ELSEVIER

Desalination 220 (2008) 633–644

DESALINATION

www.elsevier.com/locate/desal

Solar thermal desalination technologies

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Received 19 December 2006; accepted 3 January 2007

Abstract

The use of solar energy in thermal desalination processes is one of the most promising applications of the renewable energies. Solar desalination can either be direct; use solar energy to produce distillate directly in the solar collector, or indirect; combining conventional desalination techniques, such as multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis, with solar collectors for heat generation. Direct solar desalination compared with the indirect technologies requires large land areas and has a relatively low productivity. It is however competitive to the indirect desalination plants in small-scale production due to its relatively low cost and simplicity. This paper describes several desalination technologies in commercial and pilot stages of development. The primary focus is on those technologies suitable for use in remote areas, especially those which could be integrated into solar thermal energy systems.

Keywords: Solar energy; Desalination; Solar stills

1. Introduction

The lack of potable water poses a big problem in arid regions of the world where freshwater is becoming very scarce and expensive. Clean drinking water is one of the most important international health issues today. The areas with the severest water shortages are the warm arid countries in the Middle East and North Africa (MENA) region. These areas are characterized by the increase in ground water salinity and infrequent rainfall. The increasing world population growth together with the increasing industrial and agricultural activities all over the world contributes to the depletion and pollution of freshwater resources.

Desalination is one of mankind's earliest forms of water treatment, and it is still a popular treatment solution throughout the world today. In nature, solar desalination produces rain when solar radiation is absorbed by the sea and causes water to evaporate. The evaporated water rises above the surface and is moved by the wind. Once this vapor cools down to its dew point, condensation occurs,

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Presented at the conference on Desalination and the Environment. Sponsored by the European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort, Halkidiki, Greece, April 22–25, 2007.

doi:10.1016/j.desal.0000.00.000

and the freshwater comes down as rain. This basic process is responsible for the hydrologic cycle. This same principle is used in all man-made distillation systems using alternative sources of heating and cooling.

Desalination uses a large amount of energy to remove a portion of pure water from a salt water source. Salt water (feed water) is fed into the process, and the result is one output stream of pure water and another of wastewater with a high salt concentration.

It has been estimated by Kalogirou [23] that the production of 1000 m^3 per day of freshwater requires 10,000 tons of oil per year. This is highly significant as it involves a recurrent energy expense which few of the water-short areas of the world can afford. Large commercial desalination plants using fossil fuel are in use in a number of oil-rich countries to supplement the traditional sources of water supply. People in many other areas of the world have neither the money nor oil resources to allow them to develop on a similar manner. Problems relevant to the use of fossil fuels, in part, could be resolved by considering possible utilization of renewable resources such as solar, biomass, wind, or geothermal energy. It often happens that the geographical areas where water is needed are well gifted with renewable energy sources (RES). Thus, the obvious way is to combine those renewable energy sources to a desalination plant, in order to provide water resources as required. In fact, most developing countries, with vast areas but having no access to electric grid, appear to be well versed in renewable energies. Such sources, able to be used directly even at far remote and isolated areas, could be exploited to power low to medium scale desalination plants. The World Health Organization estimates that over a billion people lack access to purified drinking water and the vast majority of these people are living in rural areas where the low population density and remote locations make it very difficult to install the traditional clean water solutions.

Recently, considerable attention has been given to the use of renewable energy as sources for desalination, especially in remote areas and islands, because of the high costs of fossil fuels, difficulties in obtaining it, attempts to conserve fossil fuels, interest in reducing air pollution, and the lack of electrical power in remote areas. It is, however, to be noted that in spite of the aforesaid favorable characteristics, the renewable energy contribution to cover energy demand worldwide, though increasing, is still marginal. Aside from the hydroelectric energy, the other principal resources (solar, wind, geothermal) cover together little more than 1% of the energy production worldwide [9].

Owing to the diffuse nature of solar energy, 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. However, since solar desalination plants are characterized 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 [28]. Apart from the cost implications, there are environmental concerns with regard to the burning of fossil fuels. The coupling of renewable energy sources with desalination processes is seen by some as having the potential to offer a sustainable route for increasing the supplies of potable water.

Solar energy can directly or indirectly be harnessed for desalination. Collection systems that use solar energy to produce distillate directly in the solar collector are called direct collection systems whereas systems that combine solar energy collection systems with conventional desalination systems are called indirect systems. In indirect systems, solar energy is used either to generate the heat required for desalination and/or to generate electricity that is used to provide the required electric power for conventional desalination plants such as multi-effect (ME), multi-stage flash (MSF) or reverse osmosis (RO) systems [16].

2. Solar technologies

Different solar energy collectors may be used in order to convert solar energy to thermal energy. In most of them, a fluid is heated by the solar radiation as it circulates along the solar collector through an absorber pipe. This heat transfer fluid is usually water or synthetic oil. The fluid heated at the solar collector field may be either stored at an insulated tank or used to heat another thermal storage medium.

The solar collector may be a static or sun-tracking device. The second ones may have one or two axes of sun tracking. Otherwise, with respect to solar concentration, solar collectors are already commercially available; nevertheless, many collector improvements and advanced solar technologies are being developed. The main solar collectors suitable for seawater distillation are as follow.

2.1. Salinity-gradient solar ponds

This is a shallow pond with a vertical salt-water gradient, so that the denser saltier water stays at the bottom of the pond and does not mix with the upper layer of fresher water. Consequently, the lower salty layer gets very hot (70–85°C). This heat can be used to make electricity (with additional heating from traditional sources), provide energy for desalination, and to supply energy space heating in buildings. A solar pond (SP) is a thermal solar collector that includes its own storage system. A solar pond collects solar energy by absorbing direct and diffuse sunlight. It consists of three layers of saline water with different salt concentrations. Salt-gradient solar ponds have a high concentration of salt near the bottom, a non-convecting salt gradient middle layer (with salt concentration increasing with depth), and a surface convecting layer with low salt concentration. Sunlight strikes the pond surface and is trapped in the bottom layer because of its high salt concentration. The highly saline water, heated by the solar energy absorbed in the pond floor, cannot rise owing to its great density. It simply sits at the pond bottom heating up until it almost boils (while the surface layers of water stay relatively cool)! The bottom layer in the solar pond, also called the storage zone, is very dense and is heated up to 100°C [22]. This hot brine can then be used as a day or night heat source from which a special organic-fluid turbine can generate electricity. The middle gradient layer in solar pond acts as an insulator, preventing convection and heat loss to the surface. Temperature differences between the bottom and surface layers are sufficient to drive a generator. A transfer fluid piped through the bottom layer carries heat away for direct end-use application. The heat may also be part of a closed-loop Rankine cycle system that turns a turbine to generate electricity.

The annual collection efficiency for useful heat for desalination is in the order of 10–15%. Larger ponds tend to be more efficient than smaller ones due to losses at the pond edge.

Solar ponds produce relatively low grade, less than 100°C, thermal energy and are therefore generally considered well suited for supplying direct heat for thermal distillation processes. Due to their ability to store energy, however, solar ponds are also used to produce electricity. Solar ponds are particularly well suited to association with desalination plants as waste brine from desalination can be used as the salt source for the solar pond density gradient. Using desalination brine for solar ponds not only provides a preferable alternative to environmental disposal, but also a convenient and inexpensive source of solar pond salinity.

2.2. Flat-plate collector

Flat-plate collectors (FPCs) are used as heat transfer fluid, which circulates through absorber pipes made of either metal or plastic. The absorber pipes are assembled on a flat plate and they usually have a transparent protective surface in order to minimize heat losses. They may have different selective coatings to reduce heat losses and to increase radiation absorption. Thus the thermal efficiency increases although the collector cost also increase.

A typical flat-plate collector is an insulated metal box with a glass or plastic cover and a dark-colored absorber plate. The flow tubes can be routed in parallel or in a serpentine pattern. Flat plate collectors have not been found as a useful technology for desalination [5,18]. Although they have been used for relatively small desalinated water production volumes, production of large volumes of water would require an additional energy source, for example, a desalination facility in Mexico derives energy from flat plate collectors and parabolic troughs.

2.3. Evacuated tube collector

Heat losses are minimized in evacuated tube collectors (ETCs) by an evacuated cover of the receiver. This cover is tubular and made of glass. In addition, a selective coating of the receiver minimizes the losses due to infrared radiation. There are two different technologies of evacuated tubes: (1) Dewar tubes two coaxial tubes made of glass, which are sealed each other at both ends; and (2) ETC with a metallic receiver, which requires a glass to metal seal. There are different designs depending on the shape of the receiver. ETCs are set in conjunction with reflective surfaces: a flat-plate or a low-concentrate reflective surface as a compound parabolic one. Usually a number of evacuated tubes are assembled together to form a collector. Evacuated tube collectors require more sophisticated manufacturing facilities than flat-plate collectors. With evacuated tube collectors, higher temperatures can be reached and efficiencies tend also to be higher.

For the most part, however, evacuated tube collectors are preferred to flat plate collectors. Although the evacuated tube collectors are more expensive, \$300–\$550/m^2 as opposed to \$80–\$250/m^2 for flat plate collectors, less of them and less land area would be needed for the same level of energy production. Also, since evacuated tube collectors produce temperatures of up to 200°C, they are particularly suited as an energy source for high temperature distillation [5]. An evacuated-tube collector generally consists of a fluid-filled absorber tube surrounded by a vacuum.

2.4. Parabolic trough collector

A parabolic trough is a linear collector with a parabolic cross-section. Its reflective surface concentrates sunlight onto a receiver tube located along the trough's focal line, heating the heat transfer fluid in the tube. Parabolic troughs typically have concentration ratios of 10 to 100, leading to operating temperatures of 100–400°C. Parabolic trough collectors (PTCs) require sun tracking along one axis only. In this way, the receiver tube can achieve a much higher temperature than flat-plate or evacuated-tube collectors. The parabolic trough 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 [39].

Still, among solar thermal technologies, solar ponds and parabolic troughs are the most frequently used for desalination [40]. Due to the high temperatures parabolic troughs are capable of producing high-grade thermal energy that is generally used for electricity generation [5]. Parabolic troughs could be a suitable energy supply for most desalination methods, but in practice, have mainly been used for thermal distillation as these methods can take advantage of both the heat and electricity troughs produce. Other methods of desalination would receive little or no benefit from the heat produced. The unit cost of these solar thermal energy production methods directly increases with the temperatures they can yield. As such, flat plate collectors and solar ponds are the least expensive of these on a unit basis and parabolic troughs are the most expensive. Where land is inexpensive then, solar ponds are preferred due to their low cost and their ability to store energy. This is why it is sometimes economical to even produce electricity from solar ponds when thermal energy cannot be used. Where land prices are high or electricity or high temperatures are needed, parabolic troughs are generally the preferred source of solar thermal energy. Absolute preferred methods, however, can be expected to be highly site specific.

3. 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 [17]. This low production rate is explained by the low operating temperature and pressure of the steam. Numerous attempts have been made by many investigators in order to produce freshwater by means of solar energy. The simple solar still of the basin type is the oldest method and improvements in its design have been made to increase its efficiency [28].

3.1. Single-effect solar still

A solar still is a simple device which can be used to convert saline, brackish water into drinking water. Solar stills use exactly the same processes which in nature generate rainfall, namely evaporation and condensation. Its function is very simple; basically a transparent cover encloses a pan of saline water. The latter traps solar energy within the enclosure. This heats up the water causing evaporation and condensation on the inner face of the sloping transparent cover. This distilled water is generally potable; the quality of the distillate is very high because all the salts, inorganic and organic components and microbes are left behind in the bath. Under reasonable conditions of sunlight the temperature of the water will rise sufficiently to kill all pathogenic bacteria anyway. A film or layer of sludge is likely to develop in the bottom of the tank and this should be flushed out as often as necessary.

In order to evaporate 1 kg of water at a temperature of 30°C about 2.4×10^6 J is required. Assuming an insolation of 250 W/m^2, averaged over 24 h, this energy could evaporate a maximum of 9 L/m^2/day. In practice heat losses will occur and the average daily yield which might be expected from a solar still is 4–5 L/m^2/day. Today's state-of-the-art single-effect solar stills have an efficiency of about 30–40% [25].

Material selection for solar stills is very important. The cover can be either glass or plastic. Glass is considered to be best for most long-term applications, whereas a plastic (such as polyethylene) can be used for short-term use. Single-basin stills have been much studied and their behavior is well understood. Fath [14] has done a valuable review of the latest development on this topic.

The daily amount of drinking water needed by humans varies between 2 and 8 L per person [34]. The typical requirement for distilled water is 5 L per person per day. Therefore 2 m^2 of still are needed for each person served. The single-basin still is the only design proven in the field.

One of the main setbacks for this type of desalination plant is the low thermal efficiency and productivity. This could be improved by various passive and active methods. The solar still integrated with a heater or solar concentrator panel is generally referred to as an active solar distillation while others are referred to as passive stills. Passive solar distillation is an attractive process for saline water desalination in that the process can be self-operating, of simple construction and relatively maintenance free. These advantages of simple passive solar stills however, are offset by the low amounts of freshwater produced, approximately 2 L/m^2 for the simple basin type solar still [41] and for the need for regular flushing of accumulated salts [24]. Modifications using passive methods include basin stills, wick stills, diffusion stills, stills integrated with greenhouse, and other configurations. These modifications will be briefly presented.

4. Modifications using passive methods

4.1. Basin stills

The operating performance of a simple basin type passive still can be augmented by several techniques such as

- Single slope vs. double slope basin stills: Single slope still gave better performance than a double slope still under cold climatic conditions while the opposite is true under summer climatic conditions [24].
- Still with cover cooling: Increasing the temperature difference between the basin (heat source) and the cover (heat sink) lead to increase the water evaporation rate [20]. In stills with cover cooling, cooling water or saline solution is fed in the gap of a double glass cover to maximize the temperature difference. The cost, as such, is increased.
- Still with additional condenser: Fath [14] found that adding a passive condenser in the shaded region of a single slopped still increases the still efficiency by 45%.
- Still with black dye: Injecting black dye in the seawater increases the distillate yield [14].

4.2. Wick stills

In a wick still, the feed water flows slowly through a porous, radiation-absorbing pad (the wick). Two advantages are claimed over basin stills. First, the wick can be tilted so that the feed water presents a better angle to the sun (reducing reflection and presenting a large effective area). Second, less feed water is in the still at any time and so the water is heated more quickly and to a higher temperature. Tanaka et al. [36] have proven the superiority of the tilted wick type solar still and confirmed an increase in productivity by 20–50%. Simple wick stills are more efficient than basin stills and some designs are claimed to cost less than a basin still of the same output. A simple multiple wick solar still made of a frame of aluminum, a glass cover and a water reservoir made of galvanized iron was designed by Sodha et al. [32]. Foam insulation was supported beneath the aluminum bottom by a net of nylon ribbon. The authors claimed the present design to offer several advantages including lightweight and low cost of the still and a significant output.

4.3. Diffusion stills

Diffusion solar stills are comprised of two separate units. One is a hot storage tank, coupled to a solar collector, and the other is the distillation unit, which produces the distilled water. One of the most recent designs of this type of still is that described by Graeter et al. [19] and Rheinlander and Graeter [30] of a four-effect still. The evaporation process in a four-effect still for the desalination of sea and brackish water was experimentally investigated in a test facility under different modes and configurations of heat recovery, and natural or forced convection in the four distillation chambers (“effects”). The theoretical distillate output from a 4-effect distillation unit is 8.7 kg m^{-2} h^{-1} with an energy input of 2.0 kW m^{-2}, for an active cross-section of 1 m^2 of the apparatus, representing 4 m^2 of evaporator and 4 m^2 of condenser surface.

4.4. Solar still greenhouse combination

Most studies published in the last decade have focused on small-scale systems for solar desalination with capacities below 25 m^3 day^{-1} and for application in remote areas [11]. Some of these have proposed solar desalination processes used in combination with water efficient greenhouse concepts based on solar energy [10]. Integrated design of greenhouses combined with solar stills represents an interesting possibility for the development of small-scale cultivation in places where only saline water or brackish water is available [24]. The Seawater Greenhouse combines a solar desalination system with an environment for cultivating crops in which transpiration is minimized, at the same time producing sufficient water for its own use through a process of solar distillation.

A version of this system was constructed and analyzed by Chaibi [11], where the south slope of the greenhouse roof was built as a solar still. 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 favorable 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 vapor condensed on the top glazing, ran along the inner wall of the top cover, and was collected in the freshwater 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 freshwater 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.

Other designs of solar still greenhouse combinations have been proposed by other researchers. Davies and Paton [12] recently present results from the prototype greenhouse in the United Arab Emirates (UAE). The authors confirmed the feasibility of designing the greenhouse such that the amount of freshwater produced exceeds the evapotranspiration requirement.

4.5. Multiple-effect basin stills

Multiple-effect basin stills have two or more compartments. The condensing surface of the lower compartment is the floor of the upper compartment. The heat given off by the condensing vapor provides energy to vaporize the feed water above. Multiple-effect solar desalination systems are more productive than single effect systems due to the reuse of latent heat of condensation. The increase in efficiency, though, must be balanced against the increase in capital and operating costs. Efficiency is therefore greater than for a single-basin still typically being 35% or more but the cost and complexity are correspondingly higher.

Schwarzer et al. [31] have presented numerical simulation results and experimental data of a laboratory water tests for a thermal desalination unit with a heat recovery system. The desalination unit is composed of a solar collector and a desalination tower made of six stages with a water circulation system to avoid salt accumulation in the tower. The production rate of the unit can reach 25 L/m^2/day for a value of 4.8 kW h/m^2/day of solar radiation.

4.6. Externally heated (active) solar stills

The temperature of saline water in the basin can be increased through additional (external heating). For this purpose the still is integrated with a

(1) solar heater
(2) solar concentrator
(3) waste heat recovery system.

Circulation through the heater or the concentrator could either be through natural circulation (Thermosyphon) or through forced circulation using a pump.

5. 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, this may cause corrosion and scaling in the still and thereby reduce the thermal efficiency [15]. In HD desalination air is used as a working fluid, which eliminates this problem. This process operates on the principle of mass diffusion and utilizes dry air to evaporate saline water, thus humidifying the air. The HD process is based on the fact that air can be mixed with significant quantities of vapor. The vapor carrying capability of air increases with temperature, i.e. 1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature increases from 30 to 80°C. Freshwater is produced by condensing out the water vapor, which results in dehumidification of the air. A significant advantage of this type of technology is that it provides a means for low pressure, low temperature desalination that can operate off of waste heat and is potentially very cost competitive. Bourouni et al., Al-Hallaj et al. and Assouad and Lavan [2,4,7] respectively reported on the operation of HDH units in Tunisia, Jordan, and Egypt.

Muller-Holst et al. [27] fabricated an experimental Multi Effect Humidification (MEH) facility driven by solar energy and considered its performance over a wide range of operating conditions. Since the process is driven by solar energy, the freshwater production varied with seasonal changes. The average freshwater production was about 6000 L per month with a maximum of 10,500 L in May and a minimum of 1700 L in January. The principle of MEH plants is the distillation under atmospheric conditions by an air loop saturated with water vapor. The air is circulated by natural or forced convection (fans). The evaporator–condenser combination is termed a “humidification cycle”, because the airflow is humidified in the evaporator and dehumidified in the condenser.

Solar MEH-desalination system studied in [26] used 2 m^3 hot water storage tank, which increased the production rate to 500 L/day with 38 m^2 collector area (about 13 L/m^2). Two different MEH units were tested in [26]. The first one (“SODESA system”) consisted of a thermal storage tank at ambient pressure and a collector field. The feed water was heated by direct circulation through the collector. The system efficiency was high due to elimination of heat exchangers, but costly materials to resist seawater corrosion at 100°C were required for the collector.

Excellent comprehensive reviews of the HD process are provided by Al-Hallaj and Selman [3] and Parekh et al. [29]. Al-Hallaj and Selman [3] concluded that although the HD process operates off of low-grade energy, it is currently not cost competitive with reverse osmosis (RO) and multistage flash evaporation (MSF).

6. Indirect solar desalination

Indirect solar desalination methods involve two separate systems: the collection of solar energy, by a conventional solar converting system, coupled to a conventional desalination method. Desalination using thermal processes (phase change) can be accomplished using multistage flash distillation (MSF), multiple effect evaporation (MEE), vapor compression (VC), and freeze separation (FS).

6.1. Multi-stage flash process

Several medium scale plants for MSF desalination using solar energy have recently been implemented. Block [6] found that solar-powered MSF plants can produce 6–60 L/m^2/day, in comparison with the 3–4 L/m^2/day typical of solar stills. 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].

The use solar troughs for desalination was tested mainly in the USA. Commercially available are small-scale units that combine the MSF process with steam generating parabolic troughs. A typical plant uses 48 kW to produce 450 L/day in three stages. The collectors (about 45 m^2) currently cost about US$ 10,000, which translates into production costs of 7.90 US$/$m^3$ (5% interest, 20 years lifetime, annual O&M equivalent to 3% of the investment costs, 85% plant factor) [37].

In Szacsvay et al. [35], a desalination system consisting of a solar pond as the heat source and an Atlantis autoflash multistage stage desalination unit is described. Since the standard MSF process is not able to operate coupled to any variable heat source, the Atlantis Company developed an adapted MSF system called “Autoflash”. The autoflash process is based on the multistage flash process concept. Performance and layout data were obtained both from computer simulation and experimental results with a small-sized solar pond and desalination subsystem in Switzerland which had been in operation for 9 years. The authors concluded that the cost of distillate could be reduced from \$5.48/m^3 for small desalination system with a capacity of 15 to 2.39 m^3/day for desalination systems with a capacity of 300 m^3/day.

6.2. Multiple-effect distillation

Many multiple-effect distillation (MED) plants of medium capacity powered by solar energy were built worldwide. In ref. [13], 13 years operation of the MED-plant designed for a maximum capacity of 120 m^3/day with 18 stack type stages and pre-heaters was analyzed. Evacuated-tube solar collectors of 1862 m^2 were used with water as heat carrying medium. It had a heat accumulator of 300 m^3 capacity. Specific heat consumption of the plant was 43.8 kcal/kg with performance ratio of 12.4. Due to heat accumulator the evaporator could run 24 h a day during sunny days producing freshwater of 85 m^3/day. The plant was able to desalt seawater of 55,000 ppm. The total seawater requirement was 42.5 m^3/h. The major problem was the maintenance of the pumps. The authors pointed out that the acid cleaning and silt removal were extremely necessary for better performance of the plant.

The small-scale MED desalination plants are described in [1,31]. A simple prototype small-scale solar desalination system based on MED principle intended for checking the design principles and operational features for the future plant was described in [31]. It was a tower with series of flat trays for effects and used a flat plate solar collector with oil as a heating medium for thermal energy. Oil is circulated by natural convection between the solar collector and the first effect. The vapor from the first stage condenses at the bottom wall of the second stage, releasing its latent heat. The condensed water moves through a channel to be collected outside the unit. The horizontal dimensions of each stage tray was 0.8×0.8 m^2, and the distance between stages was 0.1 m. Surface area of the solar collector was 2 m^2, an average thermal efficiency was 0.5. The amount of water in each stage was 25 L, and six stages were used. A numerical simulation code was developed and tested using the experimental results. Simulation results showed that production rate could reach up to 25 L/m^2 d for 4.8 W × h/m^2 d of solar radiation (performance ratio 3.5). Tests carried out with much polluted seawater and for well water showed that product water is free of coliform group bacteria and the coliform group fecal bacteria.

In [1], a practical scale desalination system of three effects using only solar energy from solar collectors as the heat source and the electrical power from the PV-cells is presented. The unit was developed and manufactured by the Ebara Corporation (Tokyo) and tested at the Al Azhar University in Gaza. The average production rate was in the range of 6–13 L/m^2/day.

Thomas [38] reported that solar MED and MSF experiments in Kuwait experienced difficulties operating under the variable conditions of solar insolation. Greater success has been found with self-regulating solar MSF plants than solar MED plants. Solar MED and MSF cannot yet be considered proven technologies.

In Fiorenza et al. (2003) the water production cost for seawater desalination by MED powered by a solar thermal field has been estimated. The results obtained for plants of capacity varying between 500 and 5000 m^3/d have shown that the cost of water produced can be reduced by increasing the plant capacity; i.e. 3.2 \$/m^3 for the 500 m^3/d plant capacity and 2 \$/m^3 for the 5000 m^3/d plant capacity.

6.3. Freezing

While freeze desalination has been proposed as a method for desalination for several decades, only demonstration projects have been built to date. The concept is appealing in theory because the minimum thermodynamic energy required for freezing is less than for evaporation since the latent heat of fusion of water is 6.01 kJ/mole while the latent heat of vaporization at 100°C is 40.66 kJ/mole.

Theoretically, freezing has some advantages over distillation. These advantages include a lower theoretical energy requirement, minimal potential for corrosion, and little scaling or precipitation. The disadvantage is that it involves handling ice and water mixtures that are mechanically complex to move and process. Despite the process advantage, freezing has not established itself as a commercial desalination technique because of the cost and complications of refrigeration systems and the need for freshwater to wash the crystals prior to melting.

There are many designs of freeze separation processes as there are methods of refrigeration. The most commonly used methods are: vacuum-freezing vapor compression, vacuum-freezing ejector-absorption, and refrigeration freezing, and secondary refrigerant.

In refrigeration freezing, a standard refrigeration cycle is used to cool the product water stream until ice forms. The ice is scraped off and melted. The most recent significant example of this type is the solar-powered unit constructed in Saudi Arabia in the late 1980s by Chicago Bridege and Iron Inc. as part of the SOLERAS program, a joint venture between the United States and Saudi Arabia. The system was highly inefficient. It used point-focused solar collectors to heat oil, which heated salt, which acted as a storage medium for continuous operation, to heat water, to produce steam, to produce shaft power for the condenser of the refrigeration cycle. The Florida Solar Energy Center (FSEC) [6] calculates that the system uses 108 kW h/m^3. A 43,800 m^2 collector area was required for the plant, which produces between 48 and 178 m^3/day. The salt provided enough heat storage for 10 days of operation [21]. The plant was shut down in 1989 because it was not economically viable [33].

A recent study of applying this approach to saline groundwater (5000 ppm) in North Dakota concluded that a 1 million gal/day plant could produce water for a cost of \$1.30/1000 gallons (\$0.34/m^3) [8], which, if true, makes the process competitive with RO.

7. Summary

An overview of solar thermal desalination technologies is presented, focusing on those technologies appropriate for use in remote villages. Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe.

Solar desalination processes can be devised in two main types: direct and indirect collection systems. The “direct method” use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and the other one for desalination). The direct solar energy method uses a variety of simple stills which are appropriate for very small water demands; indirect methods use thermal or electrical energy and can be classified as: distillation methods using solar collectors or membrane methods using solar collectors and/or photovoltaics for power generation.

Solar thermal desalination plants utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification/dehumidification, multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC) and membrane distillation (MD).

Acknowledgements

The authors want to thank the European Commission for financial support through ADIRA project. The project ADIRA is supported by the European Commission under contract number ME8/AIDCO/2001/0515/59610, with the partners Egyptian Water and Energy Association (EWE), Foundation Marrakech 21 (FM21), the Agricultural University of Athens (AUA), National Center for Scientific Research DEMOKRITOS (NCSR), Canary Islands Institute of Technology (ITC), Jordan University of Science and Technology (JUST), Istanbul Technical University (ITU) and Fraunhofer Institute for Solar Energy Systems (ISE) as well as the subcontractor WIP-Renewable Energies. The views expressed herein are those of JUST and can therefore in no way be taken to reflect the official opinion of the European Commission.

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