Solar Thermal Technologies for Seawater Desalination: state of the art

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ABSTRACT

Solar desalination is a rapidly growing field of research. The coming global oil crisis implies that alternatives to the conventional desalination plants based on fossil fuels must be developed. Solar desalination can be either direct, with collectors and condensers integrated with each other, or indirect, with condensers externally connected to the condensers. Direct solar desalination requires large land areas and has a relatively low productivity compared to the indirect technologies. It is however competitive to indirect desalination plants in small-scale production due to its relatively low cost and simplicity. Indirect solar desalination usually means combining conventional desalination techniques, such as MSF, ME or RO, with solar collectors for heat generation. This state of the art report presents the principles and characteristics of some of the recently developed direct and indirect solar desalination techniques.

1. INTRODUCTION

There is a severe lack of fresh water in the world today. Along with the deterioration of existing water supplies, the growing world population leads to the assumption that two thirds of the population will lack sufficient fresh water by the year 2025 [1]. The areas with the severest water shortages are the warm, arid countries in the northern Africa and southern Asia within the latitudes 15-35°N [2]. In view of these facts, desalination seems to be the only realistic hope for a new source for fresh water.

The regions in most need of additional fresh water are also the regions with the most intense solar radiation. For this reason thermal solar energy in desalination processes should be the most promising application of renewable energies to seawater desalination [16]. The situation today is, however, somewhat different, since only 0.02% of the global desalination capacity is represented by renewable energy systems [17].
The main problems with the use of solar thermal energy in large scale desalination plants are the relatively low productivity rate, the low thermal efficiency and the considerable land area required. Since solar desalination plants are characterised by free energy and insignificant operation cost, this technology is, on the other hand, suitable for small-scale production, especially in remote arid areas and islands, where the supply of conventional energy is scarce [13-14]. The use of solar energy for driving the desalination plant is also motivated in these areas by the fact that they imply a way for energy independence and water insurance [11]. The low environmental impact as well as the easy operation and maintenance are also incitements for this technology [17-18].

A solar distillation plant may consist of separated or integrated systems for the solar collector and the distiller. Integrated systems are often referred to as “direct solar desalination” and usually involve different types of solar stills. Separated systems are known as “indirect solar desalination” [16], in which the thermal energy from the sun is used for either heating the seawater or generating steam in conventional distillation plants, using for example Multi-Effect (ME), Multi-Stage Flash (MSF) or Reverse Osmosis (RO) systems [19].

2. DIRECT SOLAR DESALINATION

The method of direct solar desalination is mainly suited for small production systems, such as solar stills, in regions where the freshwater demand is less than 200 m$^3$/day [18]. This low production rate is explained by the low operating temperature and pressure of the steam.

The original solar still can be described as a basin with a transparent cover of e.g. glass. The interior of the still contains seawater and air. When the seawater is heated by solar radiation, it starts to evaporate and the formed vapour is mixed with the air above the water surface. On meeting the inside of the glass ceiling of the still the humid air is re-cooled and some of the vapour condenses on the glass. If the glass cover is tilted, the formed condensation drops will start running down the cover by gravitational forces, and may then be collected at the side of the still (fig. 1).

![Figure 1: Basic solar still for seawater desalination [18].](image-url)
One of the main setbacks for this type of desalination plant is the low thermal efficiency and productivity. This could be improved by a number of actions, e.g. injecting black dye in the seawater, reducing the heat conduction through basin walls and top cover or reusing the latent heat emitted from the condensing vapour on the glass cover. Another solution would be to separate the solar collector and the saline water so that corrosion damages, and thereby efficiency losses are avoided [24].

### 2.1 Single-effect solar stills

In the original solar still construction, also called single-effect solar still, only one layer of glazing covers the still. This enables a large quantity of the latent heat from the condensation process to disappear from the still by conduction through the glazing. Today’s state-of-the-art single-effect solar stills have an efficiency of about 30 – 40 % [6] and a production rate in the order of 6 litres per day and square meter of collector surface [11], but research and development on this system continues. The development techniques may be classified as shown in fig. 2 [18]. Passive solar stills utilize the internal heat from the still for the evaporation process, while active stills make use of external sources, such as solar collectors or waste heat from industries. Fath [18] has done a valuable review of the latest development on this topic.

![Figure 2: Classifications of developments for single-effect solar stills](image)

2.1.1 Basin stills

Three of the main research topics on the passive basin still are summarised:

1. Single slope versus double slope basin stills: A comparison of a single and double slope solar still, shows that due to the daily and seasonal movement of the sun, a double-sided still can absorb more solar radiation than a single slope basin still. The single slope, on the other hand, has less convection and radiation losses, and the shaded region can furthermore be used for an additional condensation surface. Tiwari et al [20] performed a study of the two configurations and concluded that the single slope basin still performs better than a double slope in cold climate, whereas the opposite result was achieved in warm climates.
2. Still with additional cooling: The evaporation rate increases with increasing temperature difference between the water surface and the glazing. This can be done by for example heating the water more or cooling the cover. Another alternative cooling system for basin type solar stills was presented by Haddad [8], where an external condenser, constructed as a packed bed storage tank, was integrated with the still. The packed bed condenser was cooled during the night, using a radiative cooling panel by circulating water into the packed bed condenser and the radiative cooling panel (fig. 3).

![Figure 3: Schematics of the solar still and condenser [8].](image)

The cooling panel utilized the cold effective sky temperature, which normally is 10-25°C lower than the ambient temperature, in order to cool the rock domain in the packed bed storage during the night. In doing so, the tank temperature was lowered to nearly effective sky temperature. At the beginning of the daylight, water was evacuated from the storage tank, as vapour started to form on the surface of the solar still. By buoyancy forces created in the condenser, the vapour was sucked through the duct between the still and the condenser, which made additional driving forces unnecessary.

Several advantages in this system were noted. Among other things was the heat loss reduced since the temperature inside the still was lowered, and the lower vapour partial pressure in the still contributed in a faster evaporation rate. Also, the low temperature of the condenser enhanced the condensation rate.

3. A typical single effect solar still was recently designed for water purification in remote areas in Venezuela. The solar distiller was of basic design and used for brackish water purification. A community of 100 inhabitants was selected for the experimental set-up. Based on the calculated required daily water consumption the plant was designed to 380 distiller units, with an estimated daily productivity of 5 litres each. Experimental and economic analysis of the system concluded that it should be an attractive alternative to the current method of water distribution by means of cistern trucks [21].
2.1.2 Stills integrated with greenhouses

Greenhouses combined with solar stills represent an interesting possibility for the development of small-scale cultivation in places where only saline or brackish water is available. A version of this system was constructed and analysed by Chaibi et al [3-4], where the south slope of the greenhouse roof was built as a solar still (fig. 4).

![Figure 4: System principle for water desalination integrated in a greenhouse roof. [3]](image)

During the day, saline water was pumped from a reservoir to the rooftop of the greenhouse, from where it was distributed evenly to the evaporation surface in the still. The top cover of the still was a regular glass sheet, while the bottom of the solar still consisted of an only partly light transparent material, which absorbed a substantial amount of the solar irradiation, but transmitted the wavelengths that are favourable for the photosynthesis of vegetation (the photosynthetic active radiation, PAR, has the wavelength interval 380 – 710 nm).

Since most of the heat radiation was absorbed in the still, the temperature of the greenhouse air was lowered, which lead to better climate for the crops and less ventilation requirement. In the end, this lead to a decrease in the water consumption of the crops.

The formed water vapour condensed on the top glazing, ran along the inner wall of the top cover, and was collected in the fresh water store. The residue of the feed water was collected in a separate storage. The returned feed water was partly returned to the feed water duct for another loop in the still, and some of the residue saline water was also mixed with the fresh water before the irrigation to bulk
out the supply. The desalination roof was operated during both day and night, as excess heat was stored in the saline water storage.

Compared to a conventional single glass greenhouse, considerable less extreme climate conditions inside the greenhouse could be registered with the roof desalination system. It was also shown that with 50% of the roof built as a solar still, the irrigation need for low canopy crop could be satisfied, but analyses of crop growth also indicated a lesser yield by approximately 25%. An economical analysis of the described system, a single-effect desalination system with heat pipe collectors and a solar multiple condensation evaporation (SMEC) cycle process were performed, which showed that the integrated solar still was more economical than the other two by 35% and 50%, respectively [4].

2.2 Multi-effect solar stills

Multi-effect solar stills are designed to recycle some of the latent heat from the condensation by using it for preheating either the feed water or the seawater within the still. The former may be accomplished by e.g. using the feed water duct as the condensation surface for the water vapour. The saline feed water is then preheated by the heat released from the condensing vapour, and the condensation surface is kept continuously cool. A multi-effect solar still can in this way produce fresh water up to 20 litres per day and square meter of collector area. The increased production rate that follows by this recycling, must however be measured to the cost for the more complex construction that follows [18].

2.2.1 Solar still with preheating of feed water

An air-blown, double-glazed solar still has been proposed by Mink et al [6]. The solar still is divided into two chambers, the upper one being the evaporator and the lower the condenser. A metal sheet separates the evaporator and condenser along the length of the still, except for a small gap in the upper part of the still (fig. 5).

Feed water is lead upwards through the condensation chamber in a serpentine tube and is let out on to the evaporation surface, consisting of a black porous textile, on the top of the still. The textile absorbs the water evenly, as the water flows down along it. Air enters from the bottom of the evaporator, sweeps away the evaporated vapour from the wetted textile surface and leads it down to the condenser department via the upper gap between the two chambers. The vapour then condenses on the serpentine tubes and preheats the feed water. The distillate is finally collected at the bottom of the condenser.

Experimental investigations on this type of still showed that the solar still performance can be enhanced by further optimising area relations between the evaporator and the condenser. The received daily water production rate was in this experiment approximately 1 kg/m².
2.3 Water desalination with humidification-dehumidification (HD)

One of the problems that negatively influences the still performance is the direct contact between the collector and the saline water, since this may cause corrosion and scaling in the still and thereby reduce the thermal efficiency [24]. In HD desalination air is used as a working fluid, which eliminates this problem. Systems based on HD consist of a compact unit, containing two heat exchangers for evaporation and condensation, respectively. The constructions are usually lightweight and inexpensive, and work at atmospheric pressure [15]. Due to relatively low desalination capacity, the system performance must however be improved before it can be economically competitive.

2.3.1 Desalination with humidification – dehumidification using an open-air cycle

Dai and Zang [9-10] proposed an open-air cycle desalination system, in which seawater was heated by the sun in a collector and then sprayed on the surface of a honeycomb wall in the humidifier (fig. 6). Air was blown through the humidifier, where it became hot and humid. The air was thereafter led to the condensation area between the feed water tubes, where it was cooled and fresh water precipitated into the collection container. In order to increase the thermal efficiency, the part of the warm seawater...
that was not picked up by the air in the honey comb was collected and led back into the seawater tank for another round in the humidification-dehumidification process. Since the air flowed in a straight line, unnecessary pressure losses were avoided. During experiments with this desalination system, a freshwater gain of 6.2 kg/m² per day was observed for cases when solar irradiation was 700 W/m² and the operation time was 8 hours per day. The thermal efficiency of the system was estimated to 85 %.

2.3.2 Solar air-heating with stepwise humidification

The low water production capacity in ordinary solar stills can partly be explained by the small difference in vapour content of the air before and after the condenser [12]. In a single-step system, the only possibility for improving this is either to increase the operating air temperature or flow rate, which leads to unrealistic investments.

An interesting solution to this problem is presented by Chafik [12], where the air is heated and humidified in several steps inside a simple solar collector. This both lead to higher vapour content in the air and a lower required airflow rate. The course of the procedure is as follows (fig. 7): Air with an initial temperature and specific humidity of e.g. 25°C and 10 g vapour/kg dry air, respectively, enters
the solar air-heating collector. During the first step in the collector, the air is first warmed to 50 °C and then humidified by sprinklers with seawater until the air is approximately saturated. Due to the heat required for the evaporation of the water, the air temperature sinks to about the wet bulb temperature of 23°C. In the following step, the air is again heated to 50°C and then humidified in the same way to a vapour content of 28 g vapour/kg dry air. The air temperature goes down to 31°C. During the third step the air is heated to 56°C and humidified to 36 g vapour/kg dry air at 35°C.

The heating and humidification process goes on for 15 steps, after which the air has reached a humidity of 148 g vapour/kg dry air at 60°C (fig. 8). This high water content is identical to the humidity that can be achieved by injecting water into heated air of about 450°C. By cooling the warm, humid air exiting the 15th step to 25°C, 128 g fresh water can be extracted for 1kg of dry air. A pilot plant for this technique is presently running in Bochum, Germany, where 1 m³ per day is produced.

Figure 7: Scheme of the stepwise heating and humidification [12].

Figure 8: Psychometric chart with stepwise heating and humidification [12]
3. INDIRECT SOLAR DESALINATION

Every day desalination plants around the world produce about $23 \times 10^6$ m$^3$ of fresh water [17]. For this production rate, desalination systems of the industrial scale are required. The majority of the existing desalination plants for this purpose are of the types Multi-Effect (ME), Multi-Stage Flash (MSF) and Reverse Osmosis (RO). Usually these systems use fossil fuels as the energy source for either heating or electric power generation. They are also characterised by high operating cost and the need for highly skilled operation and maintenance personnel.

One of the most promising directions for research and development for these large-scale desalination facilities seems to be the use of solar energy because of its low cost, availability and relatively simple maintenance. An investigation by Garzia-Rodriguez [19] showed that parabolic trough collectors and salinity gradient solar ponds should be the best choices for this purpose.

3.1 Multi-Effect (ME)

The ME is one of the most promising evaporation techniques today [22]. It has long been thought that the ME system is not suitable for production rates lower than 100 m$^3$/day because of the need for qualified maintenance and electricity supply [5]. However, by the use of solar energy instead of fossil fuels, ME may well be made economically feasible [19].

The essential feature of ME is that saline water stepwise evaporates by heat transfer from condensing steam, transported in a bundle of tubes. The most commonly used configuration of an ME plant is horizontal tube bundles with 8-16 evaporation steps (fig. 9).

![Figure 9: Schematics of a ME distillation plant with horizontal tubes [22]](image)

At the first step, the condensing steam is generated externally, by for example fossil fuel or solar collectors. The produced steam from the evaporation of the brine is then used in the subsequent step,
which operates at a slightly lower pressure and temperature, so the energy retrieved from the condensing steam can be used for further evaporation of the brine [23].

Pilot plants for ME desalination with solar heating are being developed and investigated. In the Arabian Gulf, such a plant exists using parabolic through collectors for producing 6000 m$^3$/day and another ME plant using solar ponds for the production of 30 m$^3$/day are constructed at the university of Ancona, Italy, to mention just two of them [17].

### 3.2 Multi-Stage Flash (MSF)

The most common and simple technique for large-scale desalination is at present the Multi-Stage Flash distillation, which globally produces a total amount of about 10 million ton of fresh water every day.

The system works with pressurised seawater that flows through closed pipes and exchanges heat with condensing vapour. When the seawater is heated to a certain degree it is lead into a low-pressure chamber, where it is flash-evaporated. The resulting vapour is then cooled and collected in a tank for freshwater [18].

Several medium scale plants for MSF desalination using solar energy have recently been implemented. One of the most commonly type of solar collectors used are salinity gradient solar ponds, such as the desalination plant in Margarita de Savoya, Italy, with a capacity of 50 – 60 m$^3$/day, or in El Paso, Texas, with a capacity of 19 m$^3$/day. Another frequently occurring source for solar thermal energy is the parabolic trough collector, which is used in i.e. a MSF desalination plant in Kuwait for a production rate of 100 m$^3$/day [17].

### 3.3 Reverse Osmosis (RO)

In the reversed osmosis system, seawater is forced under pressure through a series of membranes that physically remove salt molecules [5]. In contrast to distillation systems, where separation occurs through difference in evaporation temperatures, the separation process is here determined by size and diffusivity differences [23].

Recent progress have been made on the subject of using RO in seawater desalination, and low pressure RO systems are now able to operate at pressures as low as 20 bar [23]. Ongoing research and development on the subject of combining RO with solar energy predict a good possibility of finding a cost-effective solution. Among the suggested solar driven plants are RO desalination driven by solar produced steam [19].
3.4 Salinity-gradient Solar ponds

As the sun shines over a lake or a pond, the water absorbs some of the irradiation and is warmed. Surface water quickly loses this added heat due to heat and mass convection with the ambient air. Since the underlying water in the pond now is warmer and thereby lighter than the surface, convective circulation begins, where warm water from the bottom rises and the colder water from the surface layer sinks.

The salinity-gradient solar pond is constructed in such a manner that the convective circulation in the pond is prohibited by making the bottom water much denser than the surface water. In doing so, the solar radiation absorbed in the deep water can be stored [16]. The general solar pond consists of three layers of different temperature and salt content (fig. 10).

![Figure 10: Typical salinity-gradient solar pond [2]](image)

The top layer, usually about 0.8 – 1 meter deep, is at atmospheric temperature and has a low concentration of salt. The second layer is the so-called gradient zone. Here the temperature and salt concentration increase with the water depth, which usually is 1 – 2 meters. The bottom layer in the solar pond, also called the storage zone, is very dense and is heated up to 100°C [2]. Since the water in the gradient zone cannot rise, due to the light water on top, and cannot fall, due to the dense water beneath, convection is prevented and the heat is stored in the storage zone. The gradient zone could hence be said to work as an insulator for the storage layer. Heat is extracted by passing the brine from the storage zone through an external heat exchanger.

Solar ponds require plenty of land area, water and salt, why it is reasonable to locate them in wastelands or in deserts, close to salt works. Many countries, such as Libya, are greatly dependent on
seawater desalination and are in supply of these characteristics. To use solar ponds instead of fossil fuel for heating the desalination plants would mean significantly lower production costs [2].
3.5 Parabolic through collectors

The parabolic through collector uses a trough-shaped reflector to concentrate sunlight on the receiver at up to 60 times its normal intensity. In this way, the receiver tube, which runs along the reflector's focal line, can achieve a much higher temperature than flat-plate or evacuated-tube collectors (fig. 11). The parabolic through collector systems usually include a mechanical control system that keeps the trough reflector pointed at the sun throughout the day. Parabolic-trough concentrating systems can provide hot water and steam, and are generally used in commercial and industrial applications [25].

![Schematics of a parabolic through collector](image)

Figure 11: Schematics of a parabolic through collector [25]

4 CONCLUSIONS

The use of solar thermal energy in seawater desalination applications has so far been restricted to small-scale systems in rural areas. The reasons for this have mainly been explained by the relatively low thermal efficiency and production rate compared to the large area required. Of the 23 million m$^3$ of fresh water produced every day, only 46 000 m$^3$, or 0.02 %, originates from plants with renewable energy systems.

However, the coming shortages in fossil fuel supply and the growing need for fresh water in order to support increasing water and irrigation needs, have motivated further development of water desalination and purification by renewable energies. The most promising source within this area is, as it seems today, solar thermal or geothermal energy.

If renewable energy could be combined with large-scale desalination plants, such as ME or MSF, to a reasonable cost, this could mean a solution to one of the most pressing environmental issues of today and the near future.
REFERENCES


