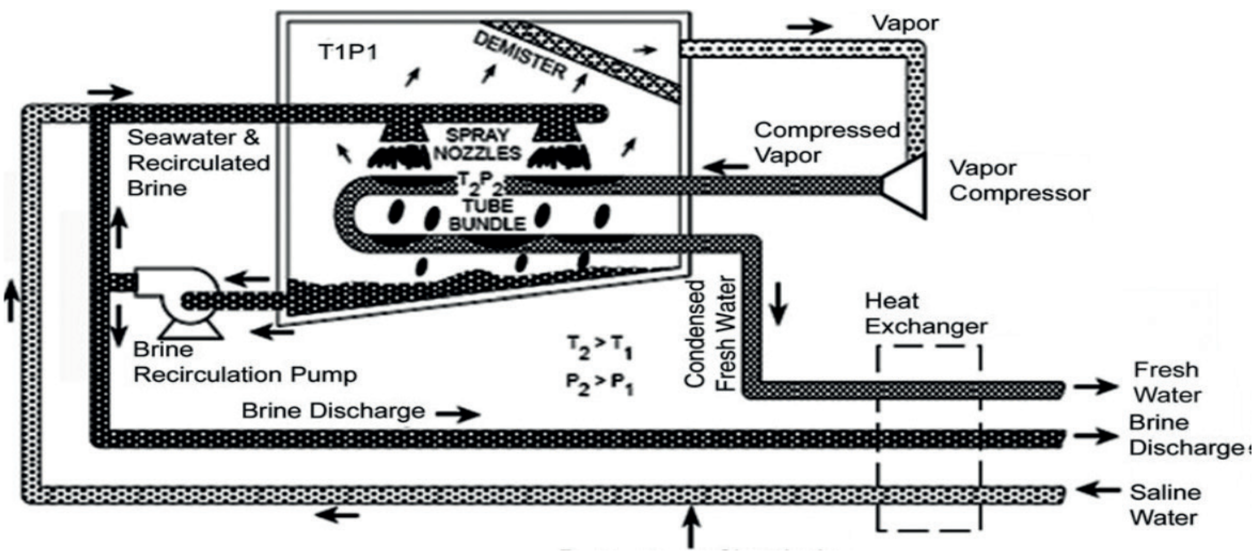

Figure 4. Vapour compression evaporation. Source: [7].

generally used to generate the heat for evaporation and it runs normally by electricity or diesel. This compressor creates vacuum in the evaporator and compresses the vapour obtained from the evaporator, condenses it in a tube bundle.

The feed water is sprayed outside the heated tube bundle. Here the water boils and gets evaporated partially creating more vapour.

In case of steam jet type of vacuum compression distillation, a venture orifice present at the steam jet creates water vapour and extracts it from the water vapour, creating a lower atmospheric temperature. The water vapour that is extracted is compressed by the steam jet and condensed on the tube walls to furnish heat of condensation to evaporate the feed water that is being pumped on the other side in the evaporator.

These units are generally smaller in capacity, and are mostly used at hotels, resorts and in industries.

3.1.3.1. Advantages and disadvantages of vapour compression evaporation

- This method is simple and reliable and hence it can be considered as a better option for small-scale desalination units. They usually have a capacity of 3000 m3/day and are generally used for resorts, industries and drilling sites where fresh water is in shortage.
- The operating temperature of VC distillation or evaporation is low which makes it a simple and efficient process in terms of power consumption.
- Since the operating temperatures are low (below 70°C), the potential for scale formation and tube corrosion is reduced.

3.1.4. Solar desalination

Solar desalination method is generally used for small-scale operations (**Figure 5**). Though the designs of these units are different, but the basic principle is the same. Here the sun provides heat energy to evaporate freshwater from salt water. In solar distillation process, the water vapour generated from the evaporation process condenses on a clear glass or plastic covering and then it is collected as freshwater in a condensate trough. The covering is used for dual purposes one to transmit radiant energy and second to allow water vapour to condense on its interior surface. The salt that is left behind and un-evaporated water present in the still basin must be disposed of appropriately [17].

Solar distillation is mostly used in arid regions where safe freshwater is not available. Solar distillation units produce varying amounts of freshwater, basing on their design and geographic location.

3.1.5. Cogeneration system for power and water desalination

There is a possibility to use energy for dual purpose or cogeneration systems in which the energy sources can perform various different functions such as electric power generation and desalination of water.

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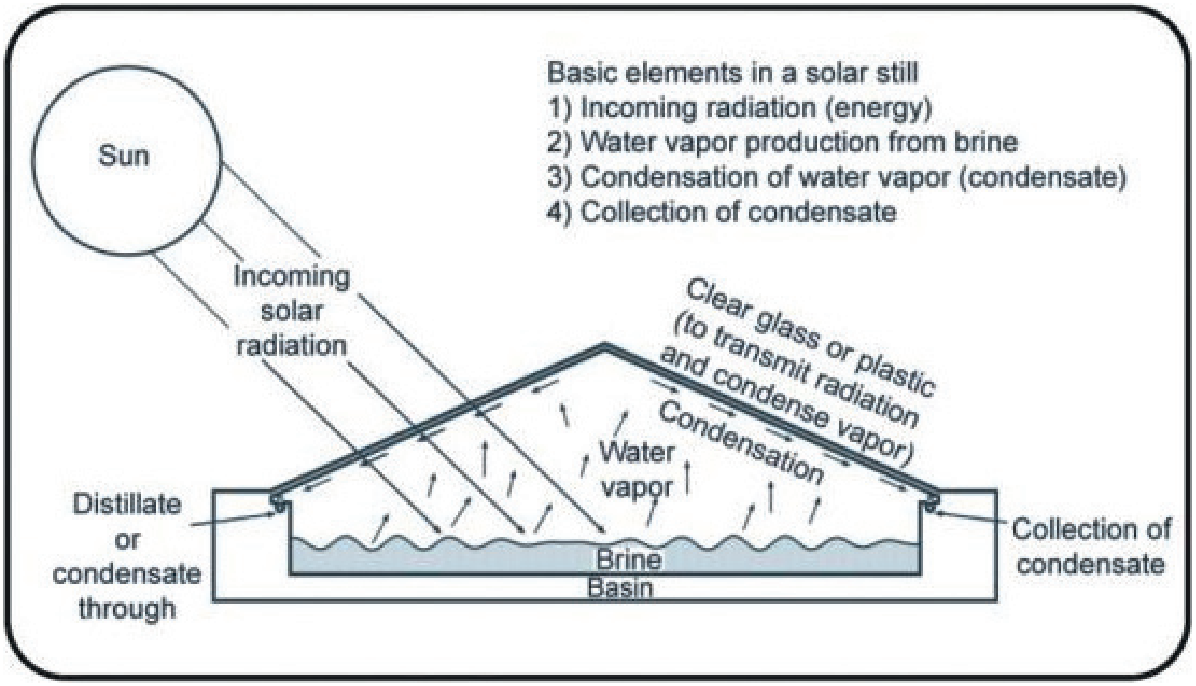

Figure 5. Solar desalination. Source: [17].

In these cogeneration plants, the electricity is generated with high-pressure steam to operate the turbines and the steam is produced by boilers at temperatures up to 5408°C. When this steam expands in turbines, its temperature and energy levels get reduced. As we know that distillation plants need steam with temperatures lower than 1208°C, this can be easily obtained at the end of the turbine after maximum energy has been utilized in electric power generation. The steam is used for the desalination process and the condensate from the steam is then returned to the boiler to get reheated again to be used in the turbine [18].

3.1.5.1. Advantages and disadvantages

- The major advantage of cogeneration system is that it uses very less fuel than other plants operating separately and the energy costs are less for desalination process.
- In contrary, one of the disadvantages is that, problems can occur due to permanent coupling between the desalination plant and the power plant which can create a problem in water production when the need for electricity is reduced or when the turbine or generator has a problem.

3.2. Membrane processes

Initially membrane applications were confined to municipal water treatment such as microfiltration and desalination but due to advancements in technology and development of new membranes, it is used not only for water purification but also in chemical separations, concentration of enzymes and purification of beverages.

Membrane processes uses a relatively permeable membrane to move either water or salt to produce two zones of differing concentrations to produce fresh water. These processes are also useful in municipal water treatment. Reverse osmosis and electro dialysis (ED) are replacing other phase change desalting technologies for supplying water to coastal and island communities all over the world. RO is emerging as an economical alternative to the traditional water softening processes [11].

Membrane technology consists of several processes, but the major difference between them lies in the size of the ions, molecules and suspended particles that are retained or allowed to pass via the membranes. Major separation processes include nano-filtration, ultra-filtration, microfiltration and filtration used in the pre-treatment stages of desalination that are used to remove large particles, bacteria, ions and for water softening.

The membrane processes are further categorized into

- Reverse osmosis
- Electro dialysis
- Membrane distillation

3.2.1. Reverse osmosis (RO) and nanofiltration (NF)

When compared to other processes, Reverse Osmosis (RO) is a relatively a new process used for desalination (**Figure 6**). The principle involved in this RO process is that, it uses pressure as the driving force to push feed water through a semi-permeable membrane into a product water stream and a concentrated brine stream [20].

Nano-filtration (NF) is also a similar membrane process which is used for removal of divalent salt ions such as Calcium, Magnesium, and Sulphate. RO is also used for removal of Sodium and Chloride ions.

Osmosis is a natural phenomenon by which water from a low salt concentration solution flows into a more concentrated solution via semi-permeable membrane. When pressure is applied to the solution of higher salt concentration solution, the water starts flowing in a reverse direction through the semi-permeable membrane, leaving the salt behind. This is known as the reverse osmosis process or RO process. Here the membrane configurations consist of spiral

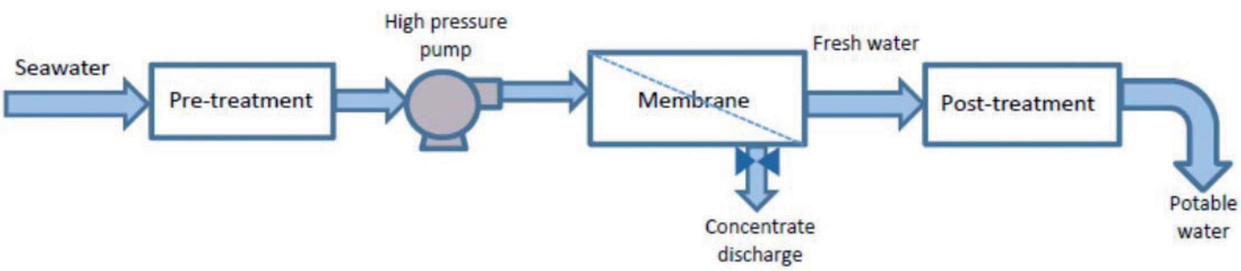

Figure 6. Reverse osmosis (RO). Source: [19].

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wound, hollow fibre and sheet with spiral. The operating pressures for reverse osmosis and nano-filtration range in between 50 and 1000psig.

An RO desalination plant mainly comprises of four major systems:

- Pre-treatment system
- High-pressure pumps
- Membrane systems
- Post-treatment

3.2.1.1. Advantages and disadvantages of RO process

- Problems related to corrosion of metals are very less compared to MSF and MED processes due to ambient temperature conditions
- Polymeric materials are preferred to metal alloys [21].
- In seawater desalination, to produce 5 gallons of usable water, 40–90 gallons of water are wasted [1].

3.2.2. Electrodialysis (ED)

Electrodialysis (ED) method is a voltage-driven process. This process uses electrical potential to remove salts using a membrane, leaving fresh water behind. ED was initially used as a seawater desalination process; it is now used for brackish water desalination process also.

Electrodialysis (ED) process is operated using direct current (DC) in which ions (contrary to water in pressure-driven processes) flow via ion selective membranes to oppositely charged electrodes. In these systems, the polarity of the electrodes is reversed repeatedly.

Since water contains dissolved salts in the form of ions and these ions get attracted towards oppositely charged electrodes, electrodialysis can be used to separate salts and fresh water-. this method uses suitable membranes to permit passage of selective ions either cations or anions [26].

3.2.3. Membrane distillation

This technology uses the principles of both thermal and membrane technologies, that is, distillation and membrane based desalination processes. In this method temperature difference is created in between the supply solution that is coming in contact with the surface on one side of microporous membrane and the space left on its other side [22]. This temperature difference causes difference in vapour pressure, resulting in the transfer of the produced vapour through the membrane onto the condensation surface. The whole process is based on the use of hydrophobic membranes that are permeable only to the vapour, thus excluding liquid vphase and dissolved particles. The vapour produced then passes through the membrane and gets condensed on the cooling surface producing fresh water.

3.2.3.1. Advantages and disadvantages of MD

- Membrane distillation is simple and operates at low temperature. Hence it utilizes less amount of heat. Coupling MD units with solar energy sources makes it more attractive.
- It operates at a lower pressure than other pressure-driven membrane processes
- Main disadvantage is that MD requires more space compared to other membrane processes [23]
- In this process the feed water should not have any organic pollutants. This fact turns to be a limitation for this process [11].

3.3. Alternative processes

Though a number of other methods have been used in water desalination process, but none of them turned to be commercially as successful as MSF, RO, and ED technologies. Some alternative methods are also used for desalination process. They are

- Freezing and ion exchange processes

3.4. Freezing

The principle involved in freezing desalination is that, in the process of freezing, the dissolved salts present in the feed water are separated during the formation of ice crystals. Seawater can be desalinated by cooling the water to form crystals under controlled conditions. Before the total amount of feed water has been frozen, the mixture is washed and rinsed to remove the salts present in the remaining water or that is sticking to the ice crystals. The ice is then melted to produce fresh water. Since the main heat transfer processes involved are freezing and melting which are regenerative, this method is said to have very high energy efficiency [24].

3.4.1. Advantages and disadvantages

- This process uses theoretically lower energy and has less chance for corrosion and scaling.
- It produces pure drinking water and also water for irrigation
- The disadvantage in this process is handling ice and water mixtures which are mechanically complicated to move and to be processed [25].

3.5. Ion exchange: Solvent process

Ion exchangers are generally organic or inorganic solids which are capable of exchanging one type of cation (or anion) immobilized on the solid surface for another type of cation (or anion) present in solution. For example, Na^+ ions in solution can be replaced with H^+ by a cation exchanger and Cl^- ions can be similarly replaced with OH^- by an anion exchanger, resulting in the complete 'demineralization' of a NaCl solution. This process can be reversed by regenerating the cation exchanger with an acid, and the anion exchanger with a base.

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4. Conclusion

The desalination of brackish water and seawater proves to be a reliable source of fresh water and is proves to be a solution for the world's water shortage problem. Desalination processes are normally used to produce drinking water in areas where only seawater or brackish water is the source of water. A number of technologies have been developed and many more methods are under R&D for desalination. They can be used for small scale, that is, supplying water for small communities (e.g. solar distillation) and large scale to supply water to cities, that is, huge plants (e.g. reverse osmosis).

Though desalination costs seem to be progressively decreasing, but they are still costlier than conventional drinking water processes. Coming to environmental aspects each desalination plant has to take proper measures in case of intake of water, pre-treatment of water as well as disposing concentrate reject water that is produced in the process because environmental aspects are equally important as commercial aspects.

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