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Perspectives of solar-assisted seawater distillation

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Abstract

The use of solar energy in thermal desalination processes is one of the most promising applications of renewable energies to seawater desalination. A solar distillation system may consist of two separated devices — the solar collector and the distiller — or of one integrated system. The first case is an indirect solar desalination process, and the second one is a direct solar desalination. This paper deals with indirect solar desalination and its perspectives in the future. First, a summary of existing plants was given. Second, different technologies were compared. Finally, the possible improvements of thermal solar and seawater distillation technologies were considered in order to analyze the perspectives of the competitiveness of solar vs. conventional energy in seawater desalination.

Keywords: Solar desalination; Multi-effect distillation; Solar parabolic troughs; Thermodynamics

1. Introduction

Several reviews of the status of solar desalination have been published [1–4] by different authors. Small production systems as solar stills can be used if fresh water demand is low and the land is available at low cost. High fresh water demands make industrial-capacity systems necessary. These systems consist of a conventional seawater distillation plant coupled to a thermal solar system. This technology is known as indirect solar desalination. Many small-size systems of direct solar desalination and several pilot plants of indirect solar desalination have been designed and implemented [4–6]. Nevertheless, in 1996 solar desalination was only 0.02% of desalted water production [2]. This paper deals with indirect solar desalination and its perspectives in the future.

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2. Indirect solar desalination

Multi-effect (ME) and multi-stage flash (MSF) distillation systems may be used in indirect solar desalination plants. Thermal vapour compression (TC) systems have a limited production and performance ratio, but they can be combined to a ME distillation system as the pilot plant of Ancona University [7]. In addition, different solar technologies are suitable to be coupled to solar distillation plants, not only one-axis sun tracking, but also static solar energy collectors: flat-plate collectors, evacuated-tube collectors, compound parabolic collectors, salinity-gradient solar ponds, parabolic trough collectors (oil-based technology), and direct steam generation (DSG) parabolic troughs.

The solar field could drive the distillation plant by both heating the seawater or brine preheated at the plant [8] or by generating steam. Steam generated by the solar collectors and an auxiliary system, if necessary, is not only able to drive a distillation system, but also a reverse osmosis (RO) plant as Childs at al. [9] proposed. They presented a system that is able to connect a RO plant with a steam supply.

Singh and Sharma [8] proposed the integration of a solar energy collection system with a MSF desalination unit by the replacement of the brine heater by the solar collector field. In addition, Rajvanshi [10] has designed and tested a simple solar collector for this application; and we [11] have evaluated the brine heating at a parabolic trough solar field.

Steam can be generated from solar collectors in three different ways:

1. At the solar collector in which a two-phase flow is allowed in the collector receiver. A parabolic trough solar collector is used in this technology (DSG). Murphy and Pederson first studied it in the early 1980s, although intensive research started in 1988 [12]. Nowadays, there are several test facilities for this technology [13,14]. Although the main application of DSG solar collectors is in solar power station, DSG parabolic troughs could be used in order to obtain steam from fresh water around 100°C, which could drive a conventional MSF or ME distillation system. DSG parabolic troughs use water as heat transfer fluid, although seawater or brine might be used instead of fresh water; thus, steam might be directly obtained from circulating brine. DSG solar collectors have not yet been tested coupled to a desalination unit. Nevertheless, the authors performed a theoretical analysis of a DSG system coupled to seawater distillation plants using both water [15,16] and seawater or brine [17] as the heat transfer fluid.

2. At an unfired boiler driven by an intermediate heat transfer fluid, which is heated in the solar collector. This is the conventional operation of parabolic troughs. Synthetic oils act as heat transfer fluids and as the heat storage medium. Different solar desalination pilot plants use these collectors (e.g., the Sol-14 plant (Plataforma Solar de Almería, Spain). The application of conventional parabolic trough collectors to seawater desalination has been thermoeconomically analyzed by the authors [18,19]. On the other hand, Kalogirou [20] has evaluated the product cost on ME distillation driven by solar parabolic troughs.

3. At a flash vessel, where pressurized water flashes after it is heated in the solar collectors. This case has been studied by Tleimat [21].

3. Pilot plants

Spain had two pilot experiences of solar thermal desalination, one of them in Gran Canaria (Canary Islands) [22] and the other at the solar research centre, Plataforma Solar de Almería (PSA) [6, 23]. Both of them use one-axis sun tracking collectors. Table 1 shows solar distillation plants in operation.

A few parabolic trough collector desalination plants have been implemented and tested [4]. At

Table 1
Solar distillation plants

Plant	Desalination process	Capacity, m^3/d	Solar collectors
La Desired Island, French Caribbean [24]	ME, 14 effects	40	Evacuated tube
Abu Dhabi, UAE [5]	ME, 18 effects	120	Evacuated tube
Kuwait [4]	MSF auto-regulated	100	Parabolic trough
La Paz, Mexico [4]	MSF,10 stages	10	Flat plate + parabolic trough
Arabian Gulf [4]	ME	6000	Parabolic trough
Al-Ain, UAE [25]	ME, 55 stages MSF, 75 stages	500	Parabolic trough
Takami Island, Japan [4]	ME, 16 effects	16	Flat plate
Margarita de Savoya,Italy [4]	MSF	50–60	Solar pond
Berken, Germany [26]	MSF	20	—
Lampedusa Island, Italy [27]	MSF	0.3	Low concentration
Islands of Cape Verde [28]	Atlantis Autoflash	300	Solar pond
University of Ancona, Italy [7]	ME–TC	30	Solar pond
PSA, Almería, Spain [6]	ME, heat pump	72	Parabolic trough
Gran Canaria, Spain [22]	MSF	10	Low concentration

the PSA, Spain [6] a parabolic trough solar field was connected to a ME distillation plant. On the second phase of the project, a double-effect absorption heat pump was coupled to the solar desalination plant. Then, in the test campaign, the performance ratio of the new system was double the previous one.

In addition, solar flat-plate collectors had been used in a few solar desalination pilot plants [4,5]. With respect to evacuated-tube collectors, El-Nashar [29] and Madani [24] reported solar desalination experiences using the ME distillation process.

Finally, different plants have been constructed coupling a solar pond to a MSF [28] or a ME [7] distillation plant. In addition, the thermal energy delivered by a salinity-gradient solar pond has been used not only in seawater distillation plants but also for seawater and brackish water RO desalination. In solar distillation plants, the seawater or brine preheated by the distillation plant absorbs the thermal energy delivered by the heat storage zone of the solar pond.

4. Technology comparison

With regard to the comparison of solar distillation technologies, there are few references that compare the production or the costs of different design arrangements or of different operation conditions [20,24,25,30–35]. Several authors have selected solar-pond-powered desalination as one of the most cost-effective solar desalination processes [36,37]. Nevertheless, Kalogirou [34] compared different conventional solar technologies costs (flat-plate, compound parabolic and parabolic trough collectors) for ME distillation, and he concluded that parabolic troughs are the most interesting technology.

Finally, we [16] have compared static and one-axis tracking solar technology under Spanish climatic conditions. As a result, the highly efficient evacuated-tube collectors and parabolic troughs have good potential for seawater desalination on the Spanish mainland, as parabolic troughs are superior in the Canary Islands. In addition, only parabolic troughs can operate at a temperature suitable for driving a heat pump as that used at the PSA [6], which increases the performance ratio of the desalination system. Therefore, if a heat pump is available to connect to the desalination system, parabolic troughs highly increase the fresh water production vs. any other solar technology. In addition, results show that the production of a distillation plant with a performance ratio equal to 10 goes up between 18–32% when the DSG is used instead of oil-based technology. Moreover, the replacing of water by seawater or brine in DSG solar collectors might increase this production an additional 8–10%.

Regardless of the great potential of parabolic troughs in seawater distillation, salinity gradient-solar ponds should not be discarded since they permit:

- the replacement of cooling seawater output by the recovery of this energy in the surface layers of the solar pond; and
- the use of the blowdown for breeding additional solar ponds.

To sum up, from the production point of view, parabolic trough collectors are the best solar technology for seawater distillation. Nevertheless, solar ponds have a few advantages such as their low cost and the possibility of energy recovery and later blow-down usefulness.

On the other hand, there is increasing concern about environmental effects of desalination [38–40]. With regard to environment impact and use of materials, DSG parabolic troughs and solar ponds are the most interesting technologies. Nevertheless, a detailed life-cycle assessment is necessary to quantify every possible impact.

Finally, the costs of high-efficiency flat-plate, evacuated-tube and compound parabolic collectors [30] are not low enough to reduce the investment cost per m^3 of desalted water vs. parabolic troughs. Nevertheless, a detailed study of the climatic conditions should be done.

5. Future perspectives

ME distillation plants have reasonable potential for development [41], but MSF distillation has rather limited development. El-Saie [42] presents as the main possibilities of development of MSF plants the improvement of anti-scale treatment and brine interstage control, carry over and general losses, that could lead to large savings in the plant capital and running costs.

Legoretta et al. [43] discussed the advantages of plate heat exchangers, which exhibit a higher heat transfer coefficient than tubular units. The higher the evaporation temperature, the larger the difference between them. This results in an extremely compact design of the desalination unit, and therefore lower engineering costs. Moreover, since the plate can be completely cleaned on both sides, the heat transfer area always remains totally effective.

Finally, the latest studies published about technological improvements that could be apply to indirect solar distillation are as follows:

- The use of flat plates instead of tubular heat exchangers: Al-Hawaj [44] and Tonner [45].
- The possibilities of a considerable increase of the top brine temperature that could highly increases the performance ratio of MSF plants: Al-Sofi et al [46].
- The selection of materials: Sommariva et al. [47].
- The coupling of heat pumps and the design of new solar heat pumps: Slesarenko [48], Gunzbourg et al. [49], Zarza [6] and Hulin et al. [50].

- The advanced solar collector technology, DSG: Zarza and Balsa, [14] and Svoboda et al., [51].
- The proposal of solar-powered desalination systems: Childs et al. [9], Müller-Holst et al. [52], Safi et al. [53], García-Rodríguez et al. [15] and García-Rodríguez and Gómez-Camacho [17].

6. Conclusions

Indirect solar desalination has interesting potential for development. Nevertheless, intensive research is necessary, especially to improve the reliability of solar heat pumps and DSG parabolic troughs or to increase the top brine temperature. In addition, the use of steam generated by solar energy to drive a RO plant may be a promising alternative to solar distillation.

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