ELSEVIER

Desalination 142 (2002) 135–142

DESALINATION

www.elsevier.com/locate/desal

Comparison of solar thermal technologies for applications in seawater desalination

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Received 28 May 2001; accepted 20 June 2001

Abstract

This paper deals with a global analysis of the use of solar energy in seawater distillation under Spanish climatic conditions. Static solar technologies as well as one-axis sun tracking were compared. Different temperature ranges of the thermal energy supply required for a desalination process were considered. At each temperature range, suitable solar collectors were compared in some aspects as: (1) fresh water production from a given desalination plant; (2) attainable fresh water production if a heat pump is coupled to the solar desalination system; (3) area of solar collector required for equivalent energy production. Results showed that direct steam generation (DSG) parabolic troughs are a promising technology for solar-assisted seawater desalination.

Keywords: Solar desalination; Solar thermal collectors; Multi-effect distillation; Multi-stage flash desalination

1. Introduction

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 process. Many small-size systems for direct solar desalination and several pilot plants of indirect solar desalination have been designed and implemented [1–3].

A solar collector field is connected to a conventional desalination plant in indirect solar distillation systems. Therefore, on the one hand, a variety of solar collectors may be used. On the

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PII: S0011-9164(01)00432-5

other hand, a multi-stage flash or a multi-effect distillation plant may be selected. The solar field could drive the distillation plant both, by heating the seawater or brine preheated at the plant or by generating steam. This steam might be generated (1) at the solar collector (direct steam generation, DSG), in which a two-phase flow is allowed in the collector receiver; (2) at an unfired boiler driven by an intermediate heat transfer fluid which is heated in the solar collectors; or (3) at a flash vessel where pressurised water flashes after it is heated in the solar collectors.

In this paper a global analysis of indirect solar distillation was performed. Climatic conditions of Spain were assumed [4]. Different solar technologies were compared, 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 DSG parabolic troughs. DSG parabolic troughs use water as heat transfer fluid [5]. Nevertheless, seawater or brine might be used instead of fresh water if operation temperature is low enough to avoid scale problems. Thereby, steam might be directly obtained from circulating brine [6].

A brief description of the solar technologies analysed is presented in Section 2. Section 3 shows a general background about the connection of the solar collector field and the desalination plant. The comparative study of fresh water production is showed in Section 4, and finally, conclusions are presented in Section 5.

2. Solar technologies

Different devices (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 collectors may be static or sun-tracking devices. The second ones may have one or two axes of sun tracking. Otherwise, with respect to solar concentration, solar collectors may be flat plate, line-axis concentrating, or point focusing. Different solar collectors are already commer-cially available; nevertheless, many collector improvements and advanced solar technologies are being developed.

The main solar collectors suitable for seawater distillation are as follow: flat-plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collectors (CPC) and parabolic trough collectors (PTC). On the other hand, there is a solar converter system that acts simultaneously as solar energy conversion and as thermal storage: salinity-gradient solar ponds (SP).

The selection of the most suitable collector for a given application should take into account: the operation temperature required; the ratio between beam and global solar radiation; the environmental temperatures; the solar irradiance transient and other technical and economic factors.

2.1. Salinity-gradient solar ponds (SP)

A salinity-gradient SP may be used to drive a desalination process. Since it is a solar energy conversion system as well as a thermal storage, it offers interesting potentials in seawater distillation.

A typical artificial SP is about 3.5 m deep. The SP consists of three different zones. The bottom has a salt concentration about 10 times that of seawater [7]. It is called the low convective zone, which acts as heat storage. In the region above that, called the gradient zone, the salt concentration and the density increase with depth. Finally, the upper region is a thin layer, the upper convective zone, to which relatively fresh water is added to make up for evaporation. The intermediate zone is non-convective due to density gradient, and this is the no convective zone.

2.2. Flat-plate collector (FPC)

FPCs are static and no concentrating solar energy conversion systems. They usually use water 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 minimise 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 increases.

2.3. Evacuated tube collectors (ETC)

Heat losses are minimised in ETCs by an evacuated cover of the receiver. This cover is tubular and made of glass. In addition, a selective coating of the receiver minimises 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.

2.4. Compound parabolic collectors (CPC)

CPCs are low-concentration solar collectors. Sun tracking is not required due to their low concentration ratio, normally between 1.5 and 5 [8]. Tanaka et al. [9] developed a high-efficiency and low-cost CPC evacuated tubular collector. The collector gave 0.6 of heat collection efficiency at 90°C, and they estimated a 32% in production cost reduction compared with a conventional panel (10,000 yen/m^2). Normally, CPCs are static devices; nevertheless, Khalifa, and Al-Mutawalli [10] investigated the effect of using two-axis sun tracking on the thermal performance of CPCs. The tracking CPC evaluated showed an increase of up to 75% in the collected energy compared with an identical fixed collector.

2.5. Parabolic trough collectors (PTC)

The solar technology of one-axis concentration provides a simple operation and highly reliable system to reach maximum operation temperatures about 380°C. Normally, medium concentration ratios — between 15 and 40 [8] — are attainable; therefore, one-axis sun tracking is required. Synthetic oils are used as heat transfer fluid in conventional solar PTCs (Fig. 1), which limits the top temperature. Nevertheless, the synthetic oil may be replaced by water in order to generate steam directly into the absorber pipe. Then, temperatures up to 400°C may be allowed, thus improving the performance of the power cycle in solar electricity generation systems.

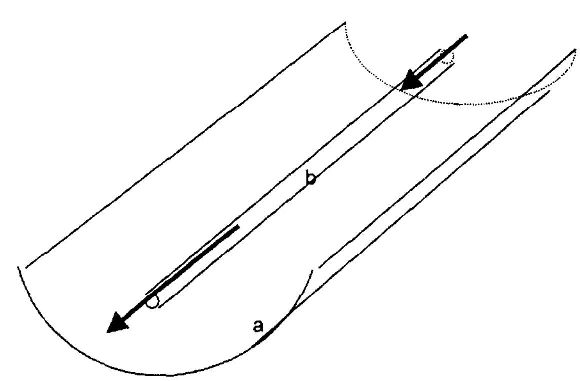

Fig. 1. Diagram of a solar parabolic trough collector. A reflective surface (a) concentrates the solar radiation onto a cylindrical receiver (b). Thermal fluid is heated as it circulates into the absorber pipe (receiver).

2.6. Direct steam generation (DSG) in parabolic troughs

DSG in parabolic troughs presents many advantages from oil-based technology [11]. Murphy and Pederson first studied it in the early 1980s, although intensive research started in 1988 [12]. There are few test facilities for this technology [13]. The axis of the solar parabolic troughs (DSG) may be tilted 8° to improve the two-phase flow pattern [5]. Odeh et al. [14] modelled DSG parabolic troughs. They have obtained efficiencies up to 65% for beam radiation greater than 600 W/m^2 at a saturation temperature 324°C. Besides that, efficiency of about 70% may be obtained at a saturation temperature of 212°C, between 600 and 800 W/m^2 of beam radiation.

The authors proposed the use of direct steam generation in seawater desalination with both water and seawater or brine as heat transfer fluid [15]. Moreover, such desalination systems were economically evaluated [6,16].

Another solar concentration collector for DSG was analysed by Barski and Jozeforwska [17]. It is a spherical concentrator. Mirror assembly is located in a spherical cover, which can move about its geometric centre on rollers, mounted on a support.

3. Solar and desalination systems connection

Solar energy collectors may be connected to a distillation plant through auxiliary equipment, a thermal storage and an unfired boiler. Nevertheless, both of them are not necessary in all cases studied. Steam generated by solar collectors and an auxiliary system if necessary are able to drive not only a distillation system but also a reverse osmosis plant as Childs at al. proposed [18].

3.1. Static solar energy collectors

Static solar collectors may heat seawater or brine which is preheated in the desalination system. Otherwise, they may use water as a heat transfer fluid which provides the thermal energy required by the distillation process. Static solar collectors as well as SP may provide thermal energy at temperatures required by the main energy consumption, but also at suitable temperatures for seawater preheating.

Solar FPC had been used in a few solar desalination pilot plants [3,19]. With respect to ETC, El-Nashar [20] and Madani [21] reported solar desalination experiences using the multi-effect distillation process. Finally, the thermal energy delivered by a SP has been used not only in seawater distillation plants [22,23] but also in seawater and brackish water reverse osmosis desalination. In a solar distillation plant, the seawater or brine preheated by the distillation plant absorbs the thermal energy delivered by the heat storage zone of the SP.

Singh and Sharma [24] proposed at the International Solar Energy Congress in 1977 the integration of a solar energy collection system with a multi-stage flash desalination unit by the replacement of the brine heater by the solar collector field. Rajvanshi [25] has designed and tested a simple solar collector for this application. In addition, García-Rodríguez and Gómez-Camacho [26] have evaluated the brine heating at a PTC solar field.

3.2. One-axis sun tracking collectors

In seawater desalination a PTC field can be connected to multi-stage flash and multi-effect distillation plants through thermal storage and a boiler. The thermal storage usually consists of an oil tank stratified due to the different density — thermocline vessel. A difference of about 80°C between input and output temperatures of the thermal fluid in the solar field is required for a proper stratification of the oil tank.

The application of conventional PTC to seawater desalination has been thermoeconomically analysed by the authors [15,27]. On the other hand, Kalogirou [16] evaluated the product cost on multi-effect distillation driving by solar parabolic troughs. Moreover, Kalogirou [28] has compared different conventional solar technology costs for multi-effect distillation, and he concluded that PTC is the most interesting technology.

A few PTC desalination plants have been implemented and tested [3]. At the Plataforma Solar de Almería (PSA), Spain [29], a PTC field was connected to a multi-effect distillation plant. During the second phase of the project, a double-effect absorption heat pump was coupled to the solar desalination plant. Then, the thermal energy consumption of the desalination plant decreased from 63 kWh/m^3 to 36 kWh/m^3.

Finally, DSG parabolic troughs could be used in order to obtain steam from fresh water around 100°C, which could drive a conventional multi-stage or multi-effect distillation system. García-Rodríguez et al. [6,16] have evaluated the potential use of DSG in PTC for seawater desalination using water and seawater or brine as heat transfer fluid.

4. Solar technologies comparison

The case studied is a solar multi-effect distillation (MED) or multi-stage flash (MSF) plant. The performance ratio (PR) of the desalination plant and the coefficient of performance (COP) of the heat pump are 10 and 2, respectively.

The temperature of the heat input is considered to be about 65–75°C for the MED plant and 80–90°C for the MSF plant. Therefore, different solar energy collectors may be used: SPs, FPCs, CPCs, ETCs, PTCs, and DSG parabolic troughs. A heat storage and a boiler may be required. Besides that, a heat pump could be coupled to the solar desalination system. The prototype installed at the PSA is considered, which requires a thermal input at 180°C.

With respect to parabolic troughs, horizontal north–south collectors were considered. The proper operation of the solar field requires an oil heating about 80°C. In addition, the minimum operation temperature for the oil is 100°C. Therefore, the average operation temperature is much higher than the temperature of the steam supplied to the desalination plant. This fact results in lower performance than DSG parabolic troughs. In addition, the recommended tilting of DSG parabolic troughs [5] improves the collector efficiency. On the other hand, parabolic troughs require one-axis sun tracking and greater maintenance than static solar collectors; nevertheless, a desalination plant itself is complex enough to make this fact negligible. Moreover, the potential replacement of water by seawater or brine as the heat transfer fluid may be taken into account, too. Temperatures lower than 100°C should be maintained. The subscript DSG_{sw} symbolises this technology.

The fresh water production of different solar technologies is compared with the production of ACE 20 PTC [30] in Spain, at Madrid and at Izaña (Canary Islands). The energy production or thermal efficiency is estimated from Ajona [4] and Hull et al. [31]. A 5% of thermal losses were assumed at the boiler if necessary. In FPs, CPCs and ETCs, the heat transfer fluid is:

- brine in MSF plants
- water in MED plants

The fresh water production (q) and the collector cost (C) of every solar technology is represented by the corresponding subscript: SP, FPC, CPC, ETC, PTC, DSG, DSGsw. Figs. 2 and 3 show q and the ratio q/q_{ACE20} at Madrid and at Izaña, respectively. Maximum and minimum ratio q/q_{ACE20} were showed for FPC, CPC and ETC since different characteristics of such collectors were considered. Note that $[q/q_{\mathrm{ACE20}}]^{-1}$ is equal to the ratio A_{ACE20}/A, where A is the area of solar collector required per 1 kg/d of fresh water production. Besides that, if the ratio C/C_{ACE20} is

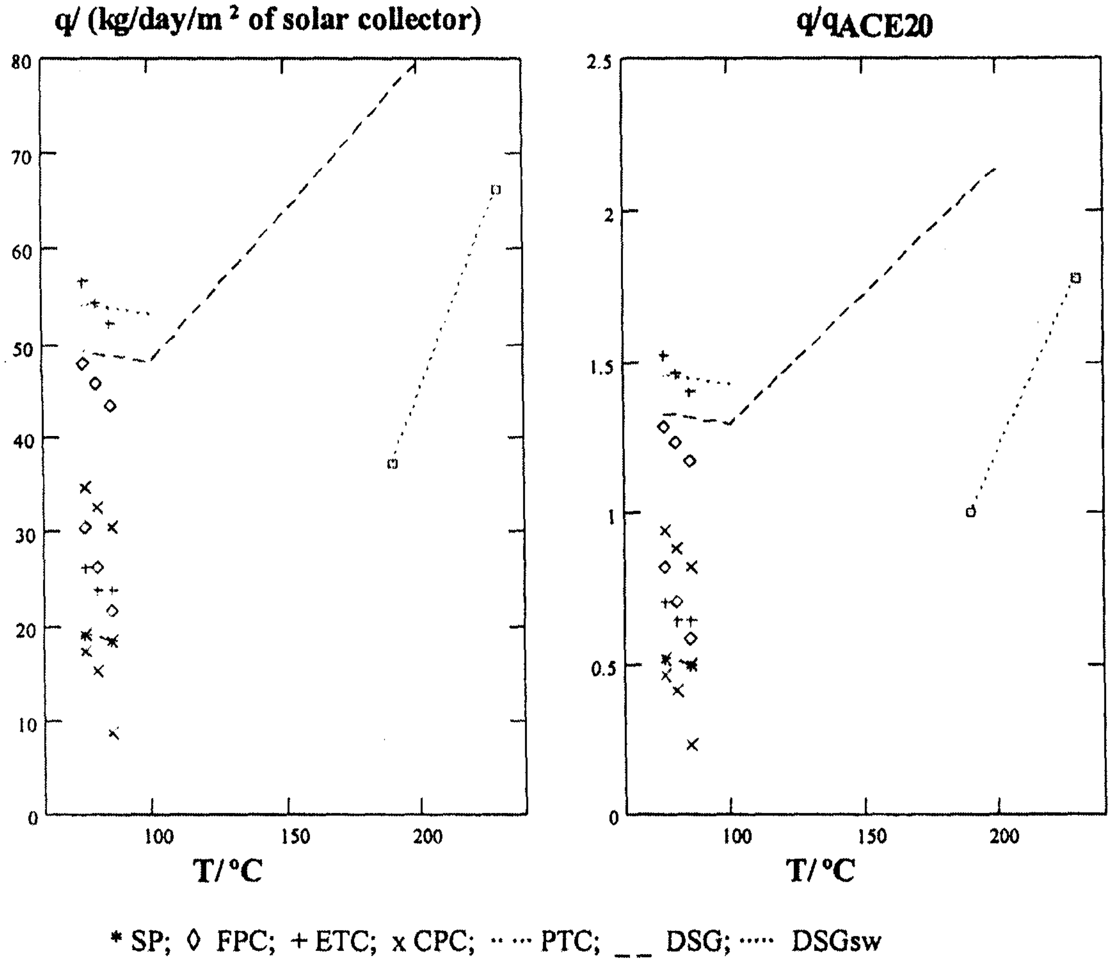

Fig. 2. Fresh water production of a solar desalination plant (PR= 10) at Madrid. The symbol q_{ACE20} represents the fresh water production for an ACE 20 PTC collector with input/output temperatures of 150°C/230°C.

Table 1
Comparison of fresh water production at Spanish climatic condition for different parabolic troughs technologies

System A	System B	Heat pump (COP= 2)	$(q_A - q_B)/q_B$, %		
			Madrid	Izaña	PSA [32]
DSGsw	PTC	No	46	28	36
DSG	PTC	No	32	18	23
DSGsw	DSG	No	10	8	10
DSG	PTC	Yes	20	13	19

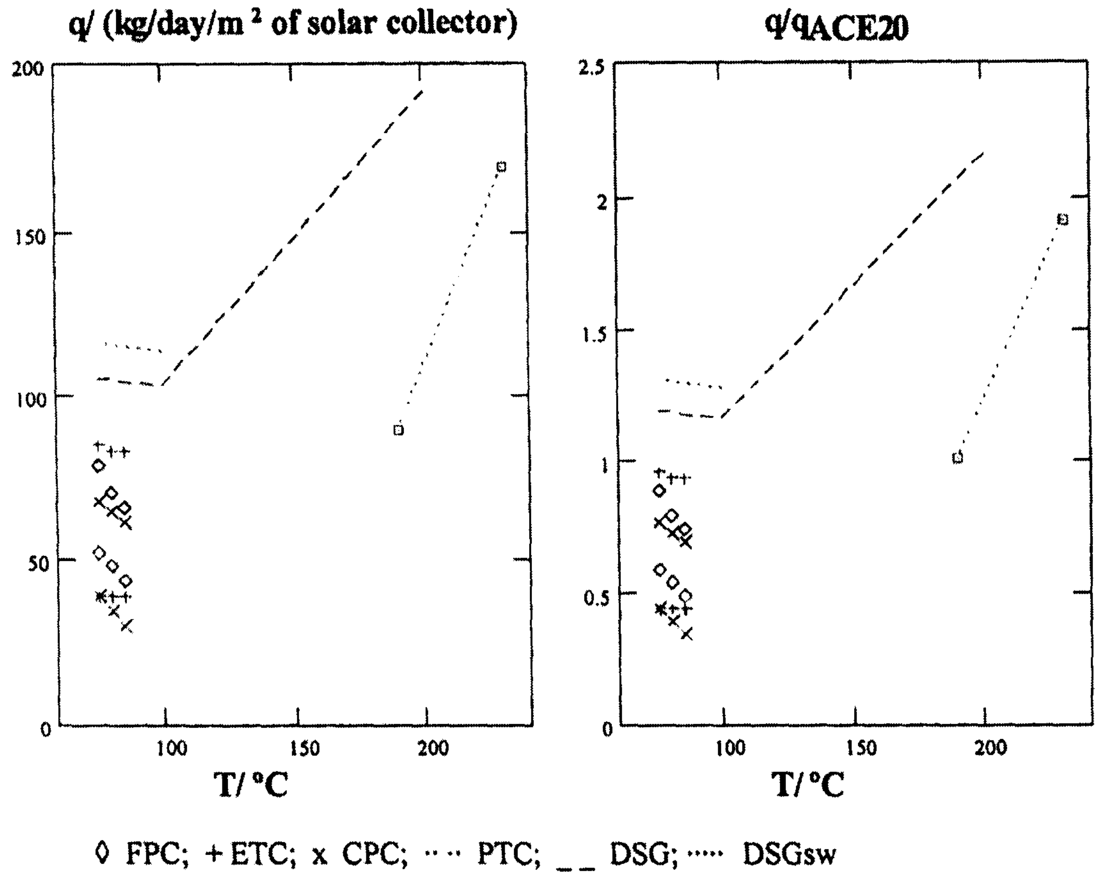

Fig. 3. Fresh water production (q) of a solar desalination plant ($PR = 10$) at Izaña, Spain.

equal to q/q_{ACE20}, the production of 1 m^3 of fresh water requires an equal investment cost of the solar energy system. Obviously, although investment cost of the solar energy system is equal, other factors should be taken into account: operation and maintenance costs, lifetime, loan interest rate, land costs. In addition, Table 1 compares the fresh water production of a desalination plant ($PR=10$) driven by different operation conditions of parabolic troughs at Madrid, Izaña and the PSA (Almería).

5. Conclusions

At Spanish climatic conditions, DSG in parabolic troughs exhibits interesting potential for seawater desalination in hybrid (solar–conventional energy) systems. The DSG increases the fresh water production of conventional PTC between 18–32% in the case studied here (performance ratio of the desalination plant: 10).

An additional advantage of one-axis sun tracking technologies is that a heat pump could be coupled to the desalination plant. Otherwise, if it is not coupled, the DSG using seawater or brine is an interesting technology for solar MSF plants.

Results obtained are useful in the preliminary design of solar-assisted desalination systems for the evaluation of daily fresh water production of 1 m^2 of the solar collector and the perspectives of solar energy costs on seawater desalination; or the selection of: the most suitable solar collector; or the system design arrangement of the solar desalination system.

Acknowledgement

This study was supported financially by the Canary Autonomous Government and La Laguna University.

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