Desalination and Solar Still: Boon to Earth

Prinshu Pandey, Om Prakash and Anil Kumar

Abstract Water is one of the most important components of the Earth. Due to rapid increasing population and pollution, shortage of freshwater has become very common to every nation, mainly to arid and semiarid regions of the world. Our Earth is covered with almost 75% brackish and brine water. To overcome the growing issue of freshwater shortage, seawater is only medium through which freshwater can be obtained. In this chapter, same has been discussed that how to utilize seawater for getting freshwater. Desalination has been proved the best way to solve the freshwater issue of this era. There are various methods for desalination like multi-stage flash distillation (MSFD), multiple-effect distillation (MED), reverse osmosis (RO), etc. It is very economical and simple method to obtain freshwater from seawater. To make best use of the concept of desalination, a new device solar still has been invented. At the present time, various researches are continued to improve its thermal efficiency. Many design changes are being made in solar still to make it applicable at large scale. Various methods of desalination, and their economics, future prospects, and benefits are discussed here.

Keywords Solar distillation · Demisters · Recovery ratio · Single-effect solar still · Multi-effect solar still · Active still · Passive still

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1 Introduction

Water is one of the most important components of Earth. It is very important for the existence of human life. It is available on Earth in abundance but very less of its availability comes under human use. Fresh and potable water is the most prominent issue at present. About 71% of Earth is covered with water, out of which 96.5% is ocean water and rest exists in river and lake, in pond, in ice caps and glaciers, in the soil and in aquifers, etc. Out of all these, only less than 1% of water is worth for human which is fresh. Issue of potable water is growing day by day [1]. There are many factors which are responsible for the depletion of such less available freshwater. Some of them are increasing population, industrialization, urbanization, transportation, etc. There is a need of water for various purposes like cooking, farming, drinking, and many more. Thus, safe water is a big challenge for current and future generations [2].

The lack of access to freshwater has an adverse effect on common people's life. There are many waterborne diseases which are being spread only because of lack of freshwater. Poor people are the main victims of this crucial problem [3]. Also in some of the regions like deserts, arid region, etc., there is very less rainfall which causes an adverse effect on human life. Estimated global water scarcity in 2030 is shown in Fig. 1 which is based upon Falkenmark Indicator.

Water occurs in a very complicated dynamic cycle that includes rain, evaporation, runoff, and many more dynamic natural processes unlike land which is considered as static resource. Water controls the nature and its components—in other words it manages ecosystem. Sustainable water management is one of the biggest challenges of this era [5]. The main cause of this problem is the uneven distribution of both human population and water resources. It is observed that densely populated regions

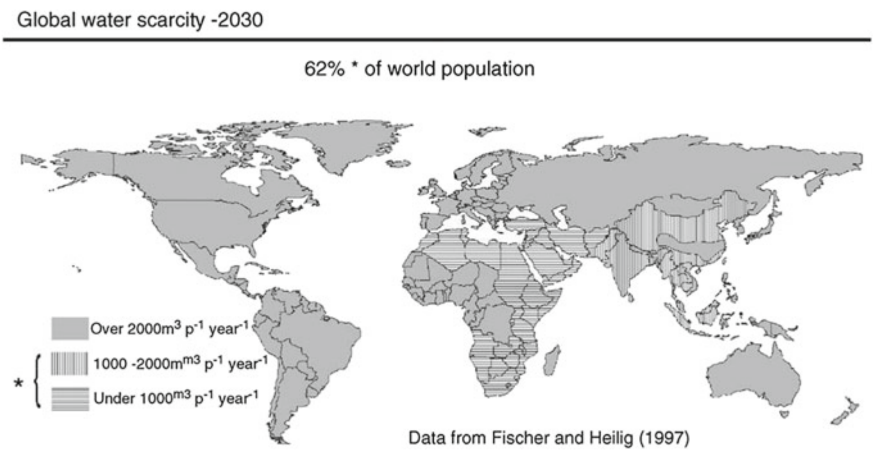

Fig. 1 Estimated global water scarcity in 2030 [4]

are having less availability of water and lower populated regions are having adequate or even surplus water availability.

It is not only physical water scarcity which are creating problems to humankind but also social water scarcity which is growing day by day. Social water scarcity is a water issue which comes into account due to political parties, policies, and socioeconomic relationships [6].

Due to rapid population growth, freshwater need is increasing day by day. It is becoming difficult to fulfill everyone's freshwater need [7]. Shortage of freshwater is damaging the ecosystem gradually which is one of the dangerous threats to mankind. Freshwater depletion is not the issue of arid regions only rather it has become common throughout the world [8]. It is very essential to keep control over the depletion of freshwater and to generate more fresh and potable water from other source of water which are not useful to human beings directly.

2 Desalination: A Solution

Water shortage is one of the toughest and threatening issues of today's generation. More than 15% of the world's population is deprived of fresh and potable water, out of which some are living in improper sanitation and unhygienic surroundings. To overcome this deteriorating condition, more and more water is made from seawater which is available in abundance on Earth [9]. This very process can be successful with desalination. Desalination is one of the simplest, earliest, best solutions to freshwater shortage.

The principle of hydrological cycle is followed in man-made desalination process using other sources of heating and cooling. Large amount of energy is needed to separate freshwater from brine and salty seawater. Desalination takes place by feeding saltwater into the method which gives two output streams as a result, one is freshwater stream and another is salt-contaminated water stream. Thus, freshwater is obtained by desalinating saltwater [10].

Desalination process has become a major method to supply freshwater to most of the regions of the world. Desalination process is mostly taken into account at coastal regions as this process can be achieved there easily due to abundant water. The most important characteristic of this process is that it is safe for all—in other words it has no adverse effect on ecosystem [11]. As per the survey made in the previous decade, about 75 million people all over the world are dependent on desalination process to obtain freshwater for their daily needs. There are many countries which are dependent on desalination to obtain freshwater. The top five leading nations in case desalination plant capacity are Saudi Arabia, USA, UAE, Spain, and Kuwait, with percentage coverage of 17.4, 16.2, 14.7, 6.4, and 5.8%, respectively [12]. Desalination production capacity for different nation is shown in Fig. 2.

There were about 18,000 desalination plants all over the world till 2015, with a total installed production capacity of 86.55 million m^3/day or 22,870 million gallons per day (MGD). Of the whole capacity, around 44% (37.32 million m^3/day or 9,860

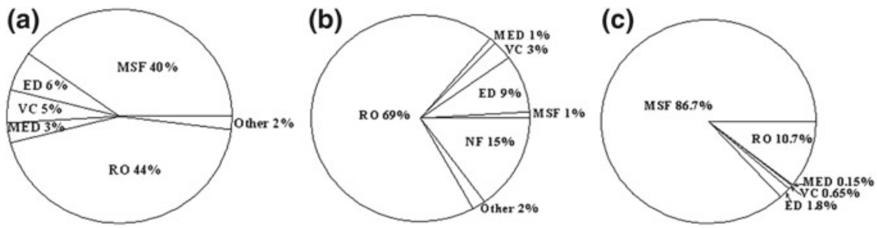

Fig. 2 Desalination production capacity with different categories for **a** the world, **b** the USA, and **c** other Middle East countries in 2002 [13]

MGD) is located in the Middle East and North Africa. Due to current advancement in technologies related to desalination, 80% of the energy used for water production over 20 years has been reduced [13].

3 Methods of Desalination

Basically, there are various methods of desalinating brackish and salty seawater. Commercially and economically out of all methods, MSFD, RO, and MED are taken into account for the desalination purpose. It has been observed that these three methods are the leading ones and in the coming future these three would be the most competitive [8]. There are various methods of desalination which are as under.

3.1 Multi-stage Flash Distillation (MSFD)

The basic principle of MSFD is flash evaporation. In this very process, evaporation of seawater takes place by the reduction of pressure as opposed so as to increase the temperature. To get the maximum product and to maintain the economies of MSFD, generally regenerative heating is done. Due to regeneration, the seawater flashing in the flashing chamber provides its heat to the seawater going through the flashing method. As this is a regenerative heating, this process needs different stages for the completion. There is a need to raise the temperature of incoming seawater at each stage gradually [14]. This gradual increase in temperature of seawater is achieved by the heat of condensation which is released by the condensing water vapor. There are basically three parameters essential for a MSFD plant, and these are heat input, heat recovery, and lastly heat rejection. There are some chances of scale formation in the MSFD plant, and to remove that scale formation, some high-temperature additives are used [15].

In modern MSFD plant, multi-stage evaporators are used in which about 19–28 stages are there [16]. The operating temperature of MSFD plant is in the range of

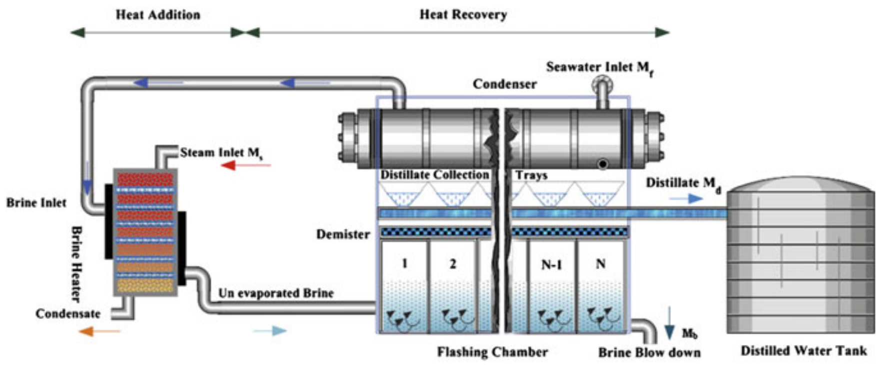

Fig. 3 Illustration of processes of MSFD [18]

90–120. As the operating temperature of the plant increases, there is an increase in the plant's efficiency, but this may lead to more scale formation. There is a need to maintain pressure below the corresponding saturation temperature of the heated seawater.

There are different equipment or accessories used in the plant for different purposes. These are demisters, decarbonator, and vacuum deaerator. This would be more clear from the Fig. 3. Demisters are provided at each stage of evaporator to minimize carryover of brine droplets into the distillate. The purpose of using decarbonator and vacuum deaerator is to remove dissolved gases from the brine [17].

The first MSFD plant was built in 1950s [19]. The Saline Water Conversion Corporation's Al-Jubail plant in Saudi Arabia is the world's largest plant with a capacity of around 815,120 m^3/day [20]. The largest MSF unit with a capacity of 75,700 m^3/day is the Shuweihat plant, situated in the UAE [21].

3.2 *Multiple-Effect Distillation (MED)*

MED process is the oldest method of all methods of desalination. Thermodynamically, MED is the most inherent method as compared to all others [22]. Here effects in MED process signify series of evaporators. The MED process takes place in series of evaporators. The basic principle involved in MED is reducing the ambient pressure at different effects. There is no need to provide or supply extra heat after the completion of first effect as this process automatically allows the seawater feed to undergo multiple boiling.

As the seawater reaches the first effect, the temperature of seawater is raised to the boiling point after being preheated in the tubes. Thereafter to carry out rapid evaporation, seawater is sprayed onto the surface of evaporator. The dual-purpose power plant is used so as to supply steam externally, and the tubes get heated. Condensation of steam occurs on the opposite side of the tube and forms steam condensate. Steam

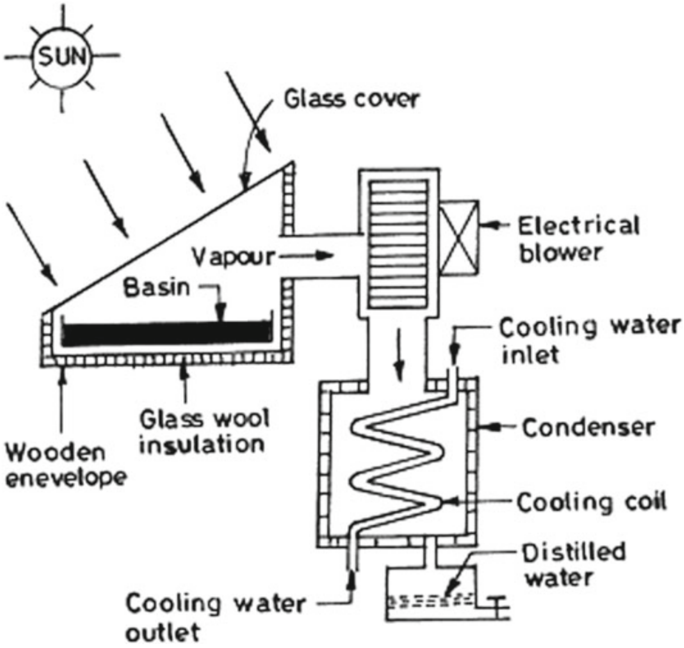

Fig. 4 Distillation using solar energy [2]

condensate is again utilized as boiler feed water after it gets recycled to the power plant. Cyclic process of hybrid solar distillation is shown in Fig. 4.

For every plant, its economy balance is quite necessary for its smooth running. Similarly for MED plant, its economy is the key factor that depends directly on its number of effects. Basically, MED is comprised of chained processes [8]. At first, evaporation of some portion of seawater in the tubes takes place at first effect. Then, the rest of seawater is again applied to the tube as it is fed to the second effect. Amid tubes are being heated by the water vapor formed in the first effect. As a result, this vapor is condensed to the required product that is freshwater. During the production of freshwater, vapor gives up its heat to evaporate the left seawater at next effect. Repetition of evaporation and condensation process takes place from one effect to another. This takes place successively at lower temperature and pressure. This process continues and makes a chained process. This continues for various effects with about 4–21 effects [23].

Top brine temperature (TBT) is one of the most important factors of MED plant. In MED plant, it is necessary to reduce scale formation of seawater in the tubes. To maintain this very challenge, most of the plant is built to operate on temperature of 70° TBT. But to carry out the processes smoothly, some additional heat transfer area is required which is generally fulfilled by the tubes. Performance ratio of MED plant ranges from 10 to 18. From the context of thermodynamics and heat transfer point of view, MED is better than MSFD as it needs less power but gives better performance.

Horizontal MED plant is more frequent than other types of plant [24]. Moreover, these are successfully operating for 30–40 years. Various types of tubes can be used in MED plant like vertical, horizontal, and submerged types. But most frequent is horizontal tubes.

3.3 Vapor Compression Distillation (VCD)

In VCD, compression of vapor plays an important role in providing heat to carry out evaporation of seawater. The basic principle of VCD is reduction of boiling point temperature by the reduction of pressure [25]. Due to this very principle, VCD takes advantage over other methods. Mainly, two methods are used to carry out VCD—they are steam jet and mechanical compressor. These two methods are used to condense water vapor so that sufficient heat can be produced to carry out evaporation of seawater. Here electrically driven method is mechanical compressor.

There exist various types of configuration of VCD units. This allows easy exchange of heat to carry out evaporation of seawater. Steam jet type of VCD is also called thermocompressor. In thermocompressor, there is a venturi orifice at the steam jet which creates and extracts water vapor from the evaporator, thus creates a lower ambient pressure. Thereafter, steam jet compresses the water vapor extracted by the venturi orifice. Then condensation of mixture takes place on the wall of tube which provides thermal energy to evaporate the seawater.

The other type of VCD is low-temperature VCD which requires only power. Hence, it is very simple, efficient, and reliable process. This method is applicable for mainly small-scale units of desalination. There are various application areas of VCD units like resorts, drilling sites, and industries. This is very beneficial as it can be used where there is lack of freshwater [26].

3.4 Reverse Osmosis (RO)

The basic principle involved in this process is that osmotic pressure is to be overcome. To overcome osmotic pressure, an external pressure is applied which is greater than that of osmotic pressure on seawater. In reverse osmosis process, flow of water reverses the direction of natural flow across the membrane; consequently, dissolved salt is left behind with increased salt concentration. In this process, there is no need of phase separation and heating. Here energy is required to pressurize the seawater feed to carry out the desalting process [27]. The key factors of RO plant is its major components. There are four major components of RO plant, and they are feed water pretreatment, membrane separation, high-pressure pumping, and permeate post-treatment.

There are various undesirable components in the seawater which can damage the membrane. Hence, there is a need to eliminate those constituents which is done

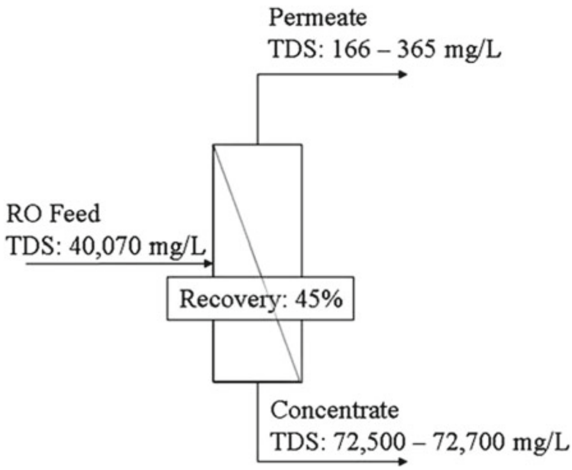

Fig. 5 Schematic of one-stage seawater RO [13]

by pretreatment [28]. Pretreatment of water includes various methods like coagulation, chlorination, acid addition, multimedia filtration, micron cartridge filtration, and dechlorination. Pretreatment of seawater feed depends on different factors like membrane type, feed water characteristics, membrane configuration, recovery ratio, and product water quality. Depending upon these factors, the type of pretreatment is selected.

The key factor of RO process is to reject salt present in the seawater, for which pretreated feedwater pressure is to be raised to that extent so that it should be appropriate to the RO membrane and water can easily pass through them. To raise such pressure, high-pressure stainless steel pumps are used. The membrane should be such that it can bear the entire pressure drop across it. Generally, centrifugal pumps are used to carry out this operation. An illustration of one-stage RO is shown in Fig. 5.

There are various membrane configurations, out of which spiral wound and hollow fine fiber (HFF) are most economical and commercially successful. The shape of HFF is like U-shaped fiber. In HFF, cellulose triacetate and polyamide are used as membrane materials [29].

Post-treatment is one of the most important components of RO process. In post treatment mainly pH is adjusted, lime is added and dissolved gases like H_2S and CO_2. Two changes and developments which were introduced in the previous decade have reduced the operating cost of RO plant. Those two developments are: development of membrane to operate efficiently for longer time and energy recovery device [30]. The devices are used for the purpose of converting pressure drop into rotating energy; hence, the devices are mechanical in nature.

3.5 Freezing

Desalination of seawater can also be done by the process of freezing. It is a very simple process to obtain freshwater from seawater. During freezing, ice crystals are formed. Due to formation of ice crystals, dissolved salts are removed. It can be achieved under controlled situation. The mixture of seawater is generally cleaned and washed for removing salt in the water left, just before the completion of freezing of whole water. Thus, freshwater is obtained by melting the frozen ice. Hence, desalination by freezing includes various processes like firstly seawater cooling, then partial crystallization of ice, thereafter ice is separated from seawater, then most importantly melting of ice to get freshwater, at last finishing processes refrigeration and heat rejection [31].

Desalination by freezing has lots of advantages. Some of them are lower power consumption, less corrosion, less scaling and precipitate formation. Along with advantages, there are disadvantages too like handling water and ice mixtures. This is very difficult to handle these two mixtures together as these are mechanically difficult to process.

Although this process has plenty of advantages, still this is not accepted commercially till now to produce freshwater in mass. Very few plants have been made till now which proves that it is not reliable. Most famous plant till now was constructed in Saudi Arabia in 1985. This very plant was an experimental solar-powered unit [32]. To govern plant status, few processes were developed like hydrate, indirect, eutectic, triple point, and secondary refrigerant processes [33].

3.6 Solar Distillation

Solar desalination is one such process of desalination in which solar energy is the primary energy source to carry out desalination of seawater. In this process, solar energy is used directly for desalinating seawater. Moreover, this process is similar to the process of hydrological cycle. In hydrological cycle, water vapor is produced by heating the seawater with the sun's ray, and then, condensation of vapor takes place which ultimately gives condensate which is further collected as product water. Greenhouse solar still is one of the examples of this type of desalination process [34].

This process was developed to increase the efficiency of solar still, but it was seen that it requires large solar collection area approximately 25 ha land/1000 m^3 of product water/day [26]. Not only space but also high capital cost and vulnerability to weather-related damage are also its disadvantages.

3.7 Potabilization

Potabilization is also a desalinating process, but it is an additive process to MSF. In other words, it is a suffix to MSF. When MSFD completes, there are some small amount of impurities like dissolved salts and minerals so the produced desalinated water is little bit corrosive to the metals used in materials for water distribution system. To avoid all these problems, potabilization is practiced [35].

There are mainly two typical methods which carry out potabilization process. These are: injection of carbon dioxide and hydrated lime [36], and carbonated water is passed through limestone bed filters [37]. Basically, there are four processes involved in potabilization process—carbonation, liming, chlorination, and aeration. Liming and carbonation processes signify remineralization of water by the addition of carbon dioxide and hydrated lime. The basic objective of liming and carbonation is to increase hardness, alkalinity, mineral content, and pH. There is a need to eliminate bacterial growth that is to disinfect water. To avoid water from infection, chlorination process is carried out [38]. It is done by injecting either chlorine gas or calcium hypochlorite. Last but not least, aeration process is carried out to replace oxygen so as to improve water taste.

4 Modification and Advancement in Different Technology of Desalination

4.1 Advancement in MSFD

MSFD is an efficient process of desalination. But there is a need for modification and optimization in design of equipment, design based on thermodynamics, selection of materials, structural aspects, techniques of construction and transportation. There has been a gradual evolution in MSFD which includes various changes in the design, construction, instrumentation, etc. [39]. There has been a gradual evolution in technologies of MSFD which includes vertical MSFD, chemical treatment, equilibration, construction materials, construction techniques, heat transfer, control, instrumentation, etc.

The concept of desalination came into account in the early 1960s. The increased demand for freshwater in the arid regions like Middle East prevailed the development of desalination. From then, desalination plant began in the market. At that time, as per the market demand, plant with capacity of 4500 m^3/day was built.

There were various problems in the initial stages of development of desalination plant. Mainly, design concept and economies were the two vital issues. Due to lack of concept of equilibration, discrepancy between brine and water vapor at low temperature increased. Due to changing and traditional technology, now plant of large size with capacity of 75,850 m^3/day is also viable like in UAE [40]. The size of MSFD plant can be extended up to 136,260 m^3/day as per the study [41].

The purity of the product water is disturbed due the entry of brine into vapor stream. To overcome this problem, "demisters" are installed. There is a need to care of the design and position of demisters in the evaporator. As the scale formation in MSFD is very less, to overcome the least amount of scale formation some chemical additives had been developed [42]. Various additives were introduced and rejected. Later high-temperature additives were taken into account which can allow the operation at even 115°.

In the initial stage of construction of MSFD plants, carbon steel (CS) material was generally used for the mechanical parts of the plant, mainly the shell. Later its use was omitted due to its heavy weight. Then stainless steel (SS) and duplex steel came into account as the major materials for mechanical components. Use of SS reduced the weight of the mechanical components and size of the plant. Moreover, the use of SS reduced the cost of production of water.

To improve heat and mass transfer performance of ejector system, titanium tubes were used. Titanium tubes controlled the corrosive vapors inside the evaporator effectively. Later Incoloy 825 nickel was also used for making ejector as it has a very high pitting resistance equivalent (PRE) number [43].

Optimization of equipment makes possible for the plant to delete major redundancies from the plant configuration. Due to certain changes and advancement in technologies in MSFD plant designing fouling factors have been reduced in thermodynamic design of MSF plants. Later on, improvement in transportation and manufacturing has also improved. Due to improvement in manufacturing and transportation, completion of whole project can be achieved in a very short time. Venting system has also been improved which has resulted in diminishing of concentration of corrosive gas inside the evaporator. This very improvement has increased the life of evaporator equipment.

Due to all these improvements and advancements, performance of the MSFD plant has improved a lot. When plant is newly set up, its performance ratio is nearly 9 and after some years it becomes 8, and 7.5 in fouled condition.

4.2 Advancement in MED

MED is one of the large-scale and cost-effective desalination plants. It consumes less power than that of MSFD [44]. It has significant potential to reduce cost of product water. Its rated power consumption is below 1.8 Kwh/m^3 of distillate.

Gained output ratio which is abbreviated as GOR is higher for MED as compared to MSFD. GOR value of MSFD is 10, whereas MED has GOR value of 15. There are various plants with various units which have been set up and some are under construction. Basically, low-temperature MED plants are being made and under construction. In Sharjah, there are two units of MED plant with the capacity of 22,700 m^3/day. There exists a design and demonstration module for capacity of 45,400 m^3/day. The main issue of desalination plant is scaling and rate of corrosion. Design of MED with TBT of about 70° has prevented this problem [45].

There was a plan in Southern California, USA, to build a unit of capacity 283,875 m^3/day whose budget was approximately $30 million. The main purpose of this plant was to use vertical tube MED process. The main objective of this plant was to reduce plant's capital cost too.

4.3 Advancement in Reverse Osmosis

There have been a lot of changes and improvements in technology in RO process. These very advancements have helped in reducing both capital and operational costs. There are various improvements in different components of the RO plant, but most of the progress has been made in the membranes. Thus, various areas were improved like resistance to compression became better, durability increased, flux was improved, and salt passage was also improved and became smooth.

In 1970s and 1980s, RO came into effect as a competitor to MSFD. It has been observed that RO train size has increased as compared to the previous RO trains. RO train size has reached to 9084–13,626 m^3/day some years back. But it is still smaller than that of the size of MSFD plants which were in the range of 56,775–68,130 m^3/day at that time. There had been a major difference in capacity of RO plant between 2005 and 2008. The capacity of plant has reached to 3.5 from 2 million m^3/day [46].

Presently, the recovery rate in the RO plant is nearly 35%. This recovery has been achieved in Middle East nations where about 70% of the desalination water in the world is produced. As per the latest report, 60% recovery rate has been reported in the region of Pacific Ocean [47].

Recovery of energy helps RO plant to consume less energy as compared to other plants. RO plant consumes approximately 6–8 kWh/m^3 excluding recovery of energy. But including energy recovery, power consumption reduces to 4–5 KWh/m^3. Currently as per the survey, energy consumption has been drastically reduced to the range of 1.8–2.2 kWh/m^3 due to advancement in RO technology [48].

RO method for desalination has lots of advantages, but there is a problem with RO method. The problem of pretreatment is a big deal for RO plant [49]. Previously for pretreatment, filtration process was used but as per the report it is an inadequate process for pretreatment. Silt Density Index (SDI) is the key factor for RO plant. It is very necessary to maintain the required filtrated SDI, but it is difficult for RO plant to maintain the required SDI which is a major disadvantage of RO plant.

To resolve this issue of pretreatment, a technology has been developed called nanofiltration (NF). NF membrane treatment proved beneficial, and excellent results were obtained [50]. This process increased the rate of production by 40% and also prevented membrane fouling. There were various materials which were used to develop RO membrane, and some of them are polyether amide hydrazide, polyhydroxyethyl methacrylate, etc.

Presently, membranes of low energy and high productivity are available. Manufacturers of membrane now provide membrane of capacity 47.5 m^3/day [46].

5 Economics Related with Desalination

The economy of a plant depends primarily on production cost, location of plant, maintenance cost, energy consumption, etc. Due to change in technologies and advancements in desalination, cost of production is decreasing gradually but on the other hand due to more contamination of water because of population, pollution, etc., cost of water treatment is increasing day by day due to high demand of pure water.

The key factors to select process between two major processes for desalination of water like RO and MSFD are technical and economic conditions. Some of the technical conditions which are taken into account are energy source, energy consumption, freshwater quality, space for plant, plant reliability, operational aspects, plant size, etc. Economic conditions are taken into account based on capital, labor, materials, chemicals, etc. [51].

For a desalination plant, a cogeneration scheme is necessary in conjunction with the generation of power for the best economy of the plant. Economics of desalination plant is determined by the life cycle cost analysis. To evaluate annual plant cost, O&M, that is operation and maintenance costs, are converted into annual cost. The cost of production of water is evaluated by dividing the sum of all costs by total quantity of water. There are various parameters which affect the life cycle cost analysis like plant life, direct capital cost, indirect capital cost, and capacity of production. This cost of production of freshwater is estimated in $\$/m^3$. For example, the world's largest RO plant has water production cost of $\$0.53/m^3$ [52].

6 Future Expectance

In last two decades, there have been various improvements in desalination of brackish and brine water. Many new technology and advancements have been introduced to increase the production of water from desalination. Economic condition has also improved due to reduction in water production costs. It has been accepted with advancement in technology mainly in arid regions of the world [8]. To minimize cost of production of water from desalination, further R&D has been taken into account. There is a need to emphasize R&D in technological advancements to improve the plant's economy. There are various parts and factors linked to desalination where R&D efforts are made and some of them are [53]: cogeneration system of desalinated water and power, energy utilization mainly solar energy and nuclear energy, thermal distillation process at very high temperature, technical aspects of different methods of desalination, chemical therapy for seawater feed, economy of different desalination processes, perfect choice of construction and manufacturing materials, promotion of large-scale plants, scale-controlling system, cost-effective materials, introduction of hybrid systems like NF-RO, MSF-RO, etc., environmentally friendly desalination, sent percent separation of seawater and freshwater.

7 Solar Still

Water is the most important component of our planet. It covers about 75% of the Earth, but still out of that much abundant water only 1% can be used as domestic purpose, perhaps which are being contaminated by various factors like pollution, sewage disposal, etc. There is a need to obtain freshwater, and most of the water present on the Earth is brackish and salty. Desalination is one of the measures to get freshwater from brackish water. To utilize desalination as an important measure, solar still is being introduced in this developing world. Solar still is a device which is completely based on the principle of desalination. It mainly uses the concept of solar distillation. It is now being used worldwide mainly in coastal areas where seawater is available in abundance. It is simple, cost-effective, and easily maintained process [54]. The main disadvantage of solar still is that it has less productivity. Various researches and developments are going on so as to enhance the efficiency of solar still.

For the development and modification of solar still, various researches are going on the basic design of solar still to increase its productivity and make it more cost-effective [55]. The main idea for increasing the productivity of solar still is by increasing heat transfer rate. To implement this very idea, many researchers have used fins [56].

Srithar and Mani are very famous scientists who have worked a lot on the development of solar still. Both of them dealt with the evaporation rate of industrial effluents. They developed a pilot plant for augmenting the evaporation rate. They developed pilot plant in two stages, one with spray network systems and another with open fiber-reinforced plastic flat plate collector. Then, they both analyzed the performances of them separately and compared to select the better one [57]. Sometimes, performance was judged by means of usage of sponges.

There are various components of solar still like glass cover, container, basin liner, and trough. In solar still, black paint is used to coat inside surface of container; then, collector is combined connected to glass cover. Saline and brackish water is filled into the container under purification. Glass cover helps the radiation from the sun to be transmitted and later would be absorbed by the basin which further heats the impure water. Thereafter, condensation of evaporated water takes place below the glass surface. Thus, it gathers in a trough which is located along the length. Simple basin solar still is shown in Fig. 6 [1].

Figure 7 shows schematic diagram of solar still with basin. This solar still consists of different parts with different application. Various components of this solar still with simple basin are storage tank, valve, wooden box, hose, glass cover, still basin, collection tray, and measuring jar. The working of this solar still is very simple. Storage tank is the reservoir of water. It can have different capacity based on the requirement. Water from the tank reaches still through two mediums—one is flexible hoses and another is valve. The role of valve is to control the flow of water as per the need. Hoses are very flexible, and to maintain its flexibility, it is made of polyvinyl chloride (PVC).

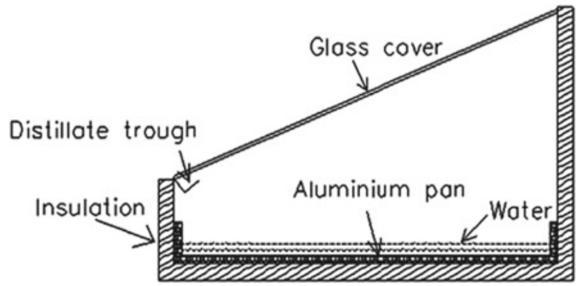

Fig. 6 Single-basin solar still [58]

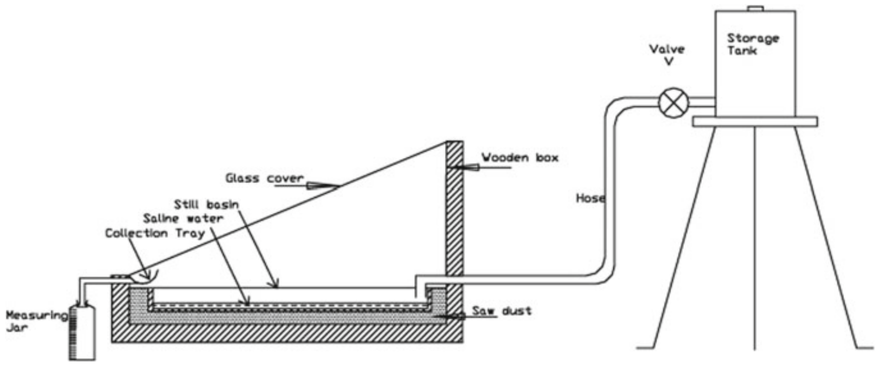

Fig. 7 Solar still with simple basin [56]

Here, still basin is painted black and is enclosed within the wooden box. Wooden box acts as a casing for still. There is a need of insulation in the still; hence, saw dust is used. It is filled below the still basin. To collect the condensate after condensation of the evaporated water, collection tray is used which is fixed to the wooden box and thus freshwater is collected.

8 Types of Solar Still

There are basically two types of solar stills which are based on the effect, and these are single- and multi-effect solar stills. These two types of solar stills are further subdivided as active and passive stills which are categorized based on the source of heat provided to carry out evaporation of water [1]. In one type, evaporation of water takes place directly but in another type an external medium is required like heat exchanger or solar collector to carry out evaporation of water. There are basically two types of solar still, and they are as follows.

8.1 Single-Effect Solar Still

The origin of the solar still development is single-effect solar still. It is also called an original solar still. It is the simplest of all solar stills [59]. In this type of solar still, there is only one layer of glazing present over the surface of water. This very characteristic of single-effect solar still has proved one of the advantages. Due to presence of single layer of glazing, large quantity of heat loss takes place thus reduces its efficiency. This heat loss takes place in form of conduction. Thus, efficiency of this type of solar still is about 30–40% [1]. This type of solar still is also known as single-slope solar still. Many experiments and studies have been done to improve its efficiency. Experimental setup for single-effect solar still comprised of various components like glass cover, measuring devices, basin liner, insulating materials, and distillate channels. Every component has different functions, and all works together to carry out easy and proper desalination process. A simple single-effect solar still is shown in Fig. 7 with full illustration. The working and function of different components of single-effect solar still is as under:

- Glass cover: It is the most important component of solar still. It is setup at an angle to the horizontal. Generally, to strengthen the contact between glass and other components of the solar still, silicon rubber is used. Another important additive is sealant, which acts as a frame to the still. It resists and compensates any expansion and contraction between different materials.
- Basin liner: It is the base of the solar still. It has many properties like high resistance to hot brackish water, high absorptivity, etc. Its main task is to absorb the radiation coming from the glass cover. It can be easily mended if damaged. Generally, asphalt is used as basin liner.
- Measuring devices: In solar still, there is a need to measure two parameters, one is temperature and another one is wind speed. Digital anemometer is used so as to measure the wind speed. Thermocouples are generally used to measure temperature at different locations. Here thermocouples are connected to digital thermometer. Mainly, five thermocouples are used so as to measure the temperature at five locations like vapor, water, basin, glass in and out. Also intensity of solar radiation is measured by using heliometer.

Single-effect solar stills are further divided into two categories, named active and passive solar stills which have been explained below.

8.1.1 Active Still

In single-effect solar still, active still deals with source of heat which are external like industrial waste heat or solar collectors [1]. There are various types of active stills used in single-effect solar still, and these are:

- Regenerative active solar still
- Air-bubbled solar still

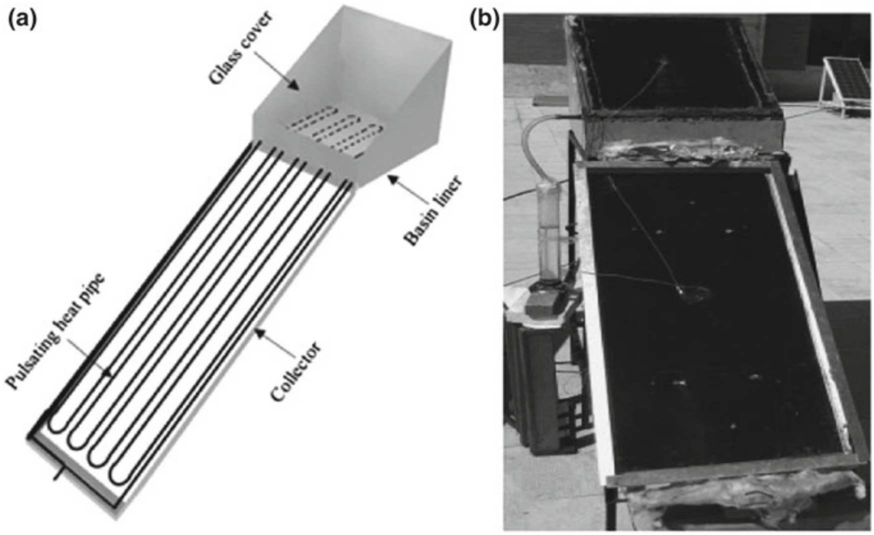

Fig. 8 Active still coupled to evacuated tube collector [60]

- Waste heat recovery active solar still
- Solar still with heat exchanger
- Solar still integrated with solar concentrator
- Solar still coupled with hybrid system
- Solar still integrated with solar heaters

Following Fig. 8 is an illustration of active still which is coupled to evacuated tube collector.

8.1.2 Passive Still

Passive still differs from active still as per the source of heat provided to evaporate the brackish water. In passive still, internal heat from the still is taken in order to carry out evaporation of brackish or brine water [1]. There are different types of passive solar still for single-effect solar still, and these are as follows:

- Basin solar still
- Wick solar still
- Weir-type still
- Spherical still
- Tubular still
- Pyramidal and rectangular still
- Diffusion still
- Greenhouse combination solar still

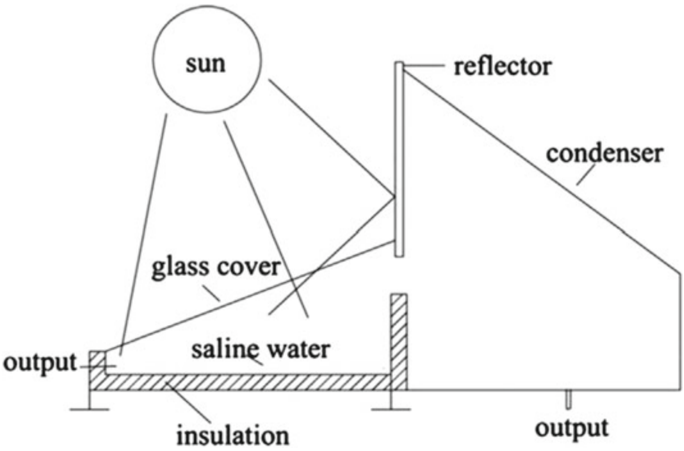

Fig. 9 Passive still coupled with outside condenser [61]

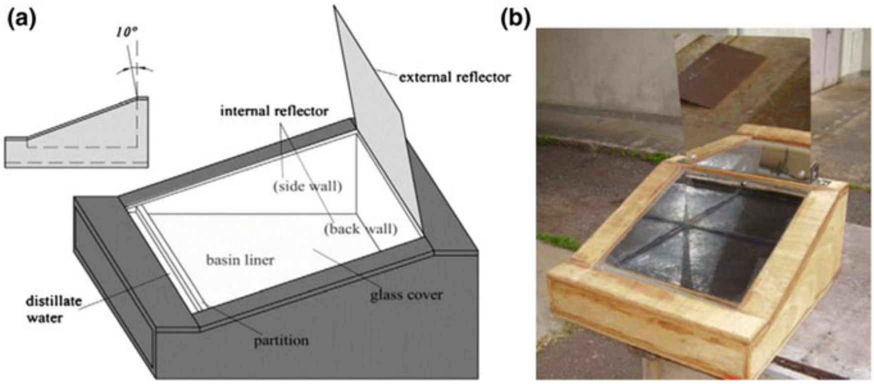

Fig. 10 Passive still coupled with internal and external reflectors: **a** schematic diagram and **b** experimental setup [62]

In Figs. 9 and 10, passive still with different arrangements is shown. Figure 9 shows passive still arrangement which is coupled with outside condenser, and Fig. 10 illustrates passive solar still which is coupled with internal and external reflectors both schematic and experimentally setup.

8.2 Multi-effect Solar Still

Multi-effect solar still is another type of solar still which is quite different from single-effect solar still. Multi-effect solar still is more efficient than that of single-effect solar still. Latent heat of condensation plays an important role in case of multi-effect solar

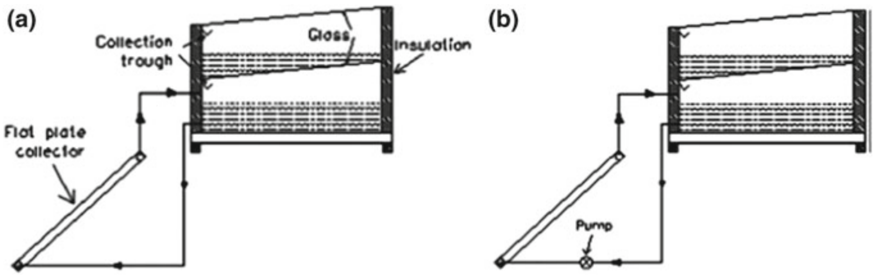

Fig. 11 Double-effect single-slope active still: **a** coupled with solar collector in thermosiphon mode and **b** coupled with solar collector in forced circulation mode [64]

still. In multi-effect solar still, recovery of latent heat of condensation takes place which is further recycled and thus increases the potential with high rate of production [63]. This is also further classified as passive and active stills based on its design. This type of solar still is also classified as active and passive stills which have been explained below.

8.2.1 Active Still

In active still based on multi-effect solar still, the basic fundamental principle is same as that of single effect; only there is the difference in context of design. Different types of active solar still based on multi-effect solar still are as follows:

- Multi-stage evacuated active solar still
- Multi-basin inverted absorber active still
- Waste heat recovery active still
- Solar still coupled with concentrating solar collectors
- Multi-effect condensation–evaporation water distillation system
- Stills coupled with solar collectors like flat plate and tube collector

In Fig. 11, multi-effect active still with single slope coupled with solar collector in thermosiphon and forced circulation mode is shown schematically. In Fig. 12, condensation–evaporation active still system is shown.

8.2.2 Passive Still

In case of multi-effect solar still, there is only a difference in context of design when passive still is considered, otherwise the whole fundamental principle is completely same. There are different types of passive solar still in case of multi-effect solar still, and these are as under:

- Wick solar stills
- Basin solar stills

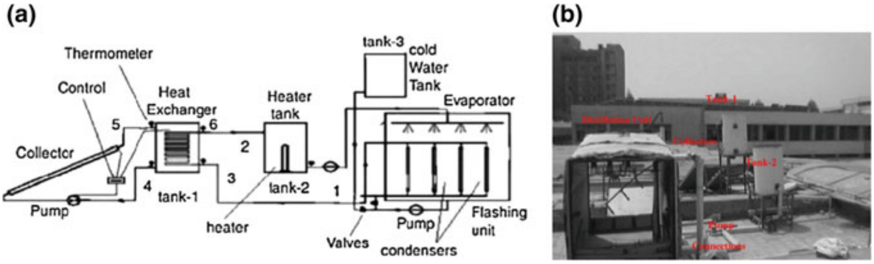

Fig. 12 Condensation–evaporation active still system: **a** schematic diagram and **b** experimental setup [65]

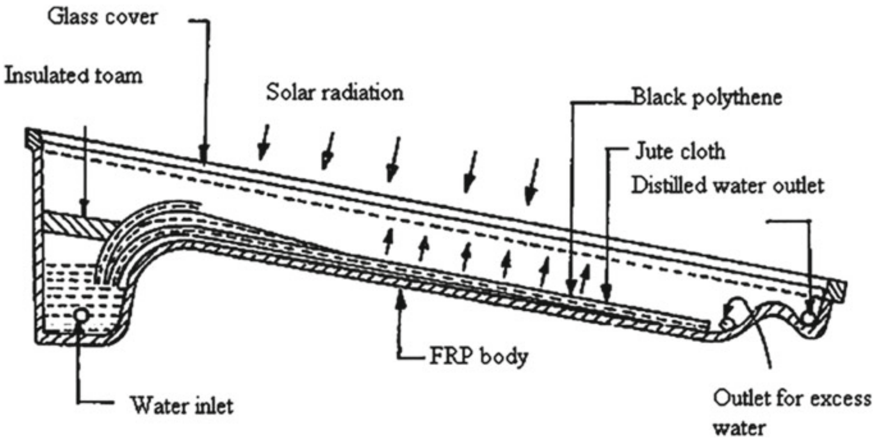

Fig. 13 Wick-type passive solar still [58]

- Weir-type solar stills
- Diffusion solar stills

In Fig. 13, passive still with wick-type solar still is depicted and in Fig. 14 double-basin double-effect passive still is shown schematically.

9 Conclusion

Water is very necessary for human beings. The rapid increasing pollution and population has resulted in contaminated water. The availability of freshwater is limited on the Earth, so there is a need to obtain more freshwater for the survival of human beings and their day-to-day utilities. Desalination has proved to be the best measure to obtain freshwater as salty water covers almost 70% of the Earth. To make best use of desalination, solar still can be used as an efficient device to obtain more and more

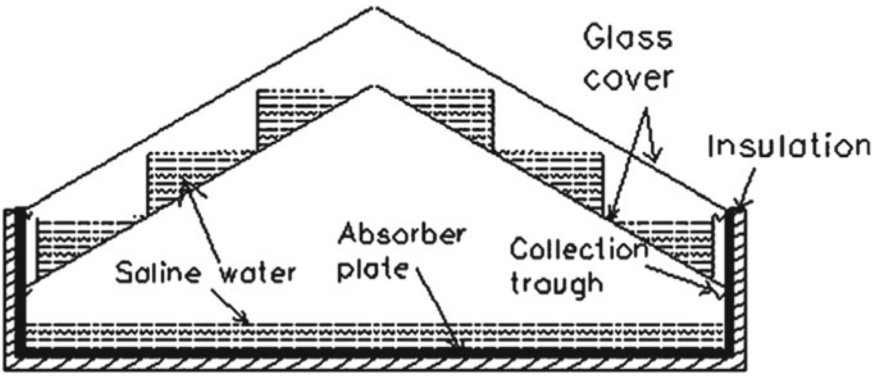

Fig. 14 Double-effect passive still with double basin [58]

freshwater. Various researches are going on in the field of solar still. These are the following points which can be concluded from this review:

- Desalination is the most cost-effective way to enhance freshwater availability on the Earth. The demand of freshwater is rapidly increasing day by day.
- Demister plays prominent role in MSFD as it is used to overcome the brine into vapor system so as to keep purity of water undisturbed.
- Stainless steel and duplex steel were accepted as the principle material to make accessories of MSFD plant. Moreover, stainless steel reduced the weight and cost of production of freshwater.
- For the construction of ejector required in MSFD, Incoloy 825 Nickel was used as the chief material due its high pitting resistance equivalent (PRE) number.
- Gained output ratio (GOR) is more for MED than MSFD. It is about 15 for MED and 10 for MSFD.
- RO is the most effective and efficient method for desalination. Pretreatment is the main issue that is to be solved smoothly in RO plant, and to overcome this problem, new technology arrived which is named nanofiltration (NF) membrane treatment. Moreover, NF technology helped in increasing production rate by 40% and avoided membrane fouling.
- Technical and economic conditions are the key factors to decide which process should be used for desalination whether RO or MSFD. These two processes are the mainly used desalination process in the growing world.
- Life cycle cost analysis plays a vital role in deciding economics for a desalination plants.
- Solar still is the simplest device to obtain freshwater from abundant salty water. It works on the basic principle of solar distillation.
- The productivity of solar still is not high so there is a need to increase heat transfer rate to increase the rate of production.

- Previously, single-plate solar stills were introduced in the market but later on after various researches and changes, multi-effect solar still arrived in the market with more efficiency and rate of production.
- Solar still is mainly categorized as active and passive stills. This classification is based on the source of heat provided so as to carry out evaporation process. Active still takes heat from the external sources like industrial waste or by using solar collectors whether passive still takes heat internally from the still to carry out evaporation of water.
- The configuration of solar still is very simple. It is very cost-effective device to obtain freshwater from brackish and brine water. It has been proved very beneficial for arid and semiarid regions where there is more shortage of freshwater as compared to other regions of the world. Various researches are going on so as to increase its efficiency and introduce it as a large-scale production device.

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