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# Solar Desalination

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## Abstract

There is an increasing demand for advancing conventional desalination technologies and developing novel solar powered desalination processes. In this chapter, the use of solar powered thermal desalination will be discussed comprehensively. The different existing methods of solar energy utilization for seawater desalination will be discussed, which includes solar stills, solar powered humidification-dehumidification (HDH) desalination, solar diffusion driven desalination, solar membrane distillation, concentrated solar power (CSP) based desalination, and solar pond distillation. The advantages and limitations of these thermal desalination technology will be discussed. In addition, the environmental impacts of solar desalination will be discussed due to its importance for adoption.

**Keywords:** desalination, solar energy, thermal processes

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## 1. Introduction

For many years, efforts have been made to use solar energy for obtaining potable water from saline water. Some of the earliest solar powered desalination technologies were developed centuries ago, such as solar stills. There is an increasing demand for advancing conventional desalination technologies and developing novel solar powered desalination processes. The increasing demand for solar powered desalination systems is driven by the increasing cost of fossil fuels for thermal and electrical energy generation, falling cost of renewable energy technologies, need for small scale decentralized desalination systems to operate in remote areas that lack access to the electrical grid, and the concern over climate change. Solar powered desalination is especially important in remote and rural areas with low infrastructure and without connection to a grid. Small-scale stand-alone solar powered desalination systems are desirable to provide a reliable source of potable water.

The best combination of renewable energy and desalination technology achieves high fresh water production at low cost with efficient energy utilization. An excellent example is the integration of thermal desalination technologies with renewable thermal energy, such as solar and geothermal energy. Solar energy is the most promising energy for seawater desalination. Solar energy utilization systems such as flat plate solar collectors, evacuated tubes, and solar ponds absorb the solar energy and convert it to thermal energy that drives thermal desalination processes. The use of solar energy for desalination can be categorized into direct, where the solar energy is absorbed directly by the saline water (solar pond and solar still), or indirect where the solar energy is absorbed by a solar collector and then transferred to the saline water. Solar energy is well suited for arid regions and rural areas where the solar intensity is high [44].

Desalination of seawater or brackish water is generally accomplished using water evaporation (phase change), or by using a semi-permeable membrane to separate fresh water from concentrated saline water, or by a combination of the two as in membrane distillation. Most conventional desalination plants are large scale centralized units that typically serve urban populations. In recent years, there is considerable interest in developing decentralized desalination technologies. An environmental advantage of decentralized desalination is that the brine discharge is spread out over a large area, and thus the environmental impact is considerably less than that associated with large scale centralized desalination plants. In rural arid regions, populations are distributed over a large land surface area. For such cases, it is more economical to install and operate decentralized water production units that serve the local population in lieu of large centralized water production where water must be transported long distances. The rural arid regions typically have excellent solar resources, and thus solar driven desalination is appealing.

Solar energy, harvested in electrical or thermal form can be used to distill water. Solar thermal energy systems, such as flat plate solar collectors, evacuated tubes, concentrating solar troughs, and solar ponds absorb the solar energy and convert it to thermal energy that drive thermal desalination processes. Solar thermal energy utilization for desalination can be categorized into direct, where the solar thermal energy is collected directly by the saline water, such as in solar stills and solar ponds, or indirect where the solar thermal energy is absorbed by a solar collector and then transferred to the saline water, such as in solar powered humidification-dehumidification (HDH) and diffusion driven desalination. Technical simplicity, low maintenance requirements, and ease of operation are very important to enable successful application of distributed solar powered desalination systems.

The distillation performance can be examined in terms of characteristic parameters which are related to the method of distillations, which include:

1. Specific daily water production which is defined as the amount of water produced using 1 m<sup>2</sup> of solar collector area per day. This parameter describes daily water production normalized by the solar collector area. This parameter is important for all solar powered desalination systems since solar collector area is indicative of the amount of energy that is flowing into the system and is also a proxy for cost. The solar collector cost typically accounts for about 40–45% of the capital cost of air-heated HDH systems and 20–35% of the capital cost of water-heated HDH systems.

2. Gained output ratio (GOR) which is defined as the ratio of the latent heat of evaporation of the distillate produced to the total heat input to the distillation process. It is a measure of how efficiently thermal energy is used in a desalination process. In the case of solar powered desalination systems, GOR is equal to the ratio of latent heat of evaporation of the distillate produced to the heat absorbed by the solar collectors.
3. Recovery ratio (RR) is defined as the ratio of the total fresh water produced to the saline feed water input. RR for small scale solar powered HDH desalination systems is much smaller than RR for conventional desalination processes, such as MSF, MED, VC and RO due to the low production efficiency of small scale systems.

## 2. Solar thermal energy desalination

### 2.1. Solar stills

The solar still is one of the oldest and by far the simplest water desalination method. A solar still consists of a structural element called a basin covered with a transparent material to allow the incident solar radiation to pass through to the basin saline water for thermal absorption and evaporation. Solar energy absorption, saline water evaporation, and fresh water condensation occur within a single enclosure for a solar still. Solar stills are inherently direct collection systems. Solar distillation using solar stills is considered to be a mature technology. Because it has a low maintenance requirement, it is used worldwide to produce fresh water. Typically, the basin is colored in dark or black to enhance solar flux absorption. The water is heated by the solar rays absorbed by the basin, which increases the water vapor pressure until some portion of the saline water evaporates as shown in **Figure 1**. The water vapor moves upward and typically condenses on the cool glass cover and run downs through a guiding channel to the collection reservoir.

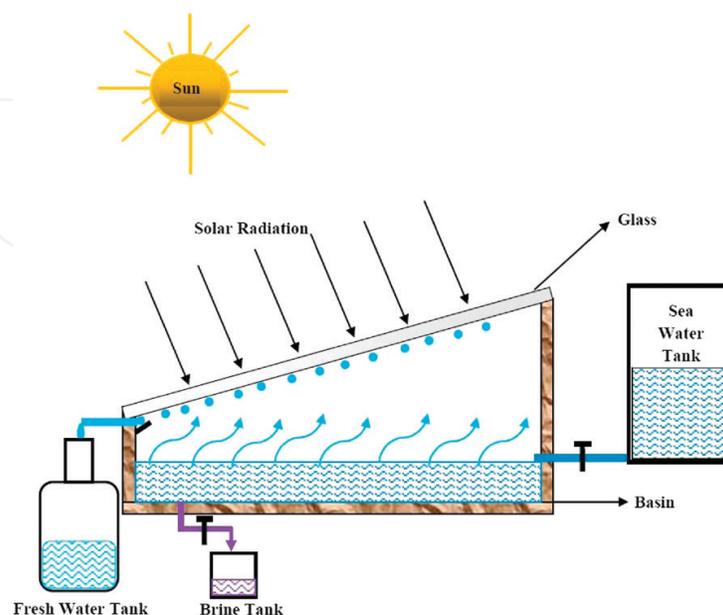


Figure 1. Solar still [47].

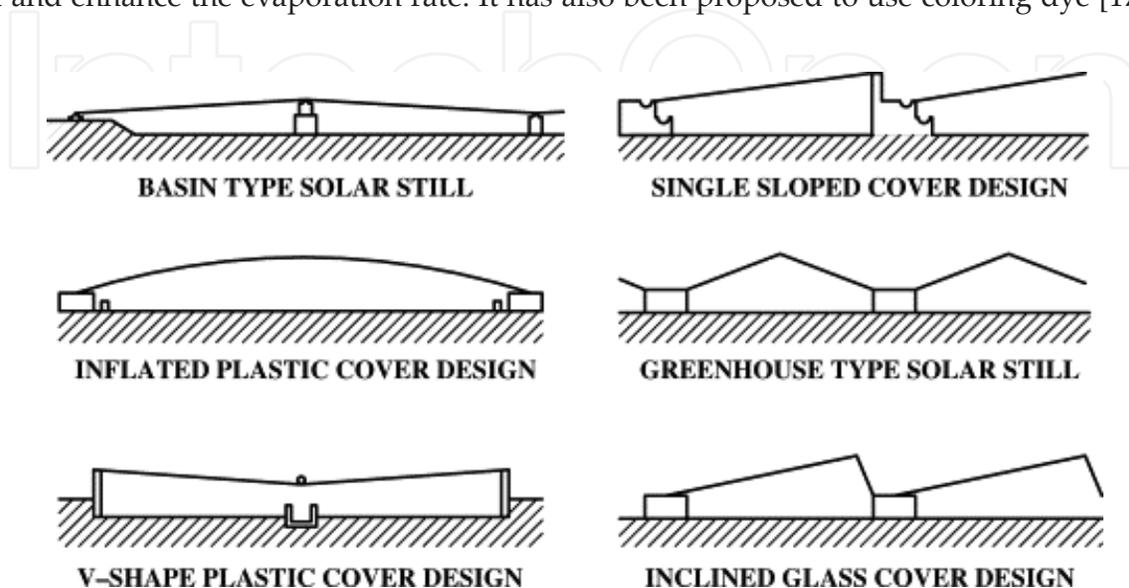
There exist many types of solar stills, including single slope, double slope, single and double basin, inverted, tubular, spherical, double effect multi wick, and greenhouse integrated solar stills as shown in **Figure 2**. Solar stills can be passive or active, depending on whether water circulation is needed. The main advantages of passive solar stills are that they do not require electrical energy for pumping (passive solar collector), it is simple, and it is easy to operate. However, the main drawback of the solar still is that it typically has low water production due to the loss of latent heat of condensation through the solar still transparent cover.

The gap distance between the solar still basin and the transparent cover surface has a considerable influence on its performance; the performance increases with decreasing gap distance. As a result, several design improvements have been considered, such as the development of a cascaded type solar still [1]. In this design, the basin is inclined and consists of many small cavities to store water; it is arranged in cascaded manner, as shown in **Figure 3**. The basin is typically made of a metallic corrugated sheet such as flat black coated aluminum.

The performance of a conventional solar distillation system can be predicted by various methods [3–12]. In general, the distillate hourly production rate per square meter of solar still ( $\dot{m}_w$ ) is given by

$$\dot{m}_w = \frac{3600 \dot{q}_{ev}}{h_{fg}} \quad (1)$$

where  $\dot{q}_{ev}$  is the evaporation rate per square meter of solar still cross section,  $h_{fg}$  is the latent heat of vaporization. The solar still performance is influenced by several parameters such as wind velocity, sky and ambient temperature, solar radiation, and salt concentration. Various researchers have proposed several modifications to enhance the performance of a conventional solar still. Some study has proposed to reduce the bottom heat loss coefficient [13]. Another study has proposed to reduce water depth in a solar still basin [5, 14, 15] which results in increased temperature and evaporation. It is also suggested to cover the back wall with cotton cloth in the solar still [16]. This is to reduce heat losses from the back of the solar still and enhance the evaporation rate. It has also been proposed to use coloring dye [17–20]



**Figure 2.** Common designs of solar stills [2].

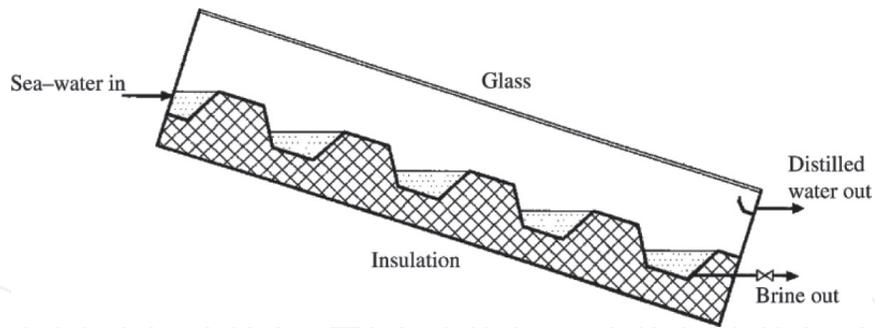


Figure 3. Schematic of a cascaded solar still [2].

and to use charcoal [21–23] to enhance solar energy absorption in the basin. Other studies have suggested to use energy storage to improve water yield [22, 23]. The use of multi-wick solar stills has been suggested to enhance water production performance [1]. Other studies have proposed cooling of the condensing glass cover [24–28] to enhance fresh water yield.

## 2.2. Solar powered humidification-dehumidification (HDH) desalination

Solar powered humidification-dehumidification (HDH) desalination has gained recent traction because it is viewed as a reliable desalination method for small scale decentralized applications. The humidification/dehumidification (HDH) process is a thermal desalination process that mimics the natural water purification cycle. Solar HDH systems have been investigated extensively and used widely for many decades as an alternative to common desalination systems for decentralized water production, and hence extensive knowledge exists on the design of these systems. HDH is based on water evaporation of heated saline water into an air stream and its subsequent condensation. Water vapor is carried by a circulating air stream from the saline water side, usually called evaporator or humidifier, to the condenser side where vapor is condensed as potable water as shown in Figure 4. Solar energy can be used to heat saline water via flat plat or evacuated tube solar collectors and successively directed to the evaporator. In term of solar energy utilization, the water or the circulated air is heated to run the solar HDH process. There are different operating modes of humidification-dehumidification desalination process. These operating mode types include: (1) closed air-closed water cycle, (2) closed air-open water cycle (3) open air-closed water cycle, (4) open air-open water cycle. Fresh water yields depend on the HDH design, operating mode, and operating conditions. In general, the distillation yield in HDH desalination process is calculated as

$$\dot{m}_w = \dot{m}_{air}(\omega_{in} - \omega_{out}) \quad (2)$$

where  $\dot{m}_{air}$  is mass flow rate of dry air (kg/s),  $\omega_{in}$  and  $\omega_{out}$  are the humidity ratio ( $\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{dry air}}$ ) of inlet and outlet air stream to the condenser, respectively. An important parameter that is used to examine the performance of HDH desalination process is the Gained Output Ratio (GOR) which is defined as the ratio of latent heat of evaporation of the distillate to the thermal energy input by the heated saline water. GOR is defined as,

$$GOR = \frac{\dot{m}_w h_{fg}}{\dot{m}_{saline} C_p (T_{in} - T_{out})} \quad (3)$$

where  $\dot{m}_{\text{saline}}$  is mass flow rate of heated saline water (kg/s),  $c_p$  is the specific heat of the saline water,  $T_{\text{in}}$  and  $T_{\text{out}}$  are the of inlet and outlet saline water temperature to the evaporator, respectively. HDH desalination process is best suited to utilize solar energy to heat saline water to a sufficiently high temperature such that water is evaporated. The temperature of the saline water is usually raised to 60°C; this is a relatively a low water temperature, which gives the HDH process an advantage over other traditional thermal desalination processes such as MSF or VC in that inexpensive materials of construction can be used. The downside of the HDH process is that the conversion rate is low; thus it is best suited for small-scale applications.

A significant advantage of the HDH process is that it typically operates in a low temperature range, which enables it to be driven by solar energy or a low-grade heat source. HDH systems are simple in design and operation; however, their low thermal energy efficiency is a significant drawback. The low thermal efficiency associated with HDH systems is typically due to the low thermodynamic availability of low grade heat. In addition, HDH systems are commonly based on natural draft to circulate the air in the system, which is associated with low heat and mass transfer coefficients compared to forced draft air flow. Film condensation over metallic tubes is usually used to condense the water vapor in the air stream and recover the latent of condensation. Due to the low rate of heat transfer, large metallic surface area is usually required which increases the system cost. Solar HDH technologies have great promise for decentralized small-scale water production applications, although additional improvements in system efficiency are needed to reduce the capital cost.

Humidification and dehumidification method for saline water desalination has been examined by many researchers. Farid et al. proposed a design for a solar energy based HDH desalination unit [29]. The performance factor of the desalination unit for different air and water flow rates have be examined by measuring water temperature. The study observed a variation in daily performance factor between 0.95 and 1.35. It was concluded that decreasing the water mass flow rate to 70 kg/h increases water temperature which increases the performance factor. Nawayseh et al. [30] carried out a simulation study for a closed cycle HDH process to optimize its operating condition. It was concluded that the performance of HDH process is significantly influenced by both water flow rate and to the surface area of humidifier and condenser. In addition, it was found that air flow rate has a small effect on the fresh water production of the unit. The maximum fresh water production for the system less than 0.7 kg/m<sup>2</sup>h and the average daily production is 3.5 kg/m<sup>2</sup> day for about 10-h operation. Al-Hallaj et al. [31] investigated a similar process configuration to that of Nawayseh et al. [30] and noticed that fresh water production performance is not affected by air flow rate. On the other hand, when operating at low temperature (50°C), water yields improves with increasing air flow rate. In their experimental study, they reported a maximum fresh water production of 0.65 kg/h, and a total daily production of 5 L/(m<sup>2</sup>.day). Their investigation concluded that fresh water production increases significantly with increasing water mass flow rate to an optimum point. Beyond the optimum point, increasing the mass flow rate decreases fresh water production. They also suggested it is best to operate the unit with forced air circulation while operating at low temperature, and operate with natural air draft circulation the water temperatures is high.

Muller [32] analyzed a small-scale thermal seawater desalination system with a thermal storage tank to enable the system to run 24 h/d of operation. They carried out the analysis using a simulation program to optimize the performance. They proposed to use a highly efficient solar collectors to heat the water to 85°C. Dai et al. [33] have examined an open loop humidification

and dehumidification system that uses a forced convection to circulate the air. A boiler is used to represent the solar collector to heat the saline water. In their system, they reported a thermal efficiency of 80% which is defined as the ratio of the minimum energy to obtain a fixed amount of water to the total heat input. Also, in the study it was reported that the performance is significantly dependent on the inlet saline water temperature, mass flow rate of the saline water and air.

Orfi et al. [34] examined the efficiency of a desalination process with a solar air heater to improve the performance. An electric heater was used to replace the solar water heater. A constant solar irradiation flux of  $800 \text{ W/m}^2$  was used, and the maximum fresh water production was  $5.2 \text{ kg/m}^2\text{d}$ . The experimental results indicate that the performance of the system improves with increasing the ambient air temperature. It was also reported that increasing the cooling water flow rate increases the production to up to an optimum value.

A comprehensive technical review that compares between different thermal desalination techniques is presented by Parekh et al. [35]. The main limitation of the HDH process is that the heat and mass transfer coefficients in the process are low because HDH process typically operate based on a natural draft to drive the airflow in the system. Numerous simulations are required to understand the air and mass flow rate influence on the performance of the HDH desalination process. It is reported that further simulations with a thermal storage module and 24 h operation are recommended to improve the process of the HDH. Condensation over tubes is usually used to condense the water vapor in the air stream. Because of the condenser low efficiency, HDH process require a large surface area condenser which increases the cost of the system.

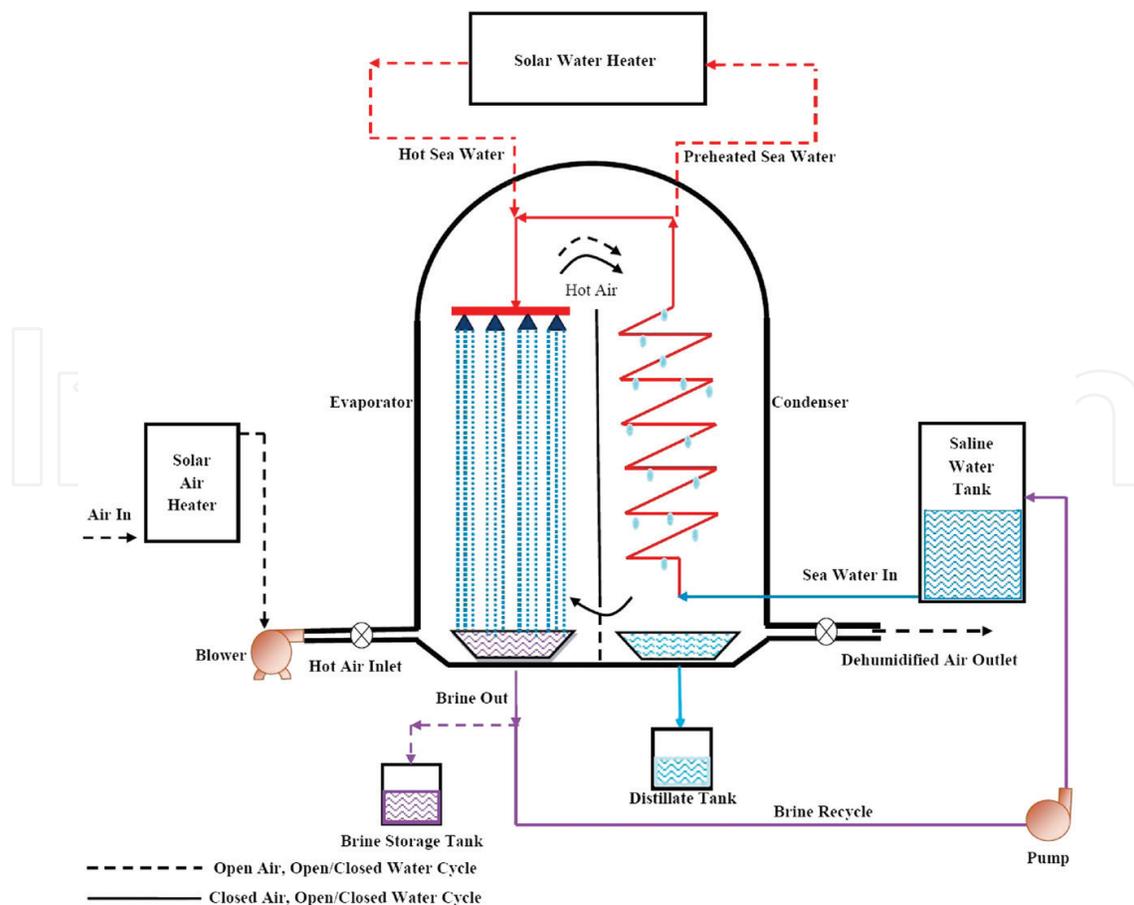


Figure 4. Schematic diagram of the solar HDH [47].

### 2.3. Solar diffusion driven desalination process

Solar diffusion driven desalination (DDD) is a thermal distillation process similar to the HDH where a solar collector is used to deliver the thermal energy. A simplified schematic diagram of the Solar DDD process is shown in **Figure 5**. The Solar DDD facility consists of two main components: evaporator and condenser. The evaporator and the condenser allows direct contact between air and water and they are mainly composed of a packing material. The packing material is characterized by a high surface area to volume ratio which improve the water and air contact area. A single nozzle is mounted at the top of the packing in the evaporator and the condenser to spray saline water over the packing material in the evaporator, and to spray the cooling water in condenser. A basin at the bottom of the evaporator is installed and used to collect the saline water and another one is installed at the bottom of the condenser to collect the freshwater [44].

The DDD process operates on the principle of humidification and dehumidification of an air stream. The first process is called air humidification and occurs in the evaporator. Heated saline water enters the evaporator, as low as 45°C, and gets sprayed at the top of the packing via the evaporator nozzle. Low humidity air is forced via a fan at the bottom of the evaporator to circulate the air through the system. With this arrangement, the drawn air is flowing counter-currently to the falling water which increase direct heat and mass transfer between air and water. This leads to humidification of the air and increases the air temperature exiting the evaporator. The humidified air leaves the evaporator at the top as fully saturated and then enters the direct contact condenser. In the direct contact condenser, cold fresh water is sprayed on the top of packed bed. As the humidified air is flowing upward, it gets in direct contact with the sprayed cold fresh water which leads to the dehumidification of the air and reduction in its temperature. In dehumidification process, heat will be transferred from air-vapor to the cold freshwater resulting in water vapor condensation which leads to fresh water production. The fresh water is collected at the basin of the condenser and sent to a fresh water production tank or to a heat exchanger to be cooled and recycled again [44].

The performance of the solar DDD have been investigated by various research groups [36–44]. A theoretical model has been developed to describe the heat and mass transfer in the process and the performance has been studied for different operating conditions. A steady state theoretical model for the evaluation of heat and mass transfer in the evaporator for the DDD process is developed by Klausner et al. and Li et al. [36–39], and it is given in Eqs. 4–6. The formulation is based on a two-fluid film model for a packed bed in which conservation equations for mass and energy are applied to a differential control volume. Eqs. 4–6 comprise a set of coupled ordinary differential equations that are used to solve for the humidity ratio, water temperature, and air/vapor mixture temperature distributions along the height of the evaporator,

$$\frac{dT_L}{dz} = \frac{G}{L} \frac{d\omega}{dz} \frac{(h_{fg} - h_L)}{Cp_L} + \frac{Ua(T_L - T_a)}{Cp_L L}, \quad (4)$$

$$\frac{dT_a}{dz} = -\frac{1}{1 + \omega} \frac{d\omega}{dz} \frac{h_L(T_a)}{Cp_G} + \frac{Ua(T_L - T_a)}{Cp_G G(1 + \omega)} \quad (5)$$

$$\frac{d\omega}{dz} = \frac{k_G a_w M_v}{G R} \left( \frac{P_{sat}(T_i)}{T_i} - \frac{\omega}{0.622 + \omega} \frac{P}{T_a} \right), \quad (6)$$

where  $L$  and  $G$  is the water and air mass fluxes, respectively,  $\omega$  is the humidity ratio  $k_G$  is the mass transfer coefficient on gas side,  $a$  is the specific area of packing, which is defined as the total surface area of the packing per unit volume of space occupied,  $a_w$  is the wetted specific area,  $M_v$  is the vapor molecular weight,  $R$  is the universal gas constant, and  $T_i$  is the liquid/vapor interfacial temperature which is defined as,

$$T_i = \frac{T_L + (U_G/U_L) T_a}{1 + (U_G/U_L)} \quad (7)$$

Similarly, a steady state theoretical model for the evaluation of heat and mass transfer in the condenser for the DDD process is given [36–39],

$$\frac{dT_L}{dz} = \frac{G}{L} \frac{d\omega}{dz} \frac{(h_{fg} - h_L)}{Cp_L} + \frac{Ua(T_L - T_a)}{Cp_L L}, \quad (8)$$

$$\frac{dT_a}{dz} = -\frac{1}{1 + \omega} \frac{d\omega}{dz} \frac{h_L(T_a)}{Cp_G} + \frac{Ua(T_L - T_a)}{Cp_G G(1 + \omega)}. \quad (9)$$

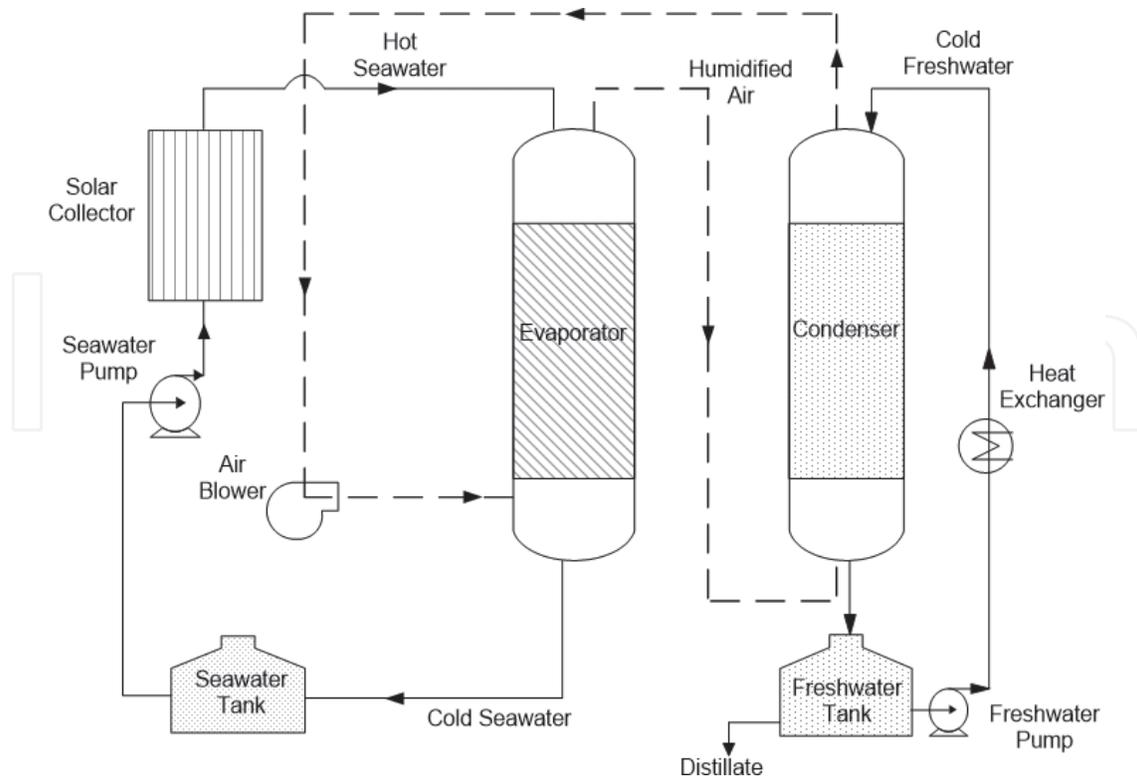


Figure 5. Schematic diagram for the solar diffusion driven desalination process [42].

$$\frac{d\omega}{dz} = \frac{dT_a}{dz} \frac{P}{P - P_{sat}(T_a)} \omega_m (b - 2cT_a + 3dT_a^2). \quad (10)$$

where  $b$ ,  $c$  and  $d$  are empirical constants that are given as  $a = 0.611379$ ,  $b = 0.0723669$ ,  $c = 2.78793 \times 10^{-4}$ ,  $d = 6.76138 \times 10^{-7}$ , and  $T_a$  (°C) is the air temperature [36–39].

A more recent formulation has been developed for transient solar DDD [40–44]. Alnaimat et al. developed a transient one-dimensional theoretical model for the evaluation of heat and mass transfer within direct-contact evaporators and condensers. Eqs. 11–14 comprise a set of coupled partial differential equations that are used to solve for the humidity ratio, water temperature, air/vapor mixture, and packed bed temperature distributions along the height of the evaporator.

$$\frac{\partial T_L}{\partial t} = \frac{L}{\rho_L \alpha_L} \frac{\partial T_L}{\partial z} - \frac{\partial \omega}{\partial z} \frac{G(h_{fg} - h_L)}{\rho_L \alpha_L C p_L} - \frac{U_L a_w (T_L - T_{pack})}{\rho_L \alpha_L C p_L} - \frac{U a_w (T_L - T_a)}{\rho_L \alpha_L C p_L} \quad (11)$$

$$\frac{\partial T_a}{\partial t} = \frac{-G}{\rho_a \alpha_a} \frac{\partial T_a}{\partial z} - \frac{(h_{fg}(T_L) - h_v(T_a))G}{\rho_a \alpha_a (1 + \omega) C p_{mix}} \frac{\partial \omega}{\partial z} + \frac{U_G (a - a_w)}{\rho_a \alpha_a (1 + \omega) C p_{mix}} (T_{pack} - T_a) + \frac{U a_w}{\rho_a \alpha_a (1 + \omega) C p_{mix}} (T_L - T_a). \quad (12)$$

$$\frac{\partial T_{pack}}{\partial t} = \frac{1}{\rho_{pack} \alpha_{pack} C p_{pack}} (U_L a_w (T_L - T_{pack}) - U_G (a - a_w) (T_{pack} - T_a)) \quad (13)$$

$$\frac{\partial \omega}{\partial z} = \frac{k_G a_w M_v}{G} \left( \frac{P_{sat}(T_i)}{T_i} - \frac{\omega}{0.622 + \omega} \frac{P}{T_a} \right), \quad (14)$$

where  $\alpha_L$  and  $\alpha_a$  is the liquid and air volume fraction,  $\rho_L$  and  $\rho_a$  the air and vapor density, respectively,  $U_L$  and  $U_G$  are the respective liquid and gas heat transfer coefficients. Similarly, Eqs. 15–18 comprise a set of coupled partial differential equations that are used to solve for the humidity ratio, water temperature, air/vapor mixture, and packed bed temperature distributions along the height of the condenser.

$$\frac{\partial T_L}{\partial t} = \frac{L}{\rho_L \alpha_L} \frac{\partial T_L}{\partial z} - \frac{\partial \omega}{\partial z} \frac{G(h_{fg} - h_L)}{\rho_L \alpha_L C p_L} + \frac{U a_w (T_a - T_L)}{\rho_L \alpha_L C p_L} + \frac{U_L a_w (T_{pack} - T_L)}{\rho_L \alpha_L C p_L} \quad (15)$$

$$\frac{\partial T_a}{\partial t} = \frac{-G}{\rho_a \alpha_a} \frac{\partial T_a}{\partial z} - \frac{(h_{fg}(T_L) - h_v(T_a))G}{\rho_a \alpha_a (1 + \omega) C p_G} \frac{\partial \omega}{\partial z} - \frac{U_G (a - a_w)}{\rho_a \alpha_a (1 + \omega) C p_G} (T_a - T_{pack}) - \frac{U a_w}{\rho_a \alpha_a (1 + \omega) C p_G} (T_a - T_L) \quad (16)$$

$$\frac{\partial T_{pack}}{\partial t} = \frac{1}{\rho_{pack} \alpha_{pack} C p_{pack}} (U_G (a - a_w) (T_a - T_{pack}) - U_L a_w (T_{pack} - T_L)) \quad (17)$$

$$\frac{\partial \omega}{\partial z} = \frac{\partial T_a}{\partial z} \frac{P}{P - P_{sat}(T_a)} \omega_m (b - 2cT_a + 3dT_a^2) \quad (18)$$

The given Eqs. 11–18 can be solved numerically simultaneously to predict water, air/vapor mixture and packed bed temperatures and humidity ratio within the evaporator and the condenser. These equations represent the heat and mass transport models in evaporator and condenser and they account for the transient variations within the packed-bed due to time varying inlet air and water temperatures and humidity. **Figure 6** shows the fresh water production rate for the given solar heat input where the condenser is operating with continuous cooling to maintain condenser inlet water temperature at 25°C. It is clear that as the solar heat input increases the evaporator inlet water temperature increases, which improve the water production. **Figure 7** shows the increase in the total fresh water produced and the decline of the saline water volume in the storage tank with time. With its low energy consumption and low fabrication cost, solar DDD is expected to be competitive with other small scale desalination units for decentralized water production. The diffusion driven desalination process is considered promising for water desalination when driven by solar energy or waste heat.

#### 2.4. Solar membrane distillation

In principles, membrane distillation (MD) is a hybrid of thermal distillation and membrane processes. MD has an important feature is that it operates at a low temperature range compared to conventional thermal distillation processes and at a low pressure compared to reverse osmosis desalination. Due to this low temperature operating range, it is well suited to be heated by solar energy. The membranes used are non-wetting (hydrophobic) and typically are made from polypropylene (PP), polyvinylidene fluoride (PVDF), polyethylene (PE), or polytetrafluoroethylene (PTFE). Different membrane module configurations exist such as plate and frame, hollow fiber, tubular, and spiral wound membrane module. Hydrophobic microporous membranes act as a physical support that separates a warm saline water chamber from a cold permeate chamber [45].

In solar membrane desalination, salty water or brackish water is heated using solar energy and then directed to a warm saline chamber. The driving force in solar MD process is vapor pressure difference across the membrane. There are different methods to create a vapor pressure difference across the membrane; thus MD can be categorized in terms of pressure difference creation into the following: direct contact membrane distillation (DCMD); air gap membrane distillation (AGMD); sweeping gas membrane distillation (SGMD); and vacuum membrane distillation (VMD). Water vapor transports through membrane pores from the high vapor pressure feed side to the low vapor pressure permeate side. The most commonly MD types used for desalination are DCMD, AGMD, and VMD as shown in **Figure 8**. **Figure 8a** depicts the direct contact membrane distillation (DCMD) process. In DCMD a pressure difference is created by a temperature difference between the feed water side and permeate side. The hot feed water is in direct contact with the membrane. As the water evaporates in the feed water side, it moves through the membranes and condenses on the lower temperature permeate side. The salty liquid feed water cannot pass through the hydrophobic membrane to the permeate side. DCMD is commonly used for saline water desalination. The main disadvantage of DCMD is the heat loss by conduction from the hot side to the cold side.

In DCMD, the mass flux is typically, assumed to be proportional to the vapor pressure difference across the membrane, and is given by:

$$J = C_m (P_f - P_p) \quad (19)$$

where  $C_m$  is the membrane coefficient,  $P_f$  and  $P_p$  are the vapor pressure at the membrane feed and permeate surfaces. Since the pressure also depends on the feed and permeate temperature, the above equation can be rewritten in terms of temperature difference across the membrane surfaces as:

$$J = C_m \frac{dP}{dT} (T_{f,m} - T_{p,m}) \quad (20)$$

where  $T_{f,m}$  and  $T_{p,m}$  is the feed and permeate temperatures at the membrane surface respectively. Here  $dP/dT$  is the variation in pressure and temperature which is given by the Clausius-Clapeyron equation, as follows:

$$\frac{dP}{dT} = \frac{h_{fg}}{RT^2} P_0(T) \quad (21)$$

where  $R$  and  $h_{fg}$  represent the universal gas constant and the latent heat of vaporization respectively. Eq. 20 is valid when the separation process is for pure water or very diluted solution, and the temperature difference across the membrane surfaces is less than or equal to 10°C [45].

And for more concentrated solutions, another relation developed by Schofield et al. [46] for the mass flux which is given by:

$$J = C_m \frac{dP}{dT} [(T_{f,m} - T_{p,m}) - \Delta T_{th}] (1 - x_m) \quad (22)$$

where  $\Delta T_{th}$  is the threshold temperature, which is given by:

$$\Delta T_{th} = \frac{RT^2}{M_w h_{fg}} \frac{x_{f,m} - x_{p,m}}{1 - x_m} \quad (23)$$

Here  $x_{f,m}$ ,  $x_{p,m}$ ,  $x_m$  represent the mole fraction of dissolved species at the hot membrane surface side, from the permeate membrane surface side and inside the membrane.

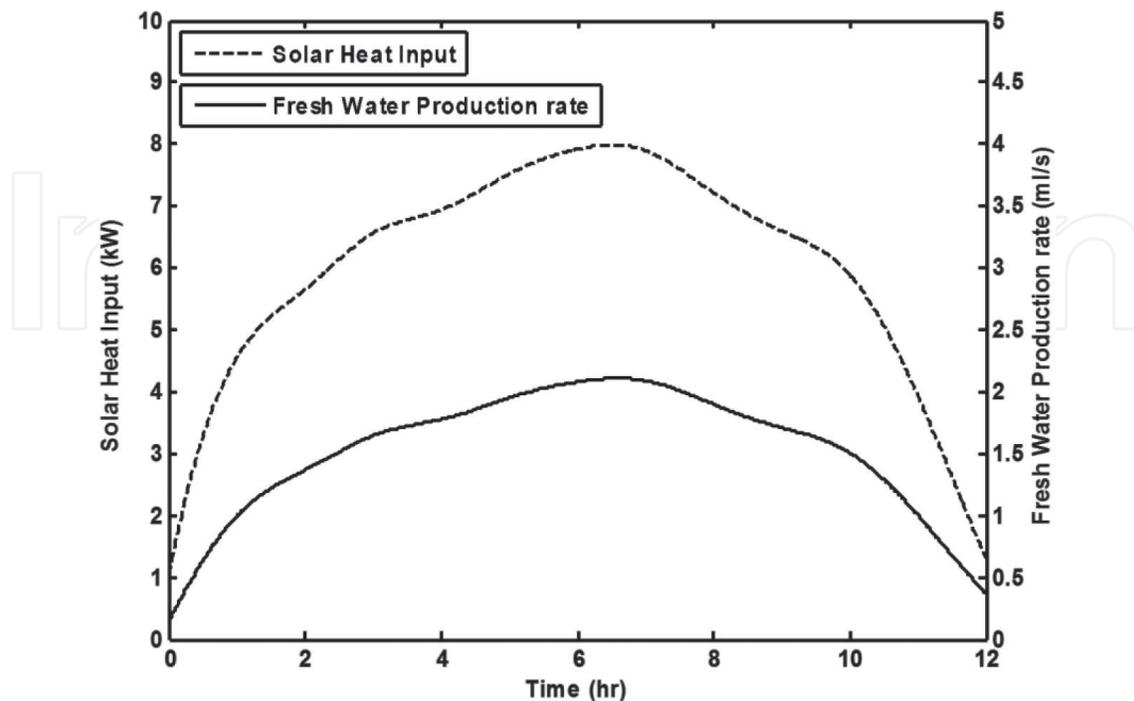
In the Air gap membrane distillation (AGMD) process, depicted in **Figure 8b**, the hot feed water is in direct contact with the membrane while the cold permeate is not in direct contact with the membrane. A stagnant air gap separates the cold water. The water evaporates in the feed water side and it moves across the membranes to condense on the lower temperature surface plate after passing the air gap. AGMD is commonly used for saline water desalination. The advantage of AGMD is that the reduction in the heat loss by from the hot side to the cold side. **Figure 8c** depicts the sweeping gas membrane distillation (SGMD) process. Carrier gas as flows in the permeate side to remove the vapor to a separate component to be condensed. SGMD is more typically used for removing volatile vapors and is less used in desalination. The main drawback of this process is the fact that it requires very large condenser to condense the vapor. In VMD process, vacuum is created in the permeate side via a pump. Water vapor passes

through the membrane due to the pressure difference between the feed water side and the permeate side as depicted in **Figure 8d**. The VMD is also achieved in a condenser outside the membrane which considered an advantageous to reduce the heat lost via across the membrane [45].

The MD process poses some advantages over RO process since it does not require high pressure feed water, and it can process very high salinity brines. The MD process can tolerate complete dry out of the membrane. In comparison with other large thermal distillation processes MD is not limited to large scale applications; it is highly scalable. In addition, MD processes include the rejection of ions, macromolecules, colloids, and other non-volatiles, lower operating temperatures compared to conventional distillation, and lower operating pressures compared to other pressure driven membrane separation processes. A disadvantage of MD process is the high cost of the membranes and the membrane susceptibility to get fouled which diminishes their durability.

### 2.5. Concentrating solar energy for desalination

Solar energy collectors can be classified in terms of the measured temperature range in the collector. Collectors are classified as low temperature when the measured collector temperature is  $<100^{\circ}\text{C}$ , medium temperature collector when temperature is in the range of  $100\text{--}150^{\circ}\text{C}$ , and high temperature collector when collector temperature is  $>150^{\circ}\text{C}$ . Solar energy plays an important role as a source of energy for low temperature desalination systems. For low temperature collectors, HDH desalination or diffusion driven desalination is very suitable. For medium and high temperature collectors such as concentrated solar trough, conventional thermal desalination such as multi-effect desalination (MED), multistage flash distillation (MSF) and vapor compression distillation (VC) is more suitable to be integrated with these

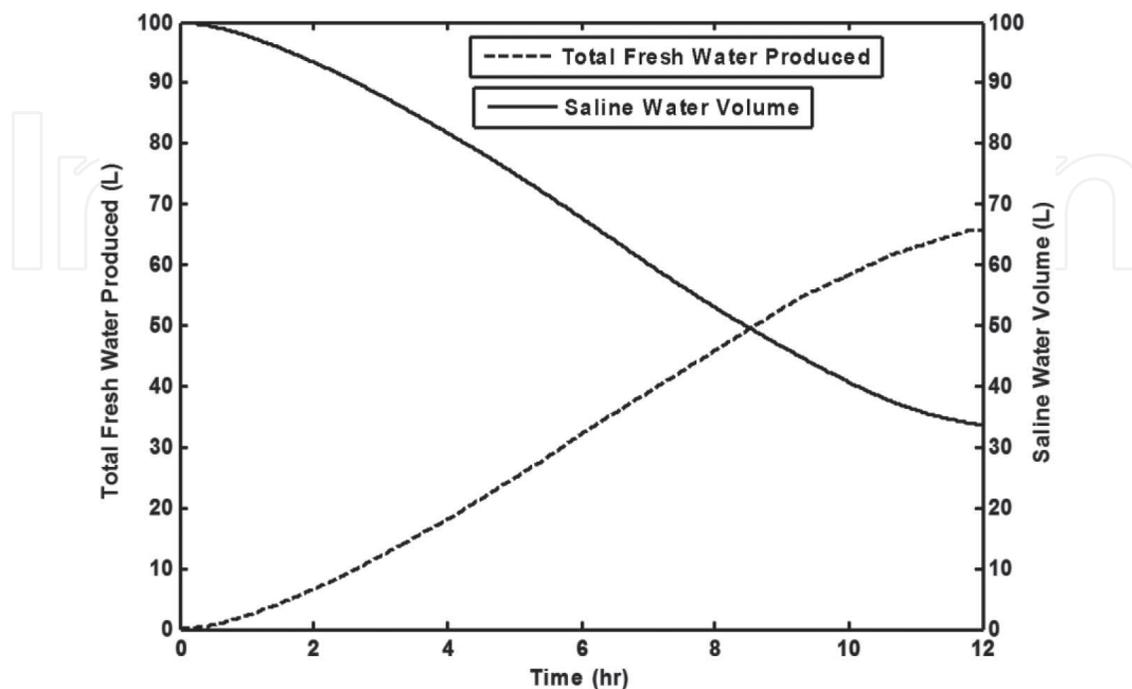


**Figure 6.** Solar heat input and fresh water production rate of the solar DDD [44].

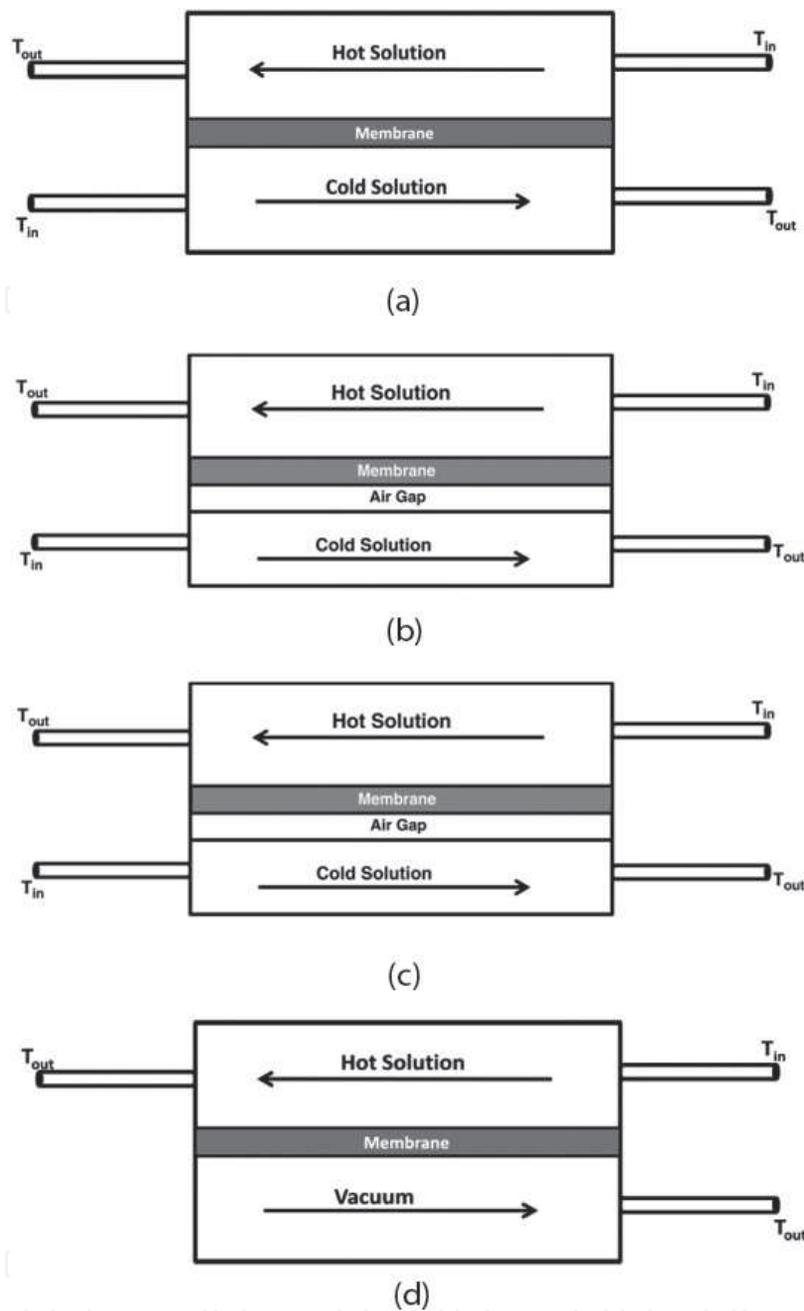
collectors. MSF, MED, and VC systems can be powered by the thermal energy captured by a concentrated solar energy to distill salty water.

The principle of using concentrated solar energy to power MSF processes is based on generating water vapor by heating seawater using concentrated solar energy. After being heated, water is introduced to a low pressure chamber, where sudden pressure drop occurs and water flashes to vapor. This process is repeated successively in a series of chambers in which the pressure is reduced at different stages. Water vapor is condensed on a heat exchanger bundle (condenser) and collected to produce freshwater. **Figure 9** shows a combined concentrated solar energy system and MSF distillation process. The distillate production rate from MSF desalination process depends primarily on the brine temperature, number of stages, feed water salinity and fouling resistance of the brine heater. The plant distillate production can be increased by increasing the temperature difference between discharged hot brine and inlet seawater temperature [48]. Distillate production in solar multi stage flash desalination could be increased by using water as the heat transfer fluid in solar collectors and also by increasing the size of thermal storage tanks [49].

For MED processes integrated with concentrated solar energy, the distillation process takes place in a series of vessels collectively referred to as effects. **Figure 10** shows a MED distillation process powered by concentrated solar energy. The thermic fluid is heated in the concentrated solar collector field, and thereafter is passed to the effect vessels to heat the sprayed saline water. As shown in **Figure 10**, a pre-heated seawater is introduced at the top of the effects, which is usually sprayed on bundle of tubes in which the thermic fluid is flowing, to create a falling film. The thermic fluid is at higher temperature than saturated temperature of the saline water. Water vapor is generated at the falling film and thereafter directed to the next effect where it releases its latent heat of condensation to the incoming saline water to produce distilled water.



**Figure 7.** Total fresh water produced and saline water volume in storage tank of the solar DDD [44].



**Figure 8.** Different types of membrane distillation process: (a) direct contact membrane distillation (DCMD), (b) air gap membrane distillation (AGMD), (c) sweeping gas membrane distillation (SGMD), (d) vacuum membrane distillation (VMD) process, adapted from [45].

For solar powered vapor compression desalination, saline water is heated by a solar collector and directed to a vessel where it flashes to vapor. **Figure 11** shows a VC distillation process powered by concentrated solar energy. The produced vapors are compressed using mechanical vapor compressor (MVC) or thermo vapor compressor (TVC) to raise the condensation pressure and temperature of the vapor. The vapor compression raises the steam pressure and its saturation temperature. The compressed vapor is then used to heat the remaining saline water in the vessel in the first step. Then vapor exits the vessel and thereafter enters the condenser to release its latent heat to the saline feed water as shown in **Figure 11**. The condensed vapor is then collected in the distilled storage tank.

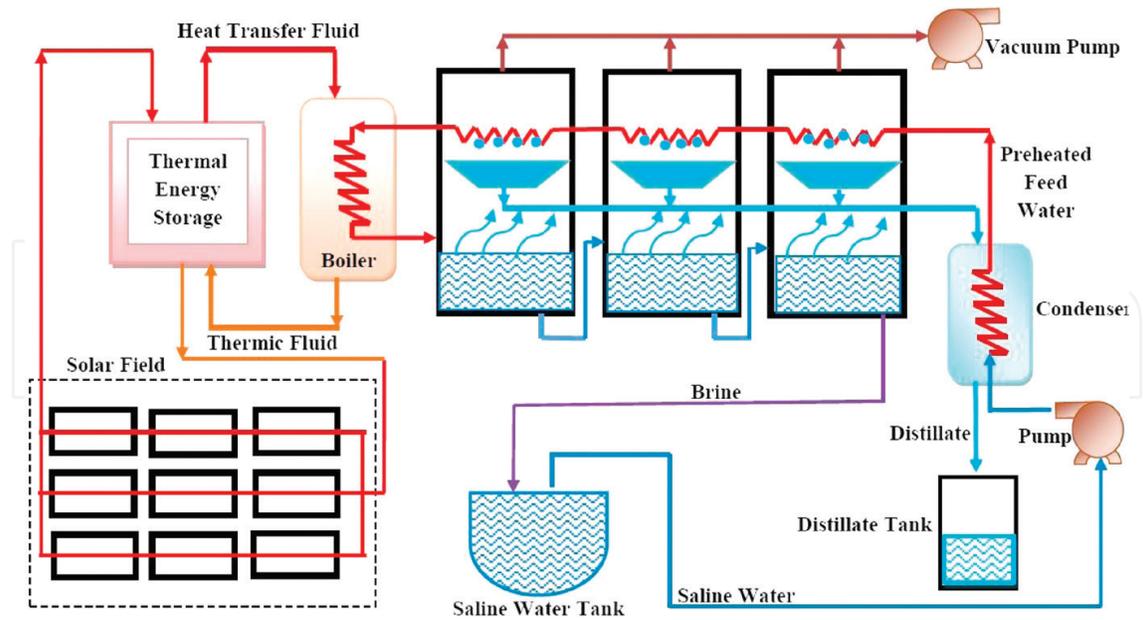


Figure 9. MSF distillation process powered by concentrated solar energy [47].

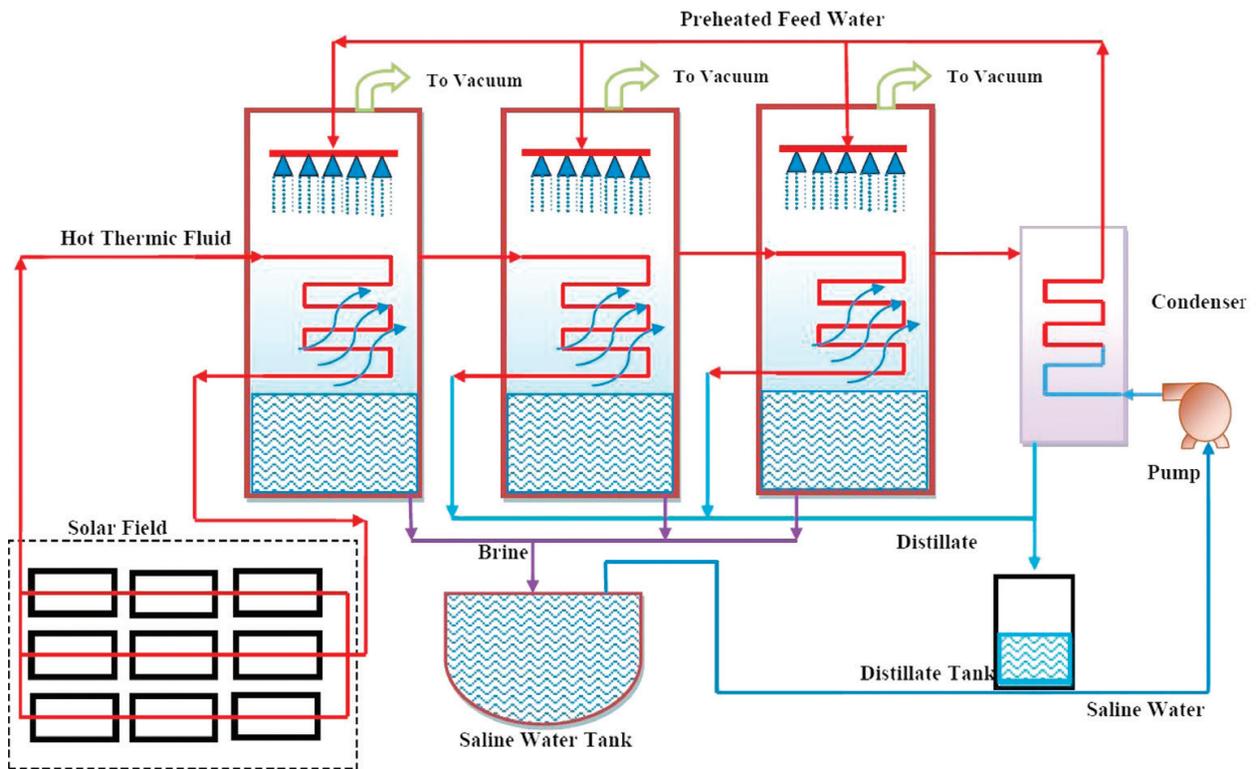


Figure 10. MED distillation process powered by concentrated solar energy [47].

In mechanical vapor compression desalination, a mechanical compressor is used to compress water vapor. The compressed vapor flows inside a bundle of tubes, which leads to condensation at a relatively high temperature. A saline water is sprayed on the outside surface of the bundle of tubes to recuperate the vapor latent heat of condensation. The saline water gets evaporated due to the heated tube bundle. The water vapor is then passed to the condenser to produce a fresh water. **Figure 12a** shows a schematic diagram of a mechanical

vapor compression distillation system coupled with MED powered by concentrated solar energy. Thermal vapor compression is usually coupled with multiple-effect distillation, which utilizes water vapor produced in each effect. Thermal vapor compression desalination process utilizes a steam jet compressor to compress the vapor. A steam jet is used to extract the low-pressure steam from the vessels by creating a vacuum and then after mixing it with high-pressure steam that is supplied to the system. The pressure of the resulting steam mixture is then raised in the diffuser to the pressure required for heating steam in the first effect. **Figure 12b** shows a schematic diagram of thermo vapor compression distillation coupled with MED powered by concentrated solar energy.

Concentrating solar power generation (CSP) for large scale seawater desalination applications is promising as it can achieve very high capacity desalination plants, which can be a primary water source for large centralized communities. It is predicted that energy from CSP plants will become a more cost effective option for electricity generation and water desalination in several decades due to the development of the technology and to more implementation of solar renewable energy projects. Additional research is required to demonstrate long-term reliability of solar powered thermal desalination technologies and to improve the thermal efficiency.

## 2.6. Solar pond distillation

Thermal desalination by salinity-gradient solar ponds is a promising desalination technology as it is less costly compared to other solar driven desalination options. Solar ponds provide the least expensive option for heat storage with solar powered desalination systems, which is an important economic aspect for desalination processes. Ideally, thermal energy obtained from a salinity-gradient solar pond can be used to power conventional thermal desalination

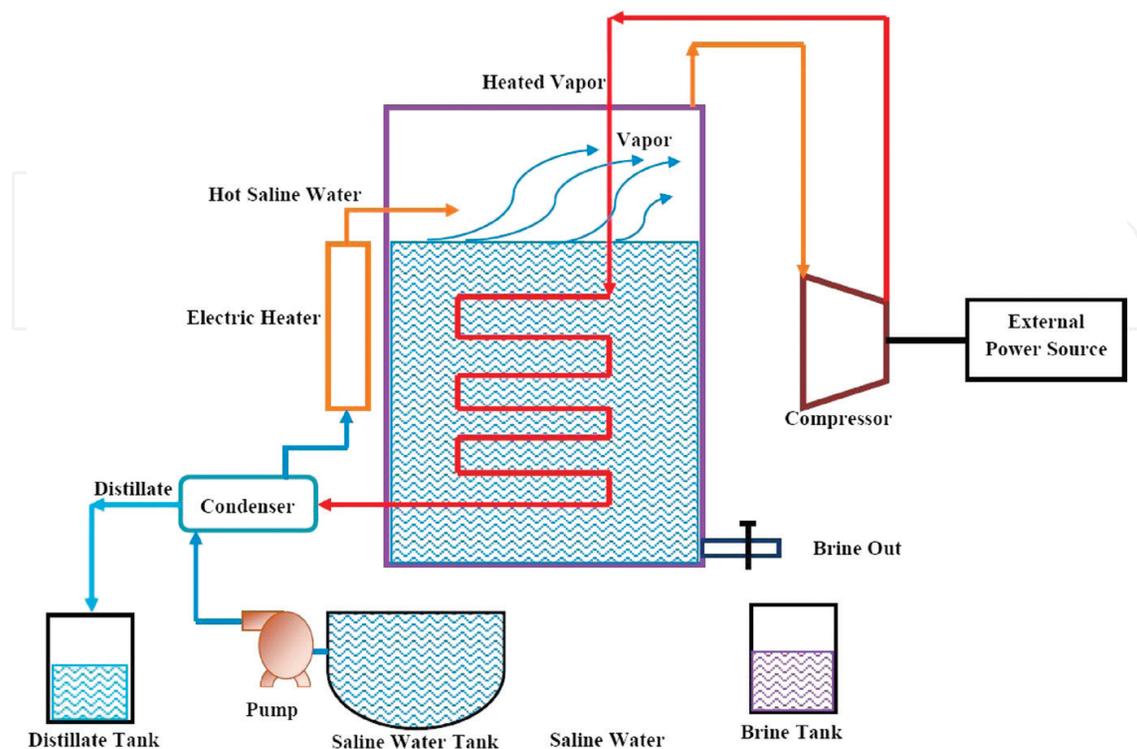


Figure 11. Concentrated solar energy powered MED distillation process [47].

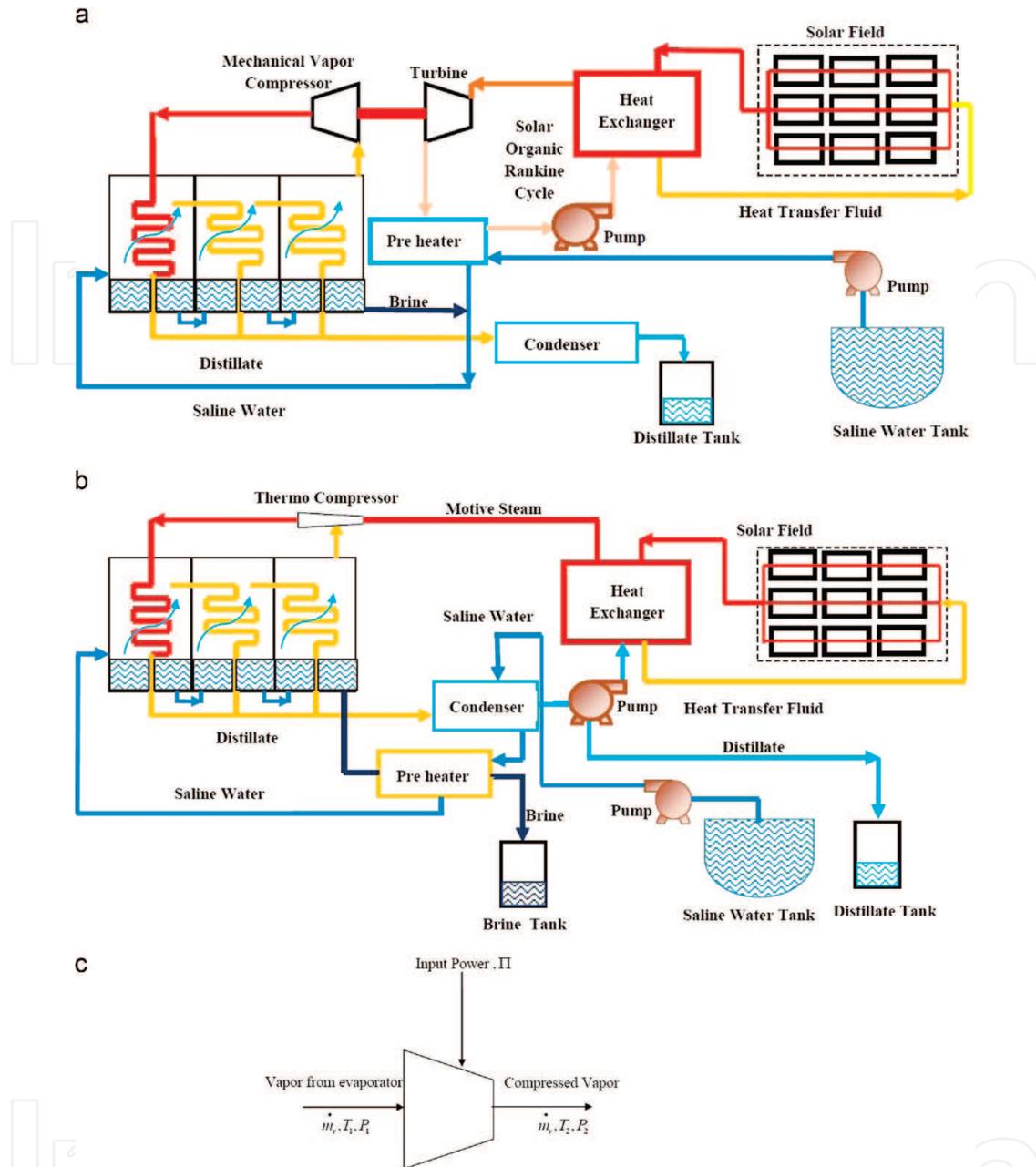


Figure 12. (a) Concentrated solar powered mechanical vapor compression unit coupled with MED, (b) concentrated solar powered thermo vapor compression unit coupled with MED [47].

technologies such as MSF, MED, and VC distillation. Although, this technology is still in the development stage, as demonstration plants have experienced operational difficulties. A lab-scale experimental investigation of an integrated solar pond of 70°C with 10 flash desalination units operating at 0.9 bar has been confirmed to produce approximately 15 m<sup>3</sup>/d of distilled water [50]. Solar pond technology integrated with MSF desalination plant has potential to be more cost effective than any other solar powered desalination technology [51]. At present, additional research is required to demonstrate long-term reliability of solar pond powered thermal desalination technologies.

### 3. Environmental impact of desalination

Fresh water shortage and demand are expected to increase in the coming few decades. The development and utilization of alternative water resources such as seawater desalination are becoming inevitable. On the other hand, desalination is very energy intensive process and has negative impact on the environment. The discharge of concentrated brine, hamper the life of marine eco systems. Waste discharge from desalination processes is considered to be a significant challenge that is becoming increasingly important. High energy consumption is considered the most influencing factor that inhibits growth of seawater desalination. Currently, most desalination processes are driven by energy obtained from fossil fuel. With such dependence on fossil fuel based energy sources, the increase in seawater desalination results in gas emissions that pollute the environment. Solar energy based desalination process is considered to be a promising method to alleviate the environmental impact of water desalination and also provide a sustainable source of potable water. This approach significantly mitigates the dependence on fossil fuel.

Large amount of concentrated brine discharge from saline water desalination plants is considered to be unpleasant waste. Marine life is strongly affected by the discharge of the concentrated brine. Concentrated brine is not only salt concentrated, but also contains chemicals such as anti-scaling agents from pre- and post-treatment. This results in high salt concentration in the area near brine discharge point. Brine disposal is a problem that challenges all desalination technologies. Brine discharged from membrane based desalination such as reversed osmosis is more concentrated than the brine discharged from thermal distillation plants. However, brine discharged from thermal distillation plants exits at a relatively high temperature compared with membrane based distillation. This influences the marine life such that only some plants or marine animal can withstand the high temperature near the outlet of thermal distillation plants. Marine life is also influenced by the intake of the seawater for the desalination plant. When a large amount of seawater is drawn from the sea, marine organisms and algae are sucked into the intake which cause a disturbance to the eco-system.

Many methods are currently used for brine disposal from desalination plants. Brine can be discharged to sea or river, discharged to solar ponds, or injected to deep saline aquifers. The discharge of brine to the sea or ocean is the least expensive method compared to other method. When brine is discharged to the sea, it tends to sink at the bottom of the sea because it has higher density than the seawater. A typical standard used in brine discharge is to diluted the brine with seawater to reduce its salinity before being discharged to sea. Furthermore, operating at lower recovery rates reduces the salinity of the brine. Brine is discharged at high depth of seawater which typically have a strong current. This reduces the detrimental effects of brine on the marine life. Brine discharges to a solar pond or the injection to a deep saline aquifer is more expensive method than sea discharge. These solar ponds and saline aquifers are typically located away from the desalination plant which require a long pipeline for transportation. This method has drawbacks because it may increase the salt in the soil and also increases the salinity of the ground water if linear is not used under the solar pond. The utilization of solar pond for brine disposal require a very large surface area, and it carries the risk of contaminating ground water.

## 4. Conclusions

Potable water is considered to be a scarce commodity especially in arid and remote regions. While conventional desalination technologies offer an excellent solution to meet water demand, they are considered to be energy intensive processes. Conventional desalination technologies are well suited for large scale applications but they are not-efficient and not suited for small scale water demand. Conventional desalination processes are expensive to operate and require continues maintenance which prevent their utilization in remote areas.

With the ever increasing energy cost and unavailability in the future, there is a need for cost effective desalination system that is well suited for small scale application. Solar desalination is expected to be a promising method to alleviate water shortage. The interests in solar desalination technologies have increased significantly in the last few decades. In order to maximize the utilization of solar desalination, the desalination efficacy needed to improved further and its cost must be reduced. Solar energy powered by desalination process can have a positive impact on reducing gas emissions and can considered to be a reliable source for potable water. Solar desalination processes can provide fresh water for remote areas in a sustainable way. Currently, more research is needed for improving solar based desalination and the treatment of waste water using these units.

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