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Advances in seawater desalination technologies

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Abstract

A number of seawater desalination technologies have been developed during the last several decades to augment the supply of water in arid regions of the world. Due to the constraints of high desalination costs, many countries are unable to afford these technologies as a fresh water resource. However, the steady increasing usage of seawater desalination has demonstrated that seawater desalination is a feasible water resource free from the variations in rainfall. A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. The process requires some form of energy to desalinate, and utilizes several different technologies for separation. Two of the most commercially important technologies are based on the multi-stage flash (MSF) distillation and reverse osmosis (RO) processes. Although the desalination technologies are mature enough to be a reliable source for fresh water from the sea, a significant amount of research and development (R&D) has been carried out in order to constantly improve the technologies and reduce the cost of desalination. This paper reviews the current status, practices, and advances that have been made in the realm of seawater desalination technologies. Additionally, this paper provides an overview of R&D activities and outlines future prospects for the state-of-the-art seawater desalination technologies. Overall, the present review is made with special emphasis on the MSF and RO desalination technologies because they are the most successful processes for the commercial production of large quantities of fresh water from seawater.

Keywords: Seawater desalination technologies; Multi-stage flash distillation desalination; Multiple-effect distillation desalination; Vapor compression distillation desalination; Reverse osmosis desalination; Freezing desalination; Solar evaporation desalination; Potabilization; Desalination research and development

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1. Introduction

Many countries in the world suffer from a shortage of natural fresh water. Increasing amounts of fresh water will be required in the future as a result of the rise in population rates and enhanced living standards, together with the expansion of industrial and agricultural activities. Available fresh-water resources from rivers and groundwater are presently limited and are being increasingly depleted at an alarming rate in many places.

The oceans represent the earth's major water reservoir. About 97% of the earth's water is seawater while another 2% is locked in icecaps and glaciers. Available fresh water accounts for less than 0.5% of the earth's total water supply [1]. Vast reserves of fresh water underlie the earth's surface, but much of it is too deep to access in an economically efficient manner. Additionally, seawater is unsuitable for human consumption and for industrial and agricultural uses. By removing salt from the virtually unlimited supply of seawater, desalination has emerged as an important source of fresh water.

Today, some countries depend on desalination technologies for the purpose of meeting their fresh water requirements. In particular, in the Middle East, seawater desalination is a vital and dependable fresh water resource in countries such as Saudi Arabia, United Arab Emirates, and Kuwait [2]. Furthermore, it is likely that desalination will continue to grow in popularity in the Middle East [3]. Overall, it is estimated that over 75 million people worldwide obtain fresh water by desalinating seawater or brackish water. The IDA Desalting Inventory 2004 Report [4] shows that at the end of 2002, installed and contracted brackish and seawater desalination plants worldwide totaled 17,348 units in 10,350 desalination plants with a total capacity of 37.75 million m^3/day of fresh water. The five world leading countries by desalination capacity are Saudi Arabia (17.4%), USA (16.2%), the United Arab Emirates (14.7%), Spain (6.4%), and Kuwait (5.8%). In 2001, seawater and brackish water accounted for about 60% and 40%, respectively, of all desalinated water sources in the world [5]. At the end of 2002, MSF and RO accounted for 36.5% and 47.2%, respectively, of the installed brackish and seawater desalination capacity. For seawater desalination MSF accounted for 61.6% whereas RO accounted for 26.7%. It should be noted that MSF holds the lead in all plants producing over 5000 m^3/day units [4]. The current world desalination plant capacity is 40 million m^3/day and the annual average growth rate for the last 5 years is 12% [6].

This paper reviews the current status, practices, advances, R&D activities, and future prospects of the state-of-the-art seawater desalination technologies. In view of the two most commercially successful processes in extensive use, this review has been made with special emphasis on MSF distillation and RO technologies.

2. Technologies

A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. This process requires some form of energy to desalinate, and utilizes several different technologies for separation. A variety of desalination technologies has been developed over the years on the basis of thermal distillation, membrane separation, freezing, electrodialysis, etc. [7–13]. Commercially, the two most important technologies are based on the MSF and RO processes. It is viewed that three processes — MSF, RO, and multiple-effect distillation (MED) — will be dominant and competitive in the future [14,15]. For instance, in 1999 approximately 78% of the world's seawater desalination capacity was made up of MSF plants while RO represented 10% [16]. However, there has been a gradual increase in RO seawater desalination primarily due to its lower cost and simplicity. The technologies used in the industry are described below.

2.1. Multi-stage flash distillation

The multi-stage flash (MSF) distillation process is based on the principle of flash evaporation. In the MSF process seawater is evaporated by reducing the pressure as opposed to raising the temperature. The economies of the MSF technology are achieved by regenerative heating where the seawater flashing in each flash chamber or stage gives up some of its heat to the seawater going through the flashing process. The heat of condensation released by the condensing water vapor at each stage gradually raises the temperature of the incoming seawater. The MSF plant consists of heat input, heat recovery, and heat rejection sections. Although a high temperature additive is commonly used for scale control, an acid dose can also be utilized [17].

Seawater heating is accomplished in the brine heater by low pressure steam externally supplied by a cogeneration power plant such as a gas turbine with a heat recovery steam generator [18,19] or an extraction steam from a steam turbine power plant [19,20]. The seawater entering the brine heater flows in the tube side of the heat exchanger located in the upper portion of the evaporator. Heat exchangers are typically arranged across the width of the evaporator. The heated seawater then flows into the evaporator flash chambers. The evaporator is made of multi-stages, typically containing 19–28 stages in modern large MSF plants [17,21–25]. The MSF plants usually operate at top brine temperatures of 90–120°C, depending on the scale control method selected [26–38]. Operating the plant at higher temperature limits of 120°C tends to increase the efficiency, but it also increases the potential for scale formation [26,27] and accelerated corrosion of metal surfaces in contact with seawater.

In each stage the pressure is maintained below the corresponding saturation temperature of the heated seawater flowing into it.The introduction of the seawater into the flash chamber causes it to boil rapidly and vigorously due to flashing. Orifices and baffles installed between stages make the brine's pressure reduce to that of the equilibrium vapor pressure required for boiling at the brine's temperature. Boiling continues until the seawater temperature reaches the boiling point at the stage (flash chamber). Therefore, flash distillation is accomplished progressively by the production of water vapor with the controlled sequential reduction of pressure on hot seawater. The unflashed brine passes from one stage to the next — a lower pressure stage for further flashing — so that the seawater can be evaporated repeatedly without adding more heat.

Each stage of the evaporator is provided with demisters to minimize carryover of brine droplets into the distillate. The evaporator has a decarbonator (if acid is used for scale control) and a vacuum deaerator to remove dissolved gases from the brine. The stripping media for the decarbonator and deaerator are air and flashed vapor, respectively. The decarbonator is employed to remove CO_2 converted from bicarbonate in the seawater by an acid such as sulfuric acid [26,27]. The bicarbonate present in the seawater is the main species that forms alkaline scale [27,33]. Vacuum in the evaporator stage is established and maintained by a steam jet ejector system complete with a vent condenser, intercondenser, aftercondenser, etc. The system extracts the noncondensable gases such as O_2, N_2, and CO_2 released during the flashing process.

The flashed water vapor is then cooled and condensed by colder seawater flowing in tubes of the condenser to produce distillate. The latent heat released from the condensation of the vapor is utilized to heat the incoming brine in the tubes. The distillate produced and collected in each stage is cascaded from stage to stage in parallel with the brine, and pumped into a storage tank. The desalinated water produced by the MSF process contains typically 2–10 ppm dissolved solids. Therefore, it is remineralized through the potabilization (or post-treatment) process [39–49].

The quantity of the water vapor formation depends upon the pressure maintained in each stage (typical flash drops of 2–5°C in each stage). The distillate production rate increases with decreases in the seawater temperature because the flash range (typically a total flash range of 50–75°C) increases with decreases in the seawater temperature. Also, the production rate depends upon the number of stages in an MSF plant that is related to the plant economics. An increase in stages providing more heat transfer area improves the plant efficiency, but it also increases the plant capital cost. The value of the performance ratio (PR) is determined to give minimum water production cost. The PRs for modern large MSF plants are in the range of 6.5–10.5 lbs/1000 Btu heat input [26].

The energy input of the brine heater is rejected by cooling seawater flowing in the heat rejection section, which is made up of commonly 2–4 stages [17,21–25]. A portion of the warmed cooling seawater leaving the heat rejection stage is diverted and used as a makeup stream to the plant. The purpose of the makeup stream is to replace the portion of the recirculating brine lost to vapor formation. A portion of the brine from the last stage of the heat recovery section is mixed with the makeup stream and then is recirculated through the tube side of the condensers to the brine heater. This brine is heated and flashed again through all the stages. This is referred to the recirculation MSF plant as opposed to a once-through plant. The major portion of the cold seawater is used as a cooling medium for the heat rejection section and is returned to the sea together with a blowdown stream taken for scale control purposes. The blowdown stream is necessary to avoid over-concentration of the flash brine that would increase the boiling point. It becomes more and more concentrated as a result of successive evaporation of the brine in the multi-stages, which increases the tendency of scale formation and corrosion.

The seawater system for supply of seawater for desalination and cooling consists of an open intake channel or submarine pipe, a pumphouse, sodium hypochrolite generators, and distribution and return piping or channel. The pumphouse is equipped with traversing trash rakes and traveling screens to remove debris. Hot spent brine from the heat rejection section is discharged to the outfall channel which extends into the sea.

MSF plants have been built since the 1950s [8]. In 1953 the US Navy constructed a 189 m^3/day MSF plant consisting of 5 stages. In 1957 four units of 2271 m^3/day capacity each were installed in Kuwait [9]. The Saline Water Conversion Corporation's Al-Jubail plant in Saudi Arabia is the world's largest plant with a capacity of 815,120 m^3/day [21]. The largest MSF unit with a capacity of 75,700 m^3/day is the Shuweiat plant, located in the United Arab Emirates [50].

2.2. Multiple-effect distillation

The multiple-effect distillation (MED) process is the oldest desalination method [51] and is very efficient thermodynamically [52]. The MED process takes place in a series of evaporators called effects, and uses the principle of reducing the ambient pressure in the various effects. This process permits the seawater feed to undergo multiple boiling without supplying additional heat after the first effect. The seawater enters the first effect and is raised to the boiling point after being preheated in tubes. The seawater is sprayed onto the surface of evaporator tubes to promote rapid evaporation. The tubes are heated by externally supplied steam from a normally dual purpose power plant. The steam is condensed on the opposite side of the tubes, and the steam condensate is recycled to the power plant for its boiler feedwater. The MED plant's steam economy is proportional to the number of effects. The total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next effect.

Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. These tubes are in turn heated by the vapors created in the first effect. This vapor is condensed to fresh water product, while giving up heat to evaporate a portion of the remaining seawater feed in the next effect. The process of evaporation and condensation is repeated from effect to effect each at a successively lower pressure and temperature. This continues for several effects, with 4 to 21 effects and performance ratio from 10 to 18 being found in a typical large plant [53].

Some plants have been built to operate with a top brine temperature (TBT) in the first effect of about 70°C, which reduces the potential for scaling of seawater [54], but increases the need for additional heat transfer area in the form of tubes. The power consumption of an MED plant is significantly lower than that of an MSF plant, and the performance ratio of the MED plant is higher than that of the MSF plant. Therefore, MED is more efficient than MSF from a thermodynamic and heat transfer point of view [55].

Horizontal MED plants have been operating successfully for almost three decades [55]. MED plants can have horizontal, vertical, or submerged tubes. The size of low temperature MED units has increased gradually. Two MED units in Sharjah, UAE have a capacity of 22,700 m^3/day each [56]. A design and demonstration module for the MED process exists for a 45,400 m^3/day unit [56]. Most of the recent applications for the large MED plants have been in the Middle East. Although the number of MED plants is still relatively small compared to MSF plants, their numbers have been increasing.

2.3. Vapor compression distillation

In the VCD process [10,57], the heat for evaporating the seawater comes from the compression of vapor. The VCD plants take advantage of the principle of reducing the boiling point temperature by reducing the pressure. Two methods are used to condense water vapor to produce sufficient heat to evaporate incoming seawater: a mechanical compressor and a steam jet. The mechanical compressor is usually electrically driven.

VCD units have been built in a variety of configurations to promote the exchange of heat to evaporate the seawater. The compressor creates a vacuum in the evaporator and then compresses the vapor taken from the evaporator and condenses it inside of a tube bundle. Seawater is sprayed on the outside of the heated tube bundle where it boils and partially evaporates, producing more vapor.

With the steam-jet type of VCD unit, called a thermocompressor, a venturi orifice at the steam jet creates and extracts water vapor from the evaporator, creating a lower ambient pressure. The extracted water vapor is compressed by the steam jet. This mixture is condensed on the tube walls to provide the thermal energy, heat of condensation, to evaporate the seawater being applied on the other side of the tube walls in the evaporator.

The low temperature VCD distillation is a quite simple, reliable, and efficient process requiring power only. Having a high capacity compressor allows operation at low temperatures below 70°C, which reduces the potential for scale formation and corrosion. The VCD process is generally used for small-scale desalination units. They are usually built up to the range of 3000 m^3/day. The larger unit's power consumption is about 8 kW h/m^3 of product water. VCD units are often used for resorts, industries, and drilling sites where fresh water is not readily available [57].

2.4. Reverse osmosis

In the reverse osmosis (RO) process, the osmotic pressure is overcome by applying external pressure higher than the osmotic pressure on the seawater. Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration. No heating or phase separation change is necessary. The major energy required for desalting is for pressurizing the seawater feed. A typical large seawater RO plant [58–61] consists of four major components: feed water pre-treatment, high pressure pumping, membrane separation, and permeate post-treatment.

Raw seawater flows into the intake structure through trash racks and traveling screens to remove debris in the seawater. The seawater is cleaned further in a multimedia gravity filter which removes suspended solids. Typical media are anthracite, silica and granite or only sand and anthracite. From the media it flows to the micron cartridge filter that removes particles larger than 10 microns. Filtered seawater provides a protection to the high pressure pumps and the RO section of the plant. The high pressure pump raises the pressure of the pretreated feedwater to the pressure appropriate for the membrane. The semipermeable membrane restricts the passage of dissolved salts while permitting water to pass through. The concentrated brine is discharged into the sea.

Pretreatment is needed to eliminate the undesirable constituents in the seawater, which would otherwise cause membrane fouling [62–67]. A typical pretreatment includes chlorination, coagulation, acid addition, multi-media filtration, micron cartridge filtration, and dechlorination. The type of pretreatment to be used largely depends on the feed water characteristics, membrane type and configuration, recovery ratio, and product water quality.

Various chemicals added to the seawater are sodium hypochlorite for the prevention of microorganism growth, ferric chloride as a flocculant, sulfuric acid for the adjustment of pH and the control of hydrolysis and scale formation, and sodium bisulfite to dechlorinate [58–61].

High pressure stainless steel pumps raise the pretreated feedwater to a pressure appropriate to the RO membranes so that water can pass through them and the salts can be rejected. The membrane must be able to withstand the drop of the entire pressure across it. A relatively small amount of salts passes through the membrane and appear in the permeate. There are membranes available which are suitable for pump operation up to 84 kg/cm^2 discharge pressure. Centrifugal pumps are generally used for this application. This pressure ranges from 50 to 80 bar for seawater, depending on the salt content of the feed water.

Two of the most commercially successful membrane configurations are spiral wound and hollow fine fiber (HFF) [68–71]. HFF is a U-shaped fiber bundle housed in a pressure vessel. The membrane materials are cellulose triacetate and polyamide [72].

The post-treatment generally includes pH adjustment, addition of lime, removal of dissolved gases such as H_2S (if any) and CO_2, and disinfection.

Major design considerations of seawater RO plants are the quantity of flux, conversion or recovery ratio, permeate salinity, membrane life, power consumption, and feedwater temperature.

In comparison to MSF, problems arising from corrosion of materials are significantly less due to the ambient temperature conditions. Therefore, the use of metal alloys is less and polymeric materials are utilized as much as possible. Various stainless steels are used quite extensively [73–75].

Two developments have helped to reduce the operating costs of RO plants during the past decade: the development of membranes that can operate efficiently with longer duration, and the use of energy recover devices [76–80]. The devices are connected to the concentrated stream as it leaves the pressure vessel. The concentrated brine loses only about 1–4 bar relative to the applied pressure from the high pressure pump. The devices are mechanical and generally consist of turbines or pumps of some type that can convert a pressure drop to rotating energy.

2.5. Other processes

A number of other processes have been developed to desalinate seawater. These processes have not achieved the level of commercial success that MSF, MED, and RO have, but they may become valuable under special circumstances or with further development. These important processes include freezing and solar evaporation.

2.5.1. Freezing

During the process of freezing, dissolved salts are excluded during the formation of ice crystals. Under controlled conditions seawater can be desalinated by freezing it to form the ice crystals. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts in the remaining water or adhering to the ice. The ice is then melted to produce fresh water. Therefore, the freezing process is made up of cooling of the seawater feed, partial crystallization of ice, separation of ice from seawater, melting of ice, refrigeration, and heat rejection. There have been several processes developed to pilot plant status. These include the triple point, secondary refrigerant, indirect, eutectic, and hydrate processes [8,81]. The advantages of freezing include a lower theoretical energy requirement, minimal potential corrosion, and little scaling or precipitation. The disadvantage of freezing involves handling ice and water mixtures which are mechanically complicated to move and process.

A small number of plants have been built over the past 40 years, but the freezing process has not been commercialized successfully to produce fresh water for municipal purposes. The most recent significant example of a freezing desalination plant was an experimental solar-powered unit constructed in Saudi Arabia in 1985 [82].

2.5.2. Solar evaporation

The use of direct solar energy for desalinating seawater has been investigated quite extensively [83–89] and used for some time. The process generally is similar to a part of the natural hydrologic cycle in which the seawater is heated by the sun's rays to produce water vapor. The water vapor is then condensed on a cool surface, and the condensate collected as product water. An example of this type of process is the green house solar still, in which the saline water is heated in a basin on the floor and the water vapor condenses on the sloping glass roof that covers the basin [57].

Variations of this type of solar still have been made in an effort to increase efficiency, but they share difficulties in the requirement of a large solar collection area (e.g. 25 hectares land/l000 m^3 of product water/day), high capital cost and vulnerability to weather-related damage [57]. Although thermal energy may be free, additional energy is needed to pump the water to and from the facility.

2.6. Potabilization

Desalinated water produced from MSF plants is of high purity with a very small amount of dissolved salts and minerals. Therefore, the water is aggressive and corrosive to the materials commonly used in water distribution systems such as metals and concrete. In order to overcome the problems with aggressiveness and poor taste of the distillate, a number of potabilization processes [39–48,90] have been practiced or proposed.

Besides chrolination in the presence [46] or absence of aeration [40,47], two typical treatment methods used are injection of carbon dioxide and hydrated lime [39,48], and the passing of carbonated water through limestone bed filters [40,46,47]. Such treatment methods aid in establishing the calcium carbonate equilibrium and forming corrosion-inhibiting protective layers of calcium carbonate. As a source of the carbon dioxide, CO_2 gas from an MSF vent stream can be utilized [91].

Accordingly, a typical potabilization process consists of four unit operations — liming, carbonation, chlorination, and aeration [39]. The water is remineralized by adding hydrate lime and carbon dioxide through the liming and carbonation steps, in order to raise hardness, alkalinity, pH, and dissolved mineral content. The chlorination is carried out by injecting chlorine gas, sodium or calcium hypochlorite to disinfect the water and eliminate bacterial growth. The aeration is done to replace oxygen driven out by the MSF distillation process, thereby improving the taste of the water.

For permeate produced from the RO process, post treatment generally includes pH adjustment, removal of dissolved gases such as CO_2 and H_2S depending on the feedwater, addition of lime, and disinfection using chlorine gas or calcium hypochrolite [58].

3. Technological advances

3.1. Multi-stage flash distillation

Progress has been made in the last 30 years to optimize the design of MSF plants. The main areas where optimization have been achieved are equipment design and configuration, thermodynamic design, material selection and structural aspects, and construction and transportation techniques. The gradual evolution made includes plant configuration, long-tube versus cross-tube, two decks versus single deck, vertical MSF, chemical treatment, brine transfer and equilibration, heat transfer, construction materials, construction techniques, control and instrumentation, pumps, and the role of computers [92]. The following shows how the desalination development proceeded during the 3 decades [92–95].

Desalination started to emerge as a larger scale process beginning approximately in 1960. The MSF concept allied with parallel development in technology coincided with increasing demand for water in arid regions such as the Middle East. This opened up a market for desalination plants. Although laboratory and prototype research was undertaken to test design concepts, the market demand was such that plants up to 4500 m^3/day were built. These plants, however, functioned largely as designed [93].

There were problems, mainly the consequence of scale-up from prototype to a large scale without a clear understanding of the design parameters. The concept of equilibration was not fully appreciated in the early sixties. This showed up as an increasing discrepancy between brine and associated vapor pressure at low temperatures. This phenomenon was not observed to the same degree in prototype tests [93]. The technology is presently moving towards larger and larger unit sizes and has reached the 75,850 m^3/day unit size at Shuweiat project in UAE [95]. A large scale unit provides important economies of scale resulting in reduced costs compared to a small scale unit. One study indicates that it is possible to extend a unit size to the order of 136,260 m^3/day [96].

Entrainment of brine in the vapor stream of certain stages led to unsatisfactory purity of the distillate. Installment of demisters contributed to the solution of this problem, but the ultimate solution involved the selection of effective antifoam agents to reduce foam levels and allow sufficient disengagement height, before the demisters [93]. Furthermore, in these plants and in the recent plants, more care has been taken in the demister design and its location within the evaporator as this plays an important role in maintaining the quality of distillate. Modifications in the profile of demisters were suggested and carried out for more efficient performance of demisters.

Although the MSF concept reduced the effects of scaling on heat transfer surfaces by eliminating boiling, some scale formation did occur. Chemical additives had been developed to control and modify the scale formed [92–94]. However, it was still a barrier to heat transfer and inhibited long term efficient operation. Acid treatment eliminated the scale but posed a corrosion risk and was expensive. It was the introduction of on-line ball cleaning in MSF systems that broke through the barriers to long-term operation [93].

The later development of high temperature additives compatible with the ball cleaning systems essentially eliminated acid as an additive and allowed operation at temperatures up to 115°C [92,93].

The MSF plants constructed before 1980 primarily used carbon steel (CS) as the material for the shell and the internals. Because the CS metal corrodes in the presence of seawater, the thickness of the CS material used in the construction of the evaporator had to be increased to compensate for the corrosion. This led to the increase in the weight and size of the units. The plants built after 1980 were constructed with superior material such as stainless steel (SS) and duplex SS.

The operation experience of MSF plants provided a better understanding of the various corrosion problems of the evaporation process. The usage of SS caused lesser thickness of metal used in various components of the evaporator and this in turn resulted in the reduction in the weight and the size of the unit as a whole. For instance, the weight of a 9084 m^3/day plant was about 1000 tons whereas that of a 36,336 m^3/day plant was 2500 tons [95]. The significant reduction of the evaporator weight resulted in a substantial cost savings in construction which lowered the water production cost.

The better understanding of the material has now led to reduced construction time and standardization. Usage of titanium tubes in the ejector condenser [95] has improved both the heat and mass transfer performance of the ejector system, and has thereby effectively controlled the presence of corrosive vapors inside the evaporator. An Incoloy 825 nickel alloy which has a high pitting resistance equivalent (PRE) number, can be also used as a corrosion resistant material for an steam jet ejector [97]. The suitable materials for MSF plants include carbon steel, stainless steel, copper-nickel alloys, aluminum alloys, titanium, and FRP, depending on usage [98–103].

Through the long operational experience of the MSF plants, many redundancies in the requirement of the plant auxiliaries could be identified. Using the equipment optimization process, it was possible to delete the major redundancies from the plant configuration such as the makeup strainer, high conductivity condensate flash tank, cooling water recirculation pump, cranes for waterboxes and pump area, ejector condensate extraction pump, and vacuum system ejector standby [95]. The deletion of this equipment decreased some cost without decrease in plant functionality, reliability, or efficiency. This also contributed to the simplification of the plant layout and savings on operation and maintenance costs, as well as a reduction in spare parts.

A reduction in the design fouling factors (FF) has been achieved over the years in the thermodynamic designs of MSF plants. A comparison between the actual heat exchange coefficient (HEC) measured during the plant operation and the projected design HEC suggested that the FF's adopted for the heat transfer design were too pessimistic. In reality, as a consequence of the high design FF imposed on the plant design, the performance of the plant was always above the guaranteed performance. For the last 3 decades the FF's have been reduced almost linearly from about 0.20 m^2°C/kW to about 0.13 m^2°C/kW, which is equivalent to % reduction of design margin from 16 to 8. For a reduction in the FF by about 16%, the margin of the heat transfer surface area will be approximately 4% [95]. This reduction has been achieved by reducing design margins with the optimization of venting of vacuum gases, sponge ball cleaning system, and distribution of process parameters across the tube bundle.

The manufacturing and transportation procedures have also improved. This has resulted in the completion of the whole project in much shorter time than it was 5 to 6 years ago [95]. The downtime of the newer plant has been also reduced drastically when compared with the older plant. This can also be attributed to improvements in the chemical dosing to control scaling, corrosion and foaming in the seawater circuit. The improvements in the venting system have also reduced concentration of corrosive gases inside the evaporator, thereby increasing the life of the evaporator internals.

Due to the improvement in material and better understanding of the corrosion associated with the process, MSF plants have a performance ratio in excess of 8 in clean conditions and minimum 7.5 in fouled conditions. The actual performance ratio in these plants is nearly 9 when the plants are new. This was possible due to the better understanding of thermodynamic design of the plants as the TBT is around 110°C as compared to 95°C in the older units [95]. Efforts are on further increasing this TBT, even though there are limitations due to the increase in the corrosion phenomena as the temperature increases.

The dynamics of the process is well understood and the modern distributed control systems are utilized for MSF, MED, and RO. The traditional control panels have been replaced with a small console of video monitors that display a wide variety of process information. Numerous studies have been conducted on control, modeling, and simulation [104–112].

A number of assessments on nuclear desalination performed indicate that it would be technically feasible and economically competitive with fossil and renewable energy. However, coupling of nuclear reactor with desalination process involves various issues including safety, prevention of radioactive contamination of product water and public acceptance. Research and development (R&D) work continues on nuclear desalination [113–116].

3.2. Multiple-effect distillation

MED is an important large-scale thermal process offering significant potential for water cost reduction [56]. The MED specific power consumption is below 1.8 kW h/m^3 of distillate, significantly lower than MSF typical 4 kW h/m^3 [56]. MED has the ability to produce a significantly higher gained output ratio (GOR) in excess of 15 kg of product per kg of steam where MSF practically limits the GOR to 10. The size of low temperature MED units is growing. Two units for a 22,700 m^3/day capacity were under construction in Sharjah, UAE. A design and demonstration module exists for a 45,400 m^3/day unit [56]. The low temperature MED units with TBT up to 70°C have reduced scaling and corrosion rates to acceptable levels, overcoming the main problems plaguing conventional high temperature distillation plants [54].

The Metropolitan Water District (MWD) of Southern California, USA had an ambitious desalination development program in the mid 1990s [117,118]. The aim of the $30 million program was to build a 283,875 m^3/day demonstration plant using a large-scale vertical tube MED process. The process had adapted some innovative ideas for a drastic reduction of the plant capital cost. The estimated water production cost was $0.584/m^3 of water. The program was postponed, but been reactivated. MWD works on a 189,250 m^3/day plant [119].

3.3. Reverse osmosis

In the last 20 years a lot of improvements have been made in the RO process, which are reflected in the dramatic reduction of both capital and operation costs. Most of the progress has been made through improvements in membranes themselves. These typically include better resistance to compression, longer life, higher possible recovery, improved flux, and improved salt passage.

During the 70's RO emerged as a competitor to MSF. The early research was directed towards the development of a satisfactory membrane, initially for brackish water and later seawater. The development work was undertaken by companies specializing in membrane manufacturing.

There has been a gradual increase in the RO train size reaching 9084–13,626 m^3/day [120], although it is still far off from a MSF unit size of 56,775–68,130 m^3/day [121] and 75,700 m^3/day [50]. The world largest seawater RO plant has a design capacity of 326,144 m^3/day and the plant consists of thirty two 10,192 m^3/day trains [50].

The current recovery rate in an RO plant in the Middle East countries, a region where about two thirds of the desalination water of the world are produced, is in the range of 35%. Recently a much higher recovery rate of 60% for the Pacific Ocean water has been reported [122].

The RO plant energy consumption is approximately 6–8 kW h/m^3 without energy recovery. Installing an energy recovery device reduces the energy consumption quite dramatically to 4–5 kW h/m^3 [123]. The unit energy consumption can be reduced to as low as 2 kW h/m^3 [124]. This achievement is dramatic and possible due to the innovation in the energy recovery device.

The major problem faced by RO plants in the Middle East and elsewhere is in the pretreatment area [124–126]. The conventional filtration methods are inadequate. The seasonal organic blooms, high biological activity, and the turbidity have caused problems with many plants. Biofouling calls for frequent chemical cleaning of the membrane and loss of production. It has become difficult to maintain the required filtrate silt density index (SDI) levels throughout the year.

The recently developed nanofiltration (NF) membrane pretreatment in conjunction with the conventional filtration system was successfully applied in a pilot plant and later in an operating plant with excellent results [127–134]. The process prevented membrane fouling by the removal of turbidity and bacteria, and a 40% production increase was achieved in the operating plant [134]. The extensive development work by Saudi Arabia's Saline Water Conversion Corporation (SWCC) on the use of the NF technology has demonstrated the technical and economic feasibility of introducing NF in conjunction with RO. It offers several benefits and advantages including the prevention of fouling and scaling, a pressure reduction for RO, an increase in production and recovery, and cost savings in water production [127–134].

The materials investigated for RO membrane include polysulfone [135], polyetheramide hydrazide [136], and polyhydroxyethyl methacrylate [137].

One method of reducing water production costs is to employ a hybrid system that consists of two or more desalination processes [138–146]. The Fujairah power and desalination complex in UAE has a capacity of 500 MW of electricity and 454,200 m^3/day of desalinated water. This world largest hybrid desalination plant is made up of 280,000 m^3/day by MSF and 170,000 m^3/day by RO [3]. The RO process is in two stages in Fujairah. The seawater passes 18 racks containing 17,136 RO membranes, and then it passes through an additional 9 RO racks of 3920 membranes.

3.4. Other processes

MED desalination at higher temperature gives a higher performance ratio, whereas low temperature operation of an MED plant results in higher energy costs. However, the higher temperature operation can cause a scale formation. One solution to this problem is to operate a low temperature MED using a vapor compressor, which would reduce the water production cost. This type of a hybrid plant can increase the performance ratio significantly at lower temperatures. Small plants based on this principle have been built, and the unit sizes have been increased. One of the disadvantages in a mechanical VCD plant is related to a compressor which has moving parts and a size limitation. Since the pressure rises at low temperatures are quite small, steam jet ejectors, called thermocompressors, can be utilized instead of a mechanical compressor. Larger plants are expected to be installed depending on the site characteristics and local economic conditions. Therefore, VCD units will grow in capacity and number of effects [56].

There has been progress in the solar evaporation field in the last three decades due to the considerable amount of R&D work [83–89] and the general interest in the utilization of solar energy. Concern for a sustainable environment boosts this interest today. Even at the current level of higher fuel prices and stricter emission levels, the present competitiveness in the energy market is only marginal. This is due to the fact that the installation cost of a solar desalination system is considerable, even though the energy for evaporation is free of charge. However, as the R&D work on the technology improvement continues, the cost efficiency is expected to improve. There are solar plants installed of a relatively small size less than 20 m^3/day of water [57].

In 1985 the King Abdulaziz City for Science and Technology, SWCC, and the King Abdulaziz University of Saudi Arabia operated a solar energy seawater desalination pilot plant in Yanbu [82]. The US Department of Energy and the Midwest Research Institute in USA also participated in the pilot test program. The pilot plant with a capacity of 100–400 m^3/day of water consisted of solar collectors, heat transfer oil circulation system, hot and warm salt storage tanks, steam generation, engine and condensate system, ammonia refrigeration system, and freezing desalination system with ice separation, washing and melting. Solar collector efficiencies in the range of 65–67% have been measured with a peak solar collector field output of 5400 kW h of thermal energy in a day. The desalination system has produced 180 m^3/day [82].

4. Economics

Over the years desalinated water production costs have decreased as a result of technological advances. At the same time, the costs of obtaining and treating water from conventional sources have risen due to the increased levels of treatment required to comply with more stringent water quality standards. Additionally, the cost of desalination is related to the location of plants, amount of energy used and other costs.

For the production of fresh water from the sea in large quantities, a choice between two major commercial desalination processes (MSF and RO) depends largely on how each of the two processes applies in a specific situation, together with both technical and economic considerations [147]. A wide range of technical parameters to be evaluated includes seawater characteristics, product water quality, source of energy and consumption, plant size, plant reliability, concentrate disposal, space requirements, operation and maintenance aspects, etc. On the other hand, the economic analysis is based on cost determining factors such as capital, energy, labor, chemicals, materials, and consumables [147,152,155]. Numerous analyses and comparisons [147–163] have been carried out to assess competing technologies and economics.

Since seawater desalination needs some form of energy, a cogeneration scheme is essential in conjunction with the power generation from an economic point of view. The industry's goal is to produce desalinated water at 50 US cents per m^3 of water and power at 2 US cents per kW h [56]. Typically a life cycle cost analysis by the equivalent uniform annual cost method is used to determine desalination economics [147]. The capital charge cost is established at an equal amount annually. The operation and maintenance (O&M) costs are converted into equivalent annual costs. The water production cost accounting for both the capital and O&M costs, expressed in $/$m^3$ of water, is obtained by dividing the sum of all costs by the total water quantity. The parameters for the analysis include production capacity, plant life, and direct and indirect capital costs. The O&M costs are made up of labor, materials, parts, consumables, electricity, chemicals, seawater costs, etc. Some recent studies indicate quite encouraging water production costs. For instance, the estimated water production cost for the seawater RO plant project with a capacity of

94,600 m^3/day in Tampa, USA was reported to be at $0.55/$m^3$ [164]. The water production cost of the world largest seawater RO desalination plant is $0.53/$m^3$ [50].

5. Future prospects

Over the last two decades, a great deal of progress has been made in seawater desalination processes, which have resulted in the significant reduction of water production costs. This has led to a higher acceptance and growth of the industry worldwide, particularly in arid regions of the world. However, because desalination costs still remain high, many countries are unable to afford these technologies as a fresh water resource. Therefore, there is a need to emphasize and revitalize R&D in technology improvements that will eventually lead to substantial reduction of desalinated water production costs. The ultimate objective is to supply readily available low-cost fresh water by seawater desalination. It is envisaged that continued R&D efforts be made in various topics related to seawater desalination processes including the following [165,166]:

- Economics and technical aspects of the various processes.
- Efficient power and desalinated water cogeneration systems.
- Nuclear and solar energy utilization.
- Chemical treatment of the seawater feed.
- Higher temperature thermal distillation processes.
- Various processes for hybrid systems such as MSF-RO, NF-RO, and MSF-NF-RO.
- Integration, optimization, and hybridization of electricity, steam, and water.
- Proper selection of materials for construction and development of lower cost materials.
- Improvement and development of RO membranes.
- Prevention and control of scale and corrosion.
- Development in mega-scale seawater desalination plants.
- Control and intelligent systems for desalination.
- Environmental aspects of brine discharge.
- Magnetically enhanced separation of seawater hardness.

6. Research and development

The progress in and development of desalination technology has resulted from the enormous R&D efforts sponsored and funded by the Office of Saline Water (OSW) of the US Department of Interior for two decades from 1952 to 1972 [167–169]. The OSW R&D program has had a great impact on the development of currently available desalination processes. Virtually all the technologies adopted commercially nowadays were developed and tested under the program.

During the 20 years that the OSW worked on the development of desalination technologies, many different desalination processes did not make it out of the laboratory or beyond the pilot plant stage of development. The processes evaluated and studied by OSW included the following:

- Various thermal distillation processes.
- Various membrane processes.
- Solar evaporation and distillation.
- Electrolytic systems.
- Use of algae for saline water conversion.
- High-pressure solvent extraction desalination.
- Removal of ions from seawater with chelates.
- Hydrate process.
- Freezing processes.

In addition, several dozen heat transfer processes studied and tested included the following:

- Submerged tube.
- Vapor compression.
- Multi-stage flash.
- Vertical tube multiple effect.
- Wiped film-fluted tube thin film.
- Liquid–liquid heat exchange.
- Horizontal spray film evaporator.

- Capillary fluted tube evaporator.
- Horizontal spray film evaporator.
- Diffusion still.

One of the most successful endeavors and technological achievements made by the OSW was the discovery and development of the RO process. OSW developed the process that allowed a dissolved solid to be removed from a liquid without a phase change. Many scientists worked on the potential osmionic demineralization under the OSW Membrane Division. Professor Charles E. Reid of the University of Florida developed the first RO membrane in 1957 [169]. Later theories on how the RO phenomena occur were developed along with a better understanding of the RO process and development of improved membranes. The initial development of the RO process is a bright legacy of the OSW program.

The OSW spent a large amount of money to demonstrate what had been learned from laboratory and theoretical research, and to advance various desalination technologies. The typical demonstration plants built and operated under the OSW program included the following:

- Long tube vertical multiple effect distillation plant, Freeport, Texas.
- Electrodialysis plant, Webster, South Dakota.
- Multi-stage flash distillation plant, Pt. Loma, California.
- Forced circulation vapor compression plant, Roswell, New Mexico.
- Various pilot plants at the R&D test facility, Wrightsville, North Carolina.

The Pt. Loma's MSF demonstration plant (the world's first MSF plant) with a capacity of 3785 m^3/day was moved to the US Navy base at Guantanama, Cuba after the Cuban Missile Crisis in 1964, reassembled, and operated, producing potable water. This plant was in operation for about 20 years at the base [168,170].

All of the results of experimental operations performed by OSW were available to anyone, foreign or domestic. It was all available in the OSW Annual Reports and the 996 OSW R&D Progress Reports. In addition to the dissemination of information through those reports, there was the participation in meetings and seminars. The largest desalination meeting ever held, The first international symposium on desalination, was held in Washington, DC on October 3–9, 1965. The conference attracted some 2500 attendees from 65 countries [169].

The OSW program was terminated in 1972 because it was believed that desalination technology had advanced to the point where industry could take over and support an aggressive R&D program from their profits.

The industry continues R&D work for better technical and economical ways to make desalination more cost effective and affordable. R&D efforts are needed in the many areas. These include distillation, membrane, hybrid, integration of energy, power and water, new alternatives, energy recovery, process configuration, materials, and chemicals [167–169].

For example, the use of duplex steel and the subsequent thickness reduction with respect to stainless steel may become attractive and cost effective with a gradual decrease in the cost of duplex steel sheets [95]. Glass reinforced pipe [171] can find an application in MSF plants for the heat rejection section, and heat recovery waterboxes of the low temperature stages and other components such as deaerator makeup spray pipe.

The combination of MSF with the NF technology has been the subject of interest for further development and testing. The implementation of this process would allow an increase in the operating TBT and subsequently lead to an increase in production and efficiency [134]. This technology can be retrofitted in the existing plants and therefore would be able to optimize plant performance.

The future development in MSF will be more on to the improvement in thermodynamics and the material selection of the evaporator with the venting and deaerating system. Innovation in design and construction techniques will also play a key role in economics of the plant.

Optimization of MSF cross-flow versus long tube design, once through versus recirculation, multi-layer flashing stages, narrow-topped MSF, and paired stage design suggests the continuous potential of MSF technology [172].

Hybrid systems consisting of Power, MSF, and RO plants offer significant advantages, including the use of a common smaller seawater intake system, blending of the product water from MSF and RO, reduction of excess power or power to water ratio, and optimization of RO feedwater using MSF heat rejection cooling water [56,165,172]. Fujairah plant in UAE is the world largest hybrid desalination plant [3] and is a good example of the hybridization.

More research is needed in the pretreatment area for the RO process. There is a need for the development of membranes that are more resistant to biofouling. In spite of the continuous improvement in the membrane technology, the membrane replacement costs to achieve desired performance level can still be high. It is hoped that a higher membrane life such as 7 years will become the industry standard.

Although present technologies are well developed, there is scope for improvements in efficiency, reliability, simplicity and investment costs. Therefore, a lot of the research efforts should be directed towards improving and enhancing the presently utilized technologies. It is also important that new technologies, or those that may significantly change existing technologies, be investigated.

The major topics for R&D programs are as follows [166,173–177]:

6.1. Thermal desalination

These are energy intensive. Research is focused on the development of performance improvements in these process technologies and simplification of the design. The following are some of the topics to be considered:

- Development of alternative energy sources.
- Mitigation and control of scaling and fouling.
- Alternate materials of construction.
- Optimization of process design.
- Improvements in component design.
- Control systems to optimize consumables consumption.

6.2. Membrane desalination

There have been considerable improvements in membrane desalination processes in recent years and these have now become cost competitive for certain sites. Research is focused on the improvement of plant performance. The following are some of the topics to be considered for improving the process:

- New membranes.
- Membrane module design.
- Membrane process design.
- Energy recovery in RO processes.
- Pretreatment methods and fouling mitigation.
- Scaling and fouling fundamentals.
- Process and ancillary equipment design.

6.3. Alternative desalination technologies

Research is focused on development and feasibility studies of new concepts for non-traditional desalination processes and feasibility studies of desalination concepts that have not been fully explored. The following are examples of areas considered for R&D activity:

- New desalination concepts and feasibility studies.
- Coupling of desalination processes with non-conventional energy sources.
- New process design concepts of reported non-conventional desalination processes.
- Development of new designs concepts for process equipment.

- Measurement and control systems.
- Scale monitoring, controlling and cleaning systems.

6.4. Energy integration

Energy consumption in all desalination processes is much higher than the thermodynamic minimum requirement. Energy cost is the major component of the operating cost of a desalination plant. Research under this topic is focused on reduction in energy consumption and the use of cheap alternative energy sources. Methods need to be developed for economically and effectively combining desalination with renewable energy systems.

6.5. Hybridized systems

R&D studies are focused on the development of hybrid desalination processes for reduction in capital, operation and maintenance costs.

6.6. Environmental aspects

The whole desalination process should be environmentally sustainable. The following areas are some of the important topics for research:

- Improvements in the desalination processes for reducing and/or disposing of effluents.
- Assessment of the composition of desalination plant effluents.
- Procedures for assessment of environmental impact of desalination plant effluents.

The environmental impacts of all desalination technologies, whether in use or under development, must be considered. This goal is pursued through vigilance in protecting the environment throughout the research. In addition, environmental issues related to the application of desalination, such as siting of desalination plants, seawater intakes and brine discharge, are subjects of research.

7. Concluding remarks

A number of seawater desalination technologies have been introduced successfully during the last several decades to augment the water supplies in arid regions of the world. Due to the constraint of high desalination costs, many countries are unable to afford these technologies as a fresh water resource. Nevertheless, the adoption of seawater desalination technologies by some countries has demonstrated that seawater desalination certainly offers a new water resource free from variations in rainfall. Although the desalination technologies are mature enough to be a reliable source of fresh water from the sea, presently active R&D work is being performed by several institutions in order to constantly improve the technologies and reduce the cost of desalination. Taking into consideration the importance of and promising potentials for desalination in the future in many countries, long term multidisciplinary and integrated R&D programs are needed for the purpose of making the seawater desalination techniques affordable worldwide. Such comprehensive and collective R&D programs would be required to develop in collaboration with the governments, industries, universities, and research institutions.

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