Chapter 8

Solar Thermal-Driven Desalination Pursuing Products of Pure Water and Salts and Leaving Minimum Impact to Environment

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Additional information is available at the end of the chapter

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Abstract

Desalination, removal of salt and other minerals from seawater, brackish water, and wastewater, is becoming a promising solution for providing the increasing need of freshwater. It is highly desirable that environmentally friendly renewable energy resources be utilized for water treatment to minimize the consumption of fossil fuels. Given that most desalination systems can directly use thermal energy, concentrated solar thermal energy is very suitable for application to the water treatment. To avoid the potential negative impacts from disposing the concentrates, recovery of important minerals from concentrates to achieve zero discharge is a promising option. The recent technology development on solar thermal energy storages has shown that sea salts are very promising materials for large-scale thermal energy storage. Hence, a full separation of salts and water in desalination process becomes a necessity in advanced water treatment technologies, which should be achieved in an economically feasible way. Literature review and studies about innovative concept of full separation desalination system will be presented in this study. A full separation device integrated with conventional multieffect distillation or multistage flashing water treatment system will be introduced into the system design to enhance the water productivity and thermal efficiency.

Keywords: desalination, full separation multieffect distillation (FSMED), concentrating solar power (CSP), thermal energy storage (TES)

1. Introduction to desalination process

The population growth, urbanization, and climate change lead to increase in household and industrial uses of more freshwater, while natural freshwater reserves cannot meet the demands. Over one-third of the population lives in water-stressed countries, and by 2025 this figure is projected to rise to two-thirds [1]. Water with sufficient quantity and good quality for household uses and industrial applications is critical to health and well-being, as well as the opportunities to achieve human and economic development. Desalination, removal of salt and other minerals from seawater, brackish water, and wastewater, is a promising solution to grow the supply for fresh water. Presently, many arid areas have to rely on desalination to provide major quantities of safe water [2].

According to the International Desalination Association (IDA), there are 18,426 desalination plants in operation in more than 150 countries in June 2015, producing about 86.8 million cubic meters of water per day [3]. This number is continuously growing as the need for fresh water supply grows. **Figure 1** shows the world desalination plants per geographical area, and over half of these plants are in the Middle East.

A simplified process sequence of a typical desalination plant is provided in **Figure 2**. A brief introduction of the source intake, pretreatment, and post-treatment is given below, whereas the detailed description of the desalination process will be given in the next section.

Basically, there are two types of intake facilities to access reliable water sources: subsurface and open ocean intakes [6]. Proper design of the intake facility would not only protect downstream equipment and reduce adverse effects on aquatic life but also be beneficial to system productivity and capital/operating costs. The choice of the intake facility depends on the geographical conditions and desalination technology employed. For example, the raw feed water obtained from the intake well (belong to subsurface intake) is pretreated via slow filtration which is beneficial to the pretreatment process. However, the intake well is usually used for small-scale desalination plant due to their small productivity [5].

In addition to dissolved solids, the raw feed water generally contains other impurities such as silt, algae, bacteria, and even small aquatic life. The pretreatment process, involving some filtration and physical-chemical processes, is mainly used to improve the quality of the raw feed water to meet the requirement of different desalination technologies. Generally, the membrane desalination requires a higher degree of pretreatment than distillation technologies. To ensure that the product water from the desalination process meets statutory water quality standards for public health and protection of the water distribution system, post-treatment of the product water is necessary. This process may involve pH adjustment, disinfection, boron removal, and addition of minerals and corrosion inhibitors.

Despite the tremendous improvements in conventional water treatment technology, desalination industry is still facing several practical challenges on high-energy consumption, using either membrane-based technologies or thermal-based phase change approaches. Therefore, it is highly desirable that environmentally friendly renewable energy resources should be utilized for water treatment to minimize the consumption of fossil fuels. More details on this issue can be found in Section 3.

Another key concern associated with the desalination is the potential negative environmental impacts caused by the concentrated discharges to the environment, such as the adverse effects on water and sediment quality, aquatic lives, and the functioning of ecosystems. The concentrate is generated as a side product of the desalination process, which contains most of the

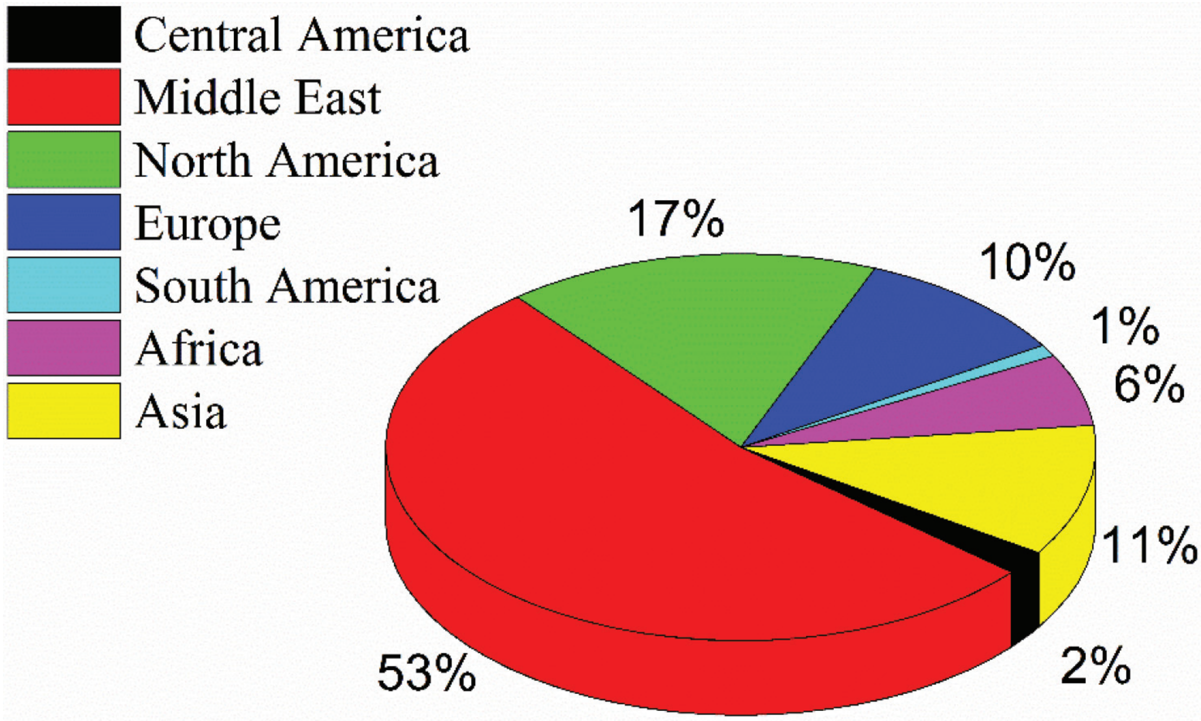

Figure 1. World desalination plants per geographical area [4].

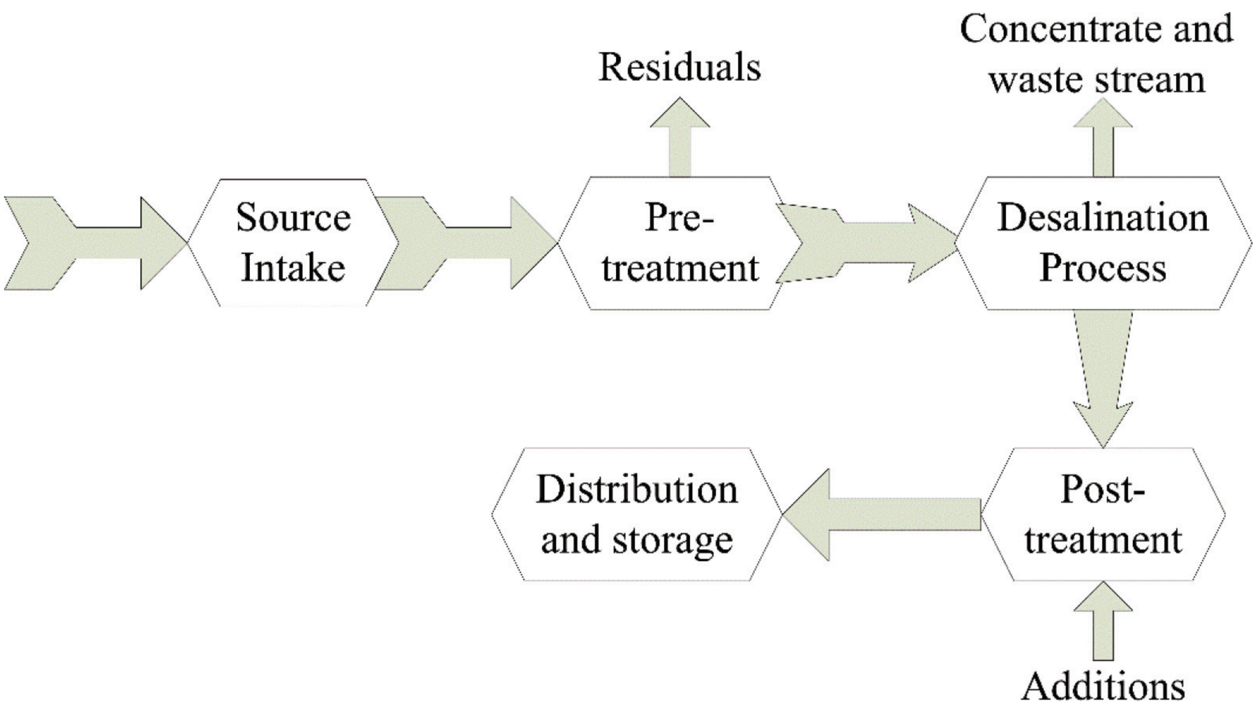

Figure 2. Typical sequence of desalination treatment and distribution processes [5].

minerals and contaminants of the source water and pretreatment additives in concentrated form. Based on a survey of concentrated disposal methods in 203 desalination plants in USA [7], it turns out that 87% of all 203 desalination plants are using surface water discharge and sanitary sewer discharge methods, while the rest part includes deep-well injection, evaporation ponds, and spray irrigation methods, unfortunately none of them has any zero-liquid discharge technology applied.

Obviously, most of the desalination brines are disposed to the sea or the sewer lines, and this will lead to adverse effects to the environment. To avoid the potential negative impacts from disposing the concentrates, exploring the options of recovering the dissolved salts from the desalination effluent to achieve zero-liquid discharge is necessary. The existing method to recover salts from desalination is solar pond approach which requires extensive areas of land. To better understand all the pros and cons, a brief review of various desalination technologies will be provided in the next section, then a novel water and solute full separation process using solar thermal energy will be introduced. Unlike the existing process which uses crystallizer, the proposed approach is a once-through process involving zero recirculation and zero-liquid discharge. It is expected that the proposed full separation thermal-driven desalination process in this work can address problems of concentrated discharge disposal, solute recovery, and high-energy consumption.

2. Classification of desalination technologies

Currently, most of the desalination plants have been implemented in large scales; there are more than 15,000 desalination plants installed by 2010 in the world, with a production capacity of 65 million m^3/day for both domestic consumption and industrial water production. There are a lot of different desalination technologies, some of them have already been fully developed at large scales, whereas others are still in pilot scales for demonstration or laboratory scales for research and development. **Figure 3** provides a list of common desalination technologies.

Basically, desalination process can be categorized as two major ones: thermal desalination and mechanical desalination. Thermal desalination utilizes the heat from combustion, power block, or even renewable energy to evaporate seawater. Vapor compression can be combined with thermal and mechanical desalination, which has the capability of increasing volumes and efficiency of the whole process. Thermal desalination has three classifications, which include filtration, evaporation, and crystallization. Mechanical desalination is discussed in this section and thermal desalination will be introduced in the next section.

Reverse osmosis (RO) is a membrane separation process that recovers water from a saline solution pressurized to a point greater than the osmotic pressure of the solution. The saline water is fed to the porous membranes at high pressures. The hydrophilic membranes allow only water to pass through it, as shown in **Figure 4**. This technique requires high-pressure pumps and costly membranes; also the membrane is susceptible to fouling and needs frequent replacement, which results in high cost of maintenance. Incorporation of energy recovery system reduces specific energy consumption and product cost but increases the capital cost. The product cost is significantly affected by the price of electricity in this technique.

Pressurizing the saline water accounts for most of the energy consumed in RO. The osmotic pressure required to separate water from the brine is related to the salt concentration; therefore,

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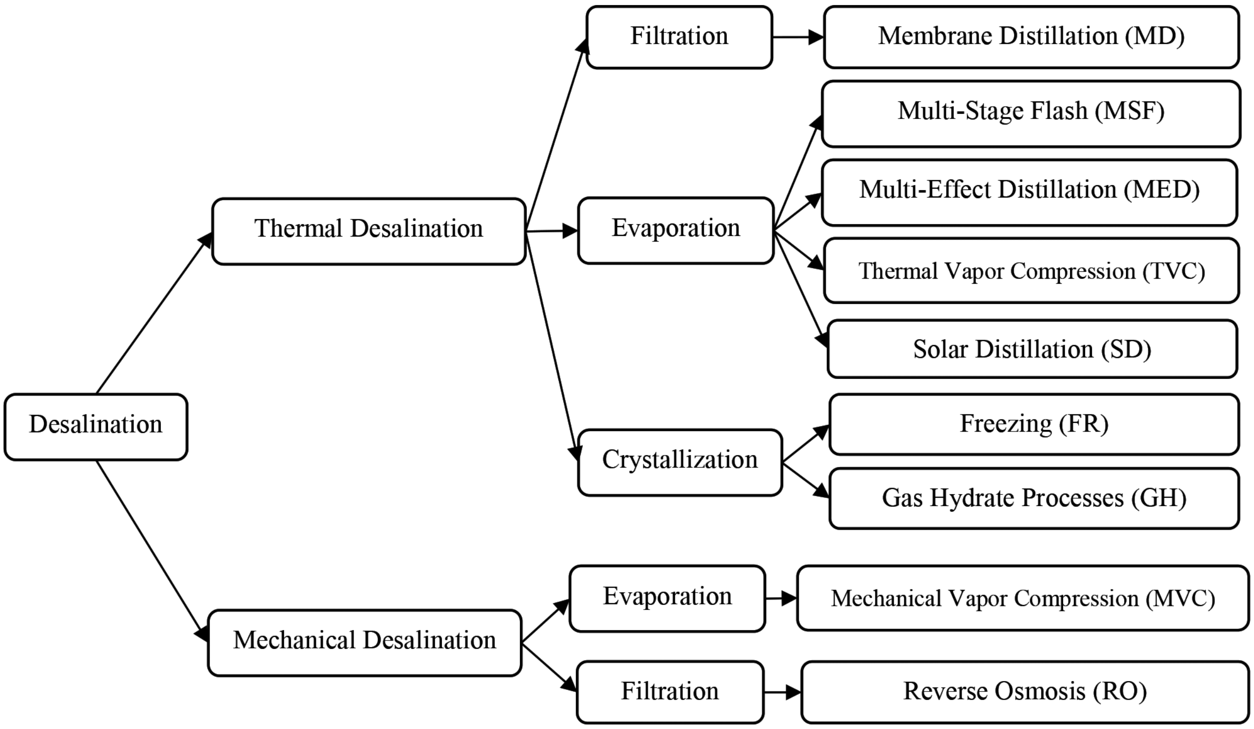

Figure 3. A list of contemporary desalination technologies.

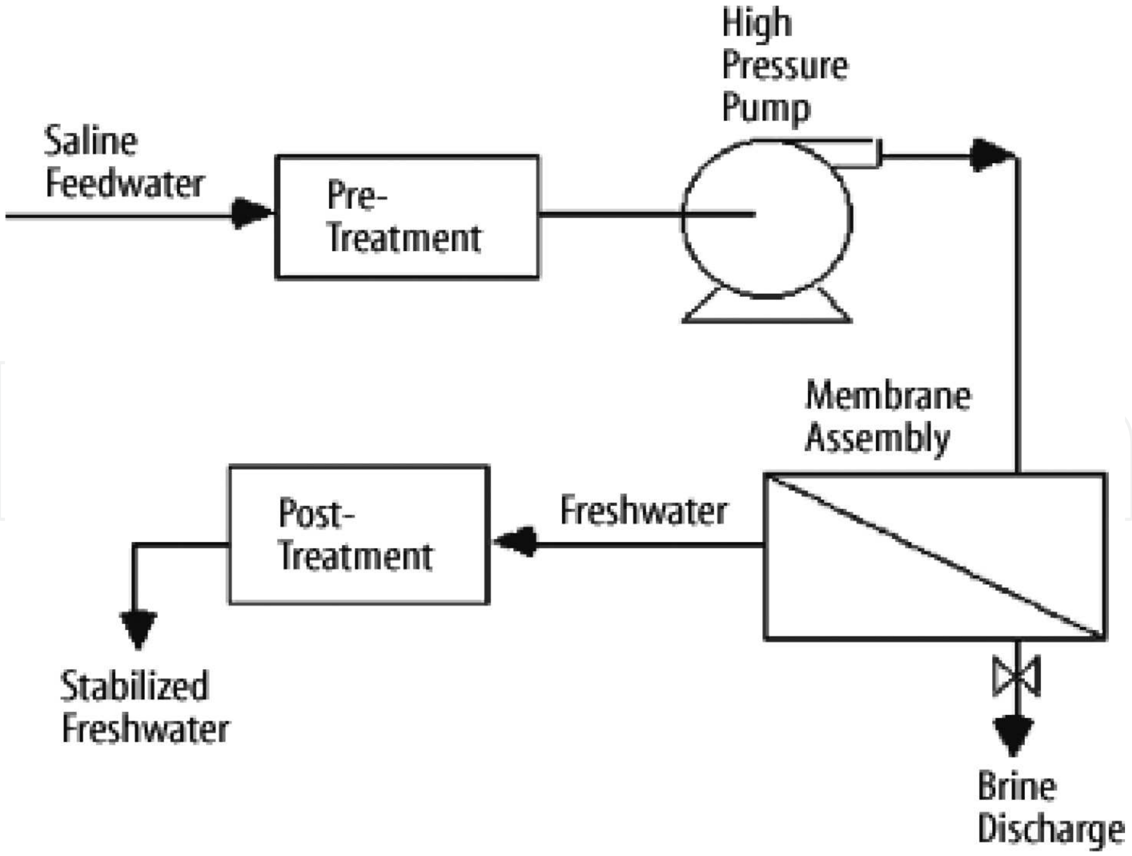

Figure 4. Schematic of RO [8].

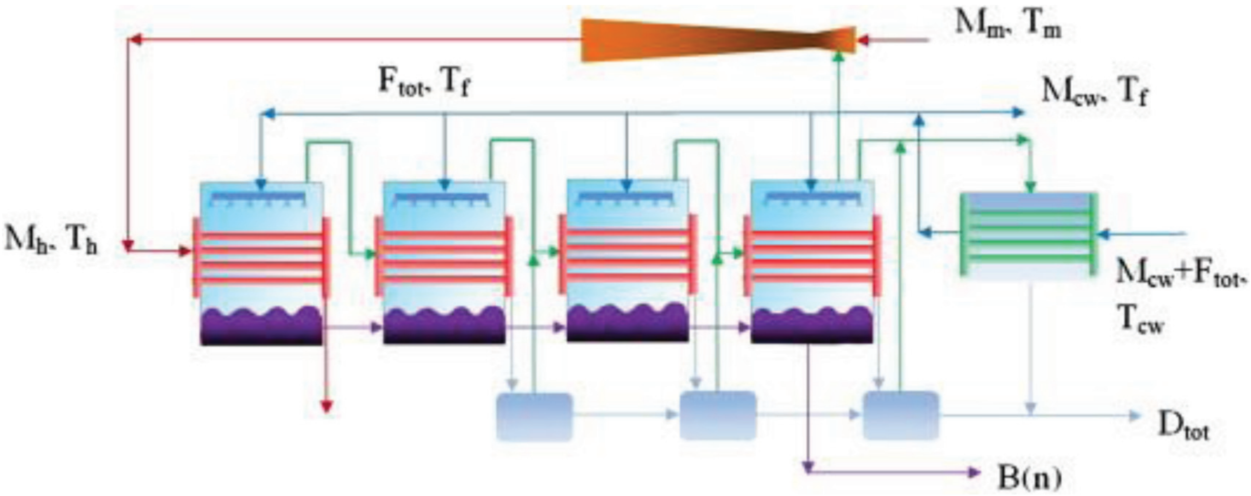

Figure 5. Principle of vapor compression [9].

RO has been considered as a practical approach for brackish water, due to the fact that brackish water only requires low to intermediate pressure range (10–15 bar) for the RO process, which is only one-fifth of the pressure for seawater RO process.

To improve the system efficiency, vapor compression can be added to a multieffect distillation (MED) process, as shown in **Figure 5**. The reuse of vapor is the key for vapor compression process, where the vapor is generated from the distiller after recompression. The first module in **Figure 5** can be heated up by utilizing the recovered heat from the partially recompressed vapor on stage. The vapor can be compressed either by a mechanical compressor or by a steam ejector, which can be categorized as mechanical vapor compression (MVC) and thermal vapor compression (TVC), respectively,

For TVC, motive steam (in ejector) at higher pressure is withdrawn from another process, for example, a steam power cycle or an industrial process steam. MVC is useful for small- or medium-scale desalination plants. MVC units typically can generate fresh water up to about 3000 m^3/day, while TVC units have much more capacity, with daily fresh water generation of 36,000 m^3. Most of MVC systems have only one stage, while TVC systems usually have several stages. This difference arises from the fact that the pressure and temperature increased by the compressor and its capacity are limited.

3. Thermal-driven desalination systems and the application of molten salts as heat transfer fluid in concentrating solar power plants

3.1. Thermal-driven desalination systems

Conventional thermal-driven desalination technologies are broadly classified into two major categories: filtration and evaporation. The thermal distillation systems will heat saline water

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and separate the relatively pure vapor for subsequent condensation and use. Membrane separation systems usually drive high-pressure pumps that overcome osmotic pressure differentials or create electric fields that drive electro-migration of ions in solution. **Figure 6** summarizes all these methods.

3.1.1. Multistage flash (MSF)

MSF is based on the principle of heating the fluid at certain pressure and then flashing it at lower pressure to form vapor, as shown in **Figure 7**. This vapor is collected and condensed which gives purified water. Here, the brine water is fed through a series of feed water heaters, to recover the energy from flashed steam, and then fed to an unfired boiler or a heat exchanger. The brine water gains maximum heat at unfired boiler and then flashed in several stages with decreasing pressure, each stage giving out some amount of steam. The difference of pressure between subsequent stages is the main factor influencing steam production in each stage. Highly concentrated brine is discharged from the last stage. The main problem of MSF process is the low-performance ratio which causes lower efficiency; however, it has lower scaling problems than that of MED due to relatively simpler design [10]. The number of MSF plants grows since its conception. And the cost of MSF equipment has been reduced by 50% in the last 20 years; however, this is accompanied with an increasing unit size [11]. Therefore, MSF units are economical with large capacities. In case of solar-coupled MSF system, the low-pressure steam can be formed by circulating water through the field of parabolic trough collectors.

An optimization study indicates that there is significant declining trend of product water cost with increasing top brine temperature (TBT). For a 30-stage MSF plant product, water cost is 1.15 $\$/m^3$ for 347 K TBT, and that for 377 K TBT is 0.95 $\$/m^3$ [13]. However, the TBT corresponding to the minimum product cost cannot be achieved due to the problem of scaling at high TBT. The area of technical optimization for MSF can be new corrosion-resistant alloys and corrosion and scale-inhibiting techniques.

3.1.2. Multieffect distillation (MED)

The governing principle for MED is to boil inlet seawater or brine in different evaporation effects, as shown in **Figure 8**. In the first effect, heat given by steam from waste heat source or solar collector is used to vaporize seawater. The generated vapor passes to the next effect. This vapor loses its latent heat to evaporate a part of seawater fed in the next effect, and so on. Flow schemes for MED systems include forward feeding, backward feeding, parallel feeding, and parallel feeding with cross flow. In forward feed, the direction of brine flow and steam flow is same and all the feed seawater is sent to first effect; in backward feeding, the direction of brine flow is opposite to steam flow and the seawater is firstly introduced into the last effect. Backward feed scheme makes more sense thermodynamically, but the first effect receives highest concentration brine at a high temperature. This escalates the scaling problems; therefore, this scheme is avoided. In parallel feed scheme, feed is equally divided and distributed to different effects. MED units typically operate below 120°C TBT, to avoid the problem of scaling.

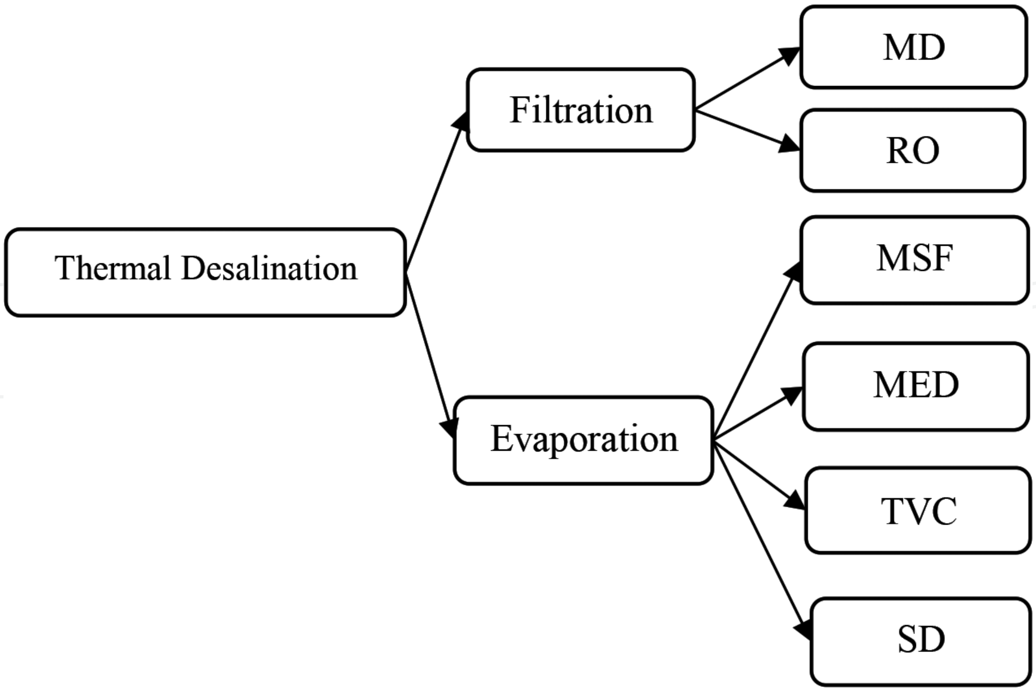

Figure 6. Thermal desalination technologies.

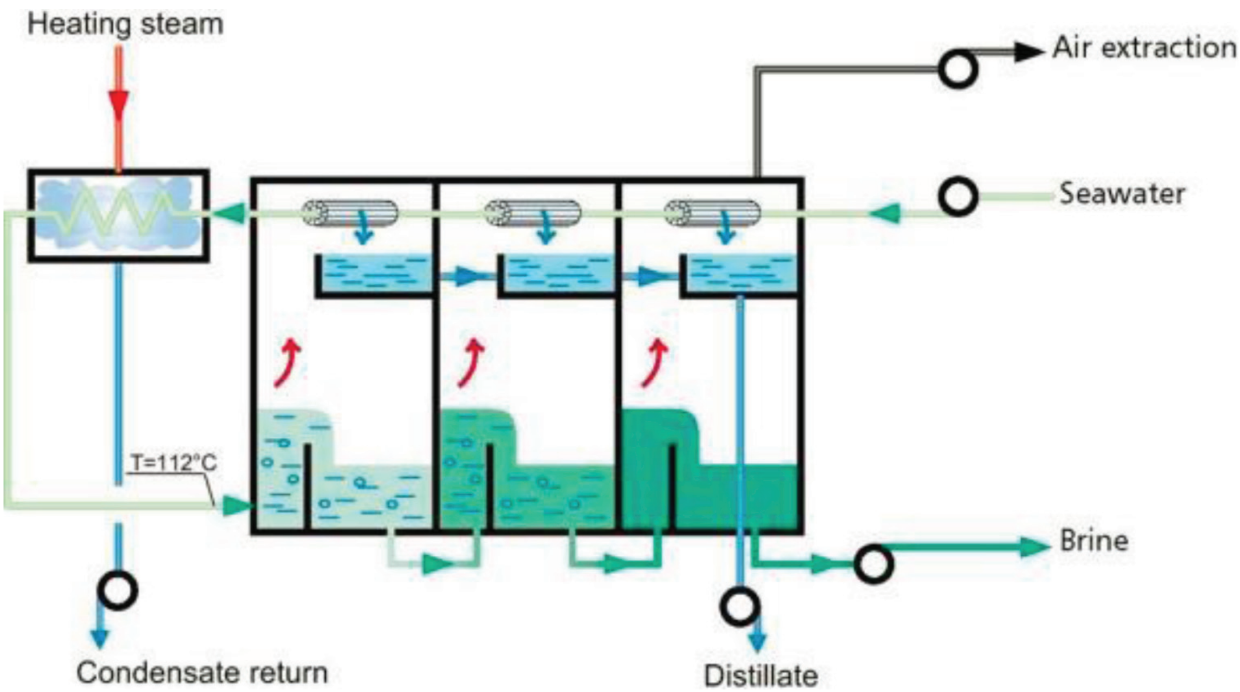

Figure 7. Schematic of MSF [12].

And the minimum brine temperature is determined by temperature difference between the last effect and ambient temperature necessary for heat transfer. MED system is usually combined with mechanical vapor compression or thermal vapor compression to use a part of steam from any of the effects and increase its pressure. MED systems can operate at low TBT, thus enabling

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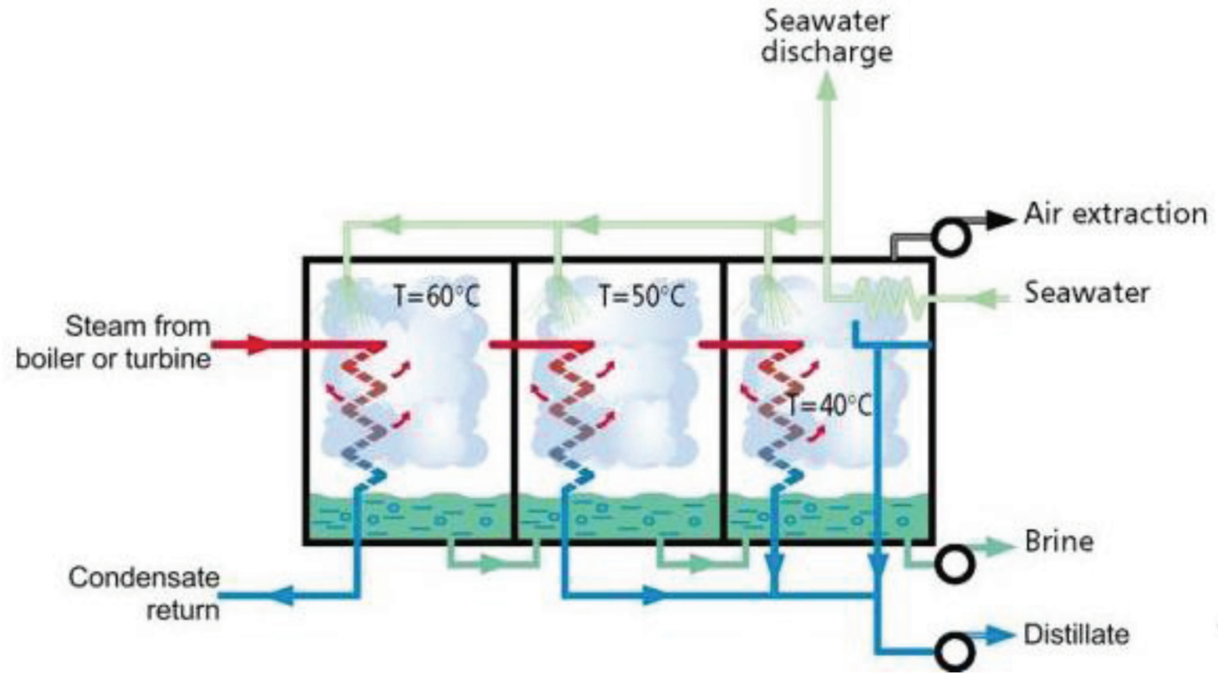

Figure 8. Schematic of triple-effect MED [14].

them to use cheap heat sources such as waste heat or solar collectors. For example, an existing diesel waste heat-coupled MED plant's energy consumption is 2 kWh/Ton for water pumps [15].

3.1.3. Membrane distillation (MD)

In membrane distillation process, feed water is heated and then allowed to flow through the porous hydrophobic membrane. The high pressure or electrical potential is applied on water vapor to produce fresh water from saline water [16]. The vapor pressure difference across membrane causes water vapor molecules to flow and it is condensed on the other side of the membrane. MD has the following characteristics: high porosity, hydrophobic and low thermal conductivity; the membrane thickness should be reduced and to maintain high pore size for the increase of flux.

The following are the operating parameters which effects distillate yield like flow rate, thickness of air gap, membrane thickness, porosity, long-term operation, thermal conductivity of membranes, and porosity. It is still a big challenge to develop high and efficient membrane technology, since MD has basic challenges to meet to compete with MSF, MED, and RO. In addition, MD system consumes a lot of energy [17, 18].

3.2. Application of molten salts as heat transfer fluid in concentrating solar power plants

Despite the tremendous improvements in conventional desalination technology, the desalination process is very energy consuming. For instance, to produce 1000 m^3/day of desalinated water in a year, nearly 10,000 tons of oil is required [16]. More detailed energy consumption data for different desalination processes are listed in **Table 1**.

Desalination process	Max seawater temperature (°C)	Energy consumption	
		Thermal energy (kJ/kg)	Electric power (kWh/m^3)
MSF	120	184–222	2.5–4
	90	252–327	2.5–4
	70	462–567	2.5–4
MED	80	176–231	1.2–1.8
	70	235–294	1.2–1.8
	60	294–394	1.2–1.8
RO (without energy recover)	–	–	7–8
RO (with energy recovery)	–	–	5–6

Table 1. Energy consumption of seawater desalination process [19].

Due to high expenses of the conventional energy resources, renewable energy sources can provide alternatives. Since most desalination systems can directly use thermal energy, concentrated solar thermal energy is very suitable for water treatment. Furthermore, the potential negative environmental impact from the desalination process is the discharge of high concentrated brine to the environment [20]. To avoid the potential negative impacts from disposing of the concentrates, the recovery of important minerals from concentrates to achieve zero discharge is a promising option. Recent development on concentrating solar thermal power generation has shown that the sea salts are very promising materials for large-scale thermal energy storage in concentrating solar power (CSP) plants. This may dramatically change the technology for desalination and water treatment because the salts may be collected for better value, rather than disposed.

A typical CSP plant consists of a solar collection system and a traditional power block. Solar energy is concentrated in the collection system, and the heat from direct normal insulation (DNI) is collected by a heat transfer fluid (HTF). The HTF circulates to the power block and transfers the collected heat to generate steam. The steam drives a turbine to produce electricity in a steam cycle [21–23]. Four most commonly used solar-concentrating methods are parabolic trough collectors, linear Fresnel reflectors, solar power tower collectors, and parabolic dish collectors. Parabolic trough and solar power tower are the two solar-concentrating methods mostly used in current CSP plants. HTF is the most important part in CSP plant beside energy storage media, because it can transfer the heat from the solar field to the power block. Currently, several typical HTFs are used in commercialized CSP plants, including air, water/steam, synthetic oils, organics, and molten salts [24, 25]. A good candidate of HTF in CSP should have the following characteristics: low freezing point, good thermal stability, low viscosity, high specific heat capacity, as well as acceptably low chemical corrosion rate, while low cost is another key criterion for industrial applications [26, 27].

Concentrates from desalting process contain inorganic salts and other compounds that may be purified for commercial value. For example, the recent technology development on solar thermal energy storages has shown that sea salts are very promising materials for large-scale thermal energy storage [28–31]. At present, salt mixtures have been considered as promising HTF candidates due to their thermal stability at high temperatures [32]. So far, alkali nitrate and nitrite mixtures are the two most successful HTF candidates. Solar salt (KNO_3 40 wt%-$NaNO_3$ 60 wt%), Hitec ($NaNO_3$ 7 wt%-KNO_3 53 wt%-$NaNO_2$ 40 wt%), and HitecXL ($NaNO_3$ 7 wt%-KNO_3 45 wt%-$Ca(NO_3)_2$ 48 wt%) are three commercialized alkali nitrate and nitrite mixtures. Other nitric salt-based HTFs include Sandia Mix ($NaNO_3$ 9–18 wt%-KNO_3 40–52 wt %-$LiNO_3$ 13–21 wt.%-$Ca(NO_3)_2$ 20–27 wt%) developed by Bradshaw and Brosseau [33] at the Sandia National Laboratories and SS-500 ($NaNO_3$ 6 wt%-KNO_3 23 wt%-$LiNO_3$ 8 wt%-$CsNO_3$ 44 wt%-$Ca(NO_3)_2$ 19 wt%) developed by Halotechnics Inc. [34]. Reddy et al. [35] developed a mixture of alkali-fluoride and carbonate salt (LiF-NaF-K_2CO_3) as the HTF with a working temperature range of 400–900°C. Li et al. [31, 36–38] recently developed a chloride salt mixture (NaCl 7.5 wt%-KCl 23.9 wt%-$ZnCl_2$ 68.6 wt%), its melting temperature is about 850°C, while its viscosity is only 0.325 Pa s at 300°C. The cost of this ternary chloride salt mixture is expected to be below 1 $/kg.

Consequently, a full separation of salts and water in desalination process needs to be developed, the byproducts of which can be utilized as the HTF in CSP plants. Furthermore, such a full separation desalination system is expected to become a necessity in advanced water treatment technologies in an economically feasible way.

4. Heat and mass transfer analysis of a novel full separation system using solar thermal energy from concentrated solar power (CSP)

4.1. Motivations

As discussed in Section 1, the disposal of high-temperature-concentrated brine is a big concern to the environment. It has been clearly documented that the discharged high-temperature concentrates can cause a lasting change in species composition and abundance in the discharge site and affect aquatic life [21]. To avoid the potential adverse effects from disposing of the concentrates, the recovery of important minerals from concentrates to achieve zero discharge is a promising option. Concentrates from desalting process contain inorganic salts and other compounds that may be purified for commercial applications. Section 3.2 introduced a ternary halide salts as a potential candidate of thermal storage material; this may dramatically change the technology for desalination and water treatment. Therefore, a full separation of salts and water for desalination becomes necessary in new water technologies. A proposed full separation multieffect distillation (FSMED) desalination system can accommodate the demands of using high-temperature thermal energy to effectively separate salts and water at 100%, resulting in simultaneous collection of pure water and dry salts.

4.2. Concepts

To achieve 100% water extraction, an innovative concept of FSMED system using solar thermal energy is proposed. In the proposed FSMED desalination system, a full separation tank (FST) is integrated to a conventional forward feed MED water treatment system to enhance the water productivity and thermal efficiency, as shown in **Figure 9**. The main advantage of forward feed system is to be able to operate at high top brine temperature. Although the mean temperature of heat addition in forward feed is lower as compared to backward feed, it is better from the operational point of view. In backward feed arrangement, the highest brine temperature occurs at the highest brine salinity, thereby causing severe scaling problems [39].

The heat source for the FST is from concentrated solar thermal system. The air feed to the FST is preheated by the exhaust air/steam mixture to achieve heat recovery. The FST receives concentrated brine from the last effect of the MED. The concentrated brine from the MED is atomized into tiny droplets and fully evaporated in the FST due to the effective convective heat transfer between water droplets and hot airflow. The brine vaporizes into steam leaving behind salt down to the bottom of the FST, resulting in the simultaneous collection of pure water and dry salts. The hot air/steam mixture leaves from the top of the FST and passes through the first effect of MED to heat the feed seawater. There is no need to retain the brine for an internal convective heat transfer process, which eliminates the scaling problem. The only section subject to a hot environment is the pipe introducing brine to the nozzles and sprayers, which can be insulated and maintained at low temperature. Therefore, this novel system can operate effectively at either very high temperatures using primary heat or at medium to low temperatures using exhaust heat.

4.3. Heat and mass transfer analysis

The proposed process is a closed-loop system which increases the nonlinearity and complexity of resulting system of equations, unlike conventional systems which are open loop. The mass and energy balance analysis for the FSMED system in steady-state operation will be introduced in this section. **Figure 10** shows the energy balance of the FSMED system.

According to **Figure 10**, the input energy involves the energy from the heat source and the feed seawater, as shown in Eq. (1)

$$E_{\text{in}} = m_{\text{air}} \cdot C_{p,\,\text{air}} \cdot (T_{\text{hs}} - T_{n,\,\text{out}}) + \left[\beta \cdot m_{s,\,n}\left(h_{\text{gs,\,hs}} - h_{\text{gs},\,n}\right)\right] + m_{\text{csw}} \cdot h_{\text{sw,amb}} \tag{1}$$

where m_{air} is the mass flow rate of the dry air and m_{csw} is the mass flow rate of the cooling seawater. The subscript n denotes the number of the effects, then $T_{n,\,\text{out}}$ and $h_{\text{gs},\,n}$ represent the parameters in the last effect. The subscript hs means the parameters are obtained under the temperature of the heat source. β is the bleed steam fraction, which indicates the ratio of mass flow of bleed steam to the mass flow of steam from which it is extracted. To reduce the thermal energy consumption, a small fraction of steam (steam 21 in **Figure 9**) from the last effect is bled and mixed with the air steam (steam 13 in **Figure 9**), and then this mixture is heated up and blown into the FST. The bleed fraction is a very important parameter which influences other crucial parameter like salinity of brine and energy requirement.

The output energy is carried out by the saturated water from each effect, collected salts and the seawater rejected from condenser, as listed in Eq. (2)

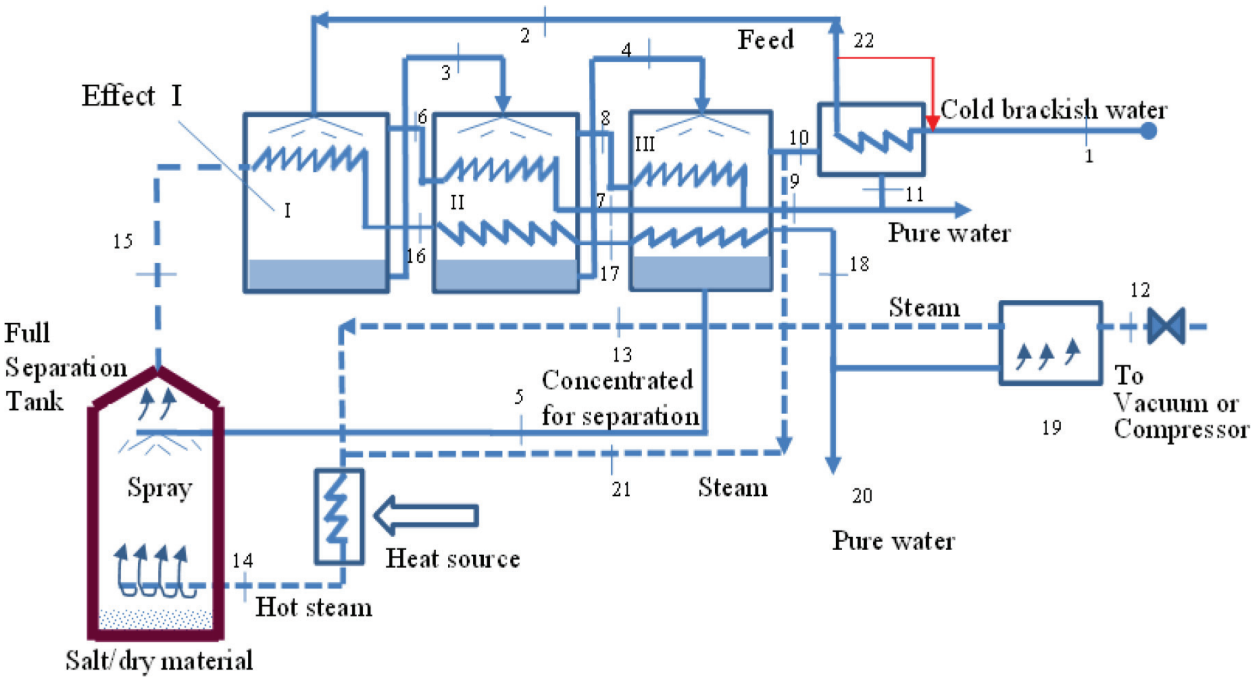

Figure 9. Concept of the FSMED desalination system.

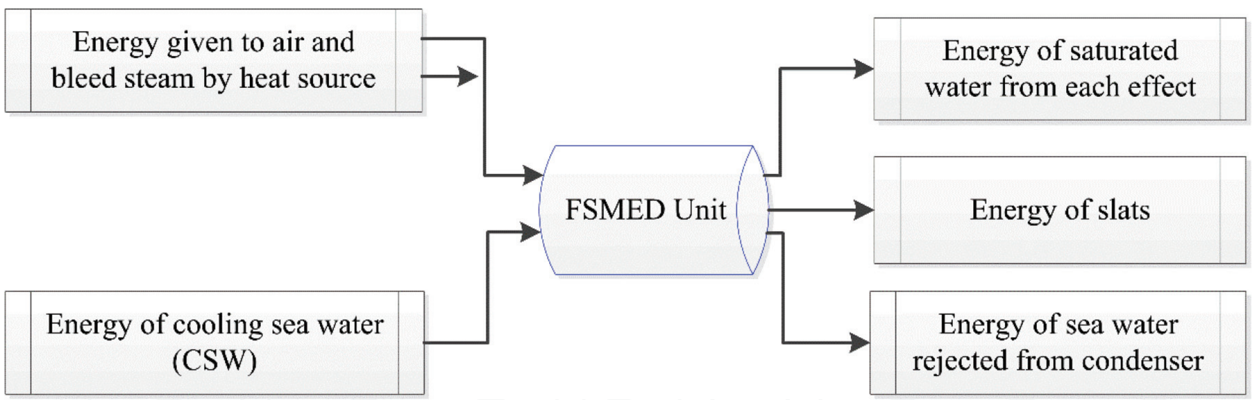

Figure 10. Energy balance of the FSMED system [40].

$$E_{\text{out}} = (1-\beta)\cdot m_{s,n}\cdot h_{fs,n} + \sum_{i=1}^{n-1} m_{s,i}\cdot h_{fs,i} + m_{\text{salt}}\cdot C_{p,\text{salt}}\cdot (T_{\text{FST}} - T_{\text{amb}}) + (m_{\text{csw}} - m_{\text{sw}})\cdot h_{\text{fsw,WH}} \quad (2)$$

where the subscript WH means the thermal properties are obtained under the temperature of the feed seawater heater.

The mass flow into the system is the cooling seawater, and the total mass flow out involves the rejected seawater, collected salts, and the pure water. The mass flow rates, salinity of different streams, and total energy consumption under different temperature of hot air going into the

FST and varying bleed steam fraction can be calculated through detailed energy and mass balance analysis of each component of the FSMED system, which is not shown here for the sake of brevity.

An example of the calculated energy consumption for FSMED system with 3, 4, and 5 as the total number of effects is shown in **Figure 11**, in which the heat source temperature varies from 150 to 400°C. The bleed steam fractions for 3, 4, and 5 effects are 0.6, 0.57, and 0.55, respectively. It is apparent that a five-effect system is the least energy consuming. The minimum energy consumption for five-effect forward feed FSMED desalination system is estimated to be about 350 kJ/kg of seawater, which compares very well to thermal energy requirements of existing MED plant which require 394 kJ/kg of seawater [19]. More detailed operating data for the five-effect FSMED system are listed in **Table 2**.

4.4. Preliminary assessment of water droplet evaporation path in FST

To achieve 100% water extraction, detailed knowledge of the water droplet behaviors in the FST is essential to the design optimization of the FSMED desalination system. It is thus necessary to determine the lifetime and trajectory of tiny water drops as a function of the drop size, the ambient temperature, and the spray-injection parameters. Given that the analysis of vaporization of saline droplet swarm is complex (involving crystallization process), the present

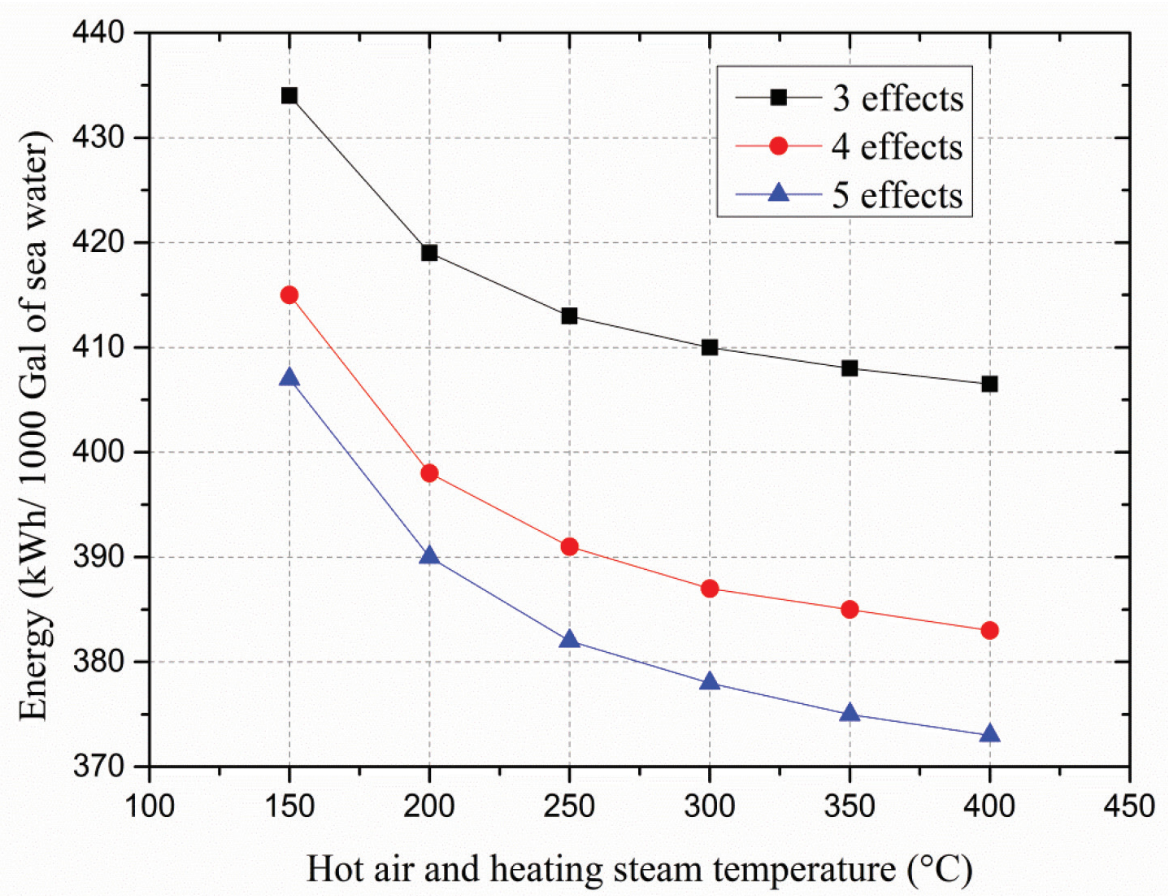

Figure 11. Thermal energy requirement of FSMED desalination system versus hot air and heating steam temperature.

Parameters	Value					
Heat source temperature (°C)	150	200	250	300	350	400
Mass flow rate of dry air (kg/s)	3.844	2.291	1.600	1.209	0.957	0.781
Mass flow rate of seawater (kg/s)	6.160	5.716	5.515	5.401	5.327	5.276
Mass flow rate of pure water (kg/s)	0.965	0.965	0.965	0.965	0.965	0.965
Energy input by heat source (kWh/1000 Gal of seawater)	407.6	390.4	382.5	378.1	375.2	373.2

Table 2. Calculated results for a FSMED system with five effects under different heat source temperature [40].

study mainly focuses on the evaporation of a single water droplet in hot air to make a preliminary assessment.

A simplified non-equilibrium vaporization model is adopted to describe the movement and evaporation behavior of a single water droplet in the FST. The model is described based on the following assumptions:

1. No temperature gradient in the droplet;
2. Thermal properties are uniform in the droplet;
3. Droplet maintains a spherical shape during falling;
4. Vapor mass fraction in the hot airflow is 0.

The droplet size change is related to the heat/mass transfer that determines the evaporation of the droplet. The conservation equations and mass transfer equation are described in the following.

Mass conservation equation:

$$\frac{d}{dt}\left(\frac{4}{3}\pi r_s^3 \rho_l\right) = -G \tag{3}$$

Energy conservation equation:

$$2\pi r_p \overline{\lambda}(T_\infty - T_s)Nu = \frac{4}{3}\pi r_s^3 \rho_l C_{p,l}\frac{dT_s}{dt} + GL \tag{4}$$

Mass transfer equation:

$$G = 2\pi r_s \overline{\rho}\overline{D} \cdot Sh \cdot Ln(1 + B_m) \tag{5}$$

where B_m is the Spalding mass transfer number, and is given by

$$B_m = \frac{Y_{\mathrm{Fs}} - Y_{F\infty}}{1 - Y_{\mathrm{Fs}}} \tag{6}$$

The droplet velocity and position are evaluated using the following equations:

$$-\frac{du_x}{dt} = \frac{3C_D}{8r_s}\left(\frac{\overline{\rho}}{\rho_l}\right)u_r \cdot u_x \tag{7}$$

$$-\frac{du_y}{dt} = \frac{3C_D}{8r_s}\left(\frac{\overline{\rho}}{\rho_l}\right)u_r \cdot (u_y - u_\infty) - g\frac{\rho_l - \overline{\rho}}{\rho_l} \tag{8}$$

The lifetime of the water droplet in the FST under different diameters and temperatures is compared in **Figure 12**. The droplet lifetime increases with an increase in the droplet diameter but decreases with an increase in the ambient temperate. In addition, the lifetime decreases with the ambient temperature increase in a nonlinear way, with a gradual decrease in the slope.

To confine the vaporization within the FST with certain size, the variations of the falling distance in the vertical direction and stopping distance in the horizontal direction were calculated for a water droplet with 400 μm in diameter under different injection parameters, as shown in **Figure 13**.

For the case of $\theta = 0°$, the falling distance decreases with the increase in the initial injection velocity. This is because the lifetime of the droplet decreases with the increase of the injection velocity. For the case of $\theta = 10°$, when the injection velocity is below 15 m/s, the influence of the lifetime decrease on the falling distance is larger than that of vertical component of the injection velocity. Hence, the falling distance decreased slightly with the initial injection velocity. When the injection velocity exceeds 15 m/s, the effect of vertical component of the injection

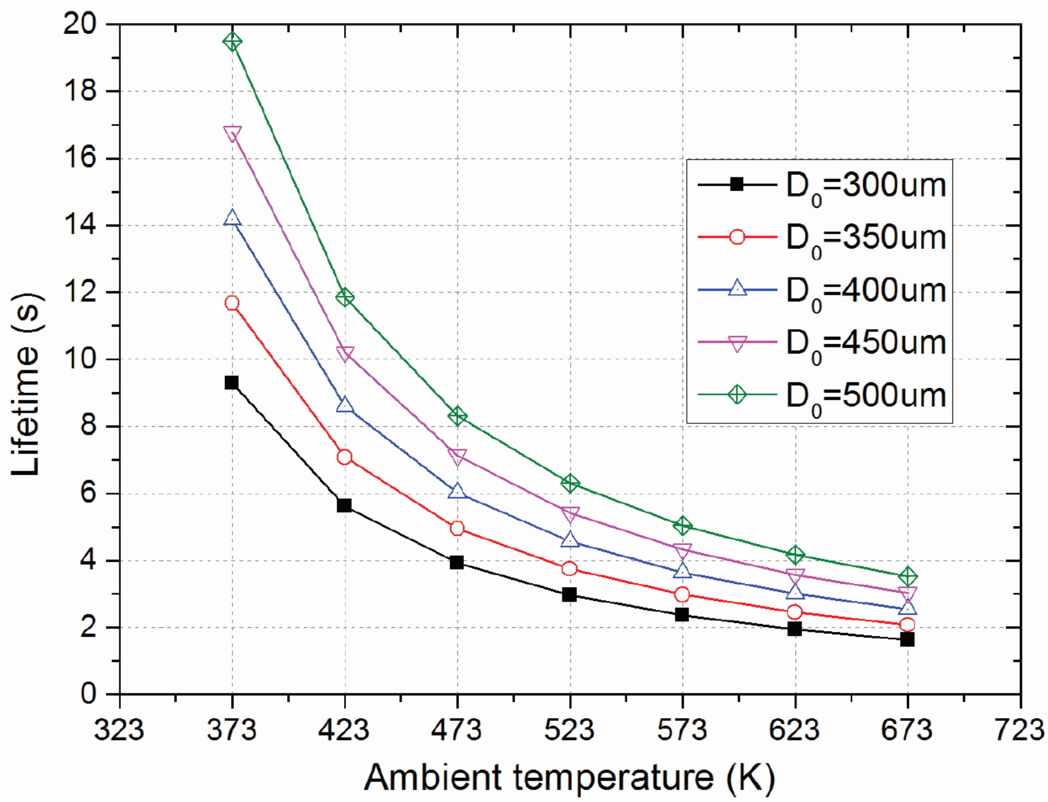

Figure 12. Comparison of the lifetime under different droplet diameters and ambient temperatures.

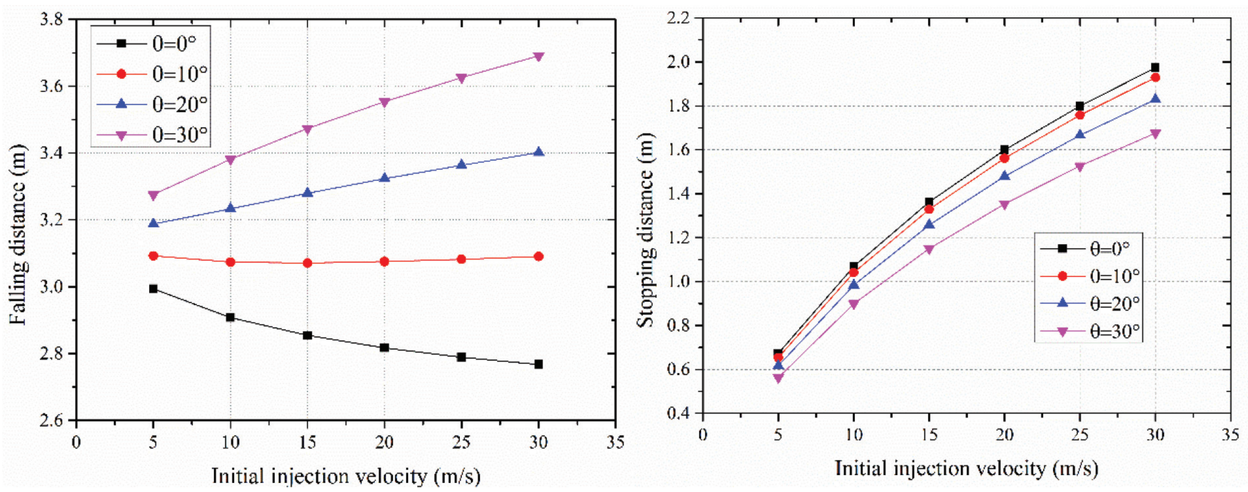

Figure 13. Variation of the falling and stopping distance with the injection velocity and angle.

velocity overshadows that of the lifetime decrease, so the falling distance increased slightly with the initial injection velocity. For the cases of $\theta = 20°$ and $30°$, because the increase of vertical component of the injection velocity always has greater influence than the lifetime decrease, the falling distance increases with the initial injection velocity. The stopping distance decreases with the injection angle due to the decrease of the horizontal component of the initial injection velocity.

5. Concluding remarks

Desalination is a promising solution for providing the increasing need of freshwater, due to the increasing growth of population and climate change. Despite the tremendous improvements in conventional water treatment technology, the desalination process is very energy consuming. Therefore, it is highly desirable that environmentally friendly renewable energy resources should be utilized for water treatment. Since most desalination systems can directly use thermal energy, concentrated solar thermal energy is very suitable for water treatment. Furthermore, recent developments on CSP have shown that the sea salts are very promising materials as HTF in thermal energy storage system, which in fact provides an alternative to desalination and water treatment by collecting the salts through full separation from seawater and brackish water, instead of disposing the high concentrate to the environment.

To achieve 100% water extraction, an innovative concept of FSMED desalination system using solar thermal energy was proposed in the present study. Compared with conventional MED, the FSMED technology will overcome the limitation of operating temperature for water desalination. The concentrated brine from the MED is atomized into tiny droplets and fully evaporated in the FST by using the high-temperature heat from concentrated solar thermal energy system, resulting in simultaneous collection of pure water and dry salts. A simplified non-equilibrium vaporization model is used to investigate the lifetime and trajectory of a tiny water droplet in the FST as a function of the droplet size, the ambient temperature, and the spray-injection parameters. The relationship of the water droplet size and falling distance with the hot air-steam temperature, and initial injection/spray parameters is investigated and presented. Results from the study provide important guidance to the design of such a water treatment system. It is expected that the proposed full separation thermal-driven desalination process can address problems of concentrated discharge disposal, solute recovery, and high-energy consumption.

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