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Temperature evolution of an experimental salt-gradient solar pond

F. Suárez, A. E. Childress and S. W. Tyler

ABSTRACT

A salt-gradient solar pond is a low-cost, large-scale solar collector with integrated storage that can be used as a source of energy in low-grade-heat thermal desalination systems. This work presents the thermal evolution of an experimental solar pond for both the maturation and heat extraction time periods. The temperature profile was measured every 1.1 cm using a vertical high-resolution distributed temperature sensing (DTS) system, with a temperature resolution of 0.04°C. Temperatures of 34 and 45°C were achieved in the bottom of the pond when the lights were on for 12 and 24 hours per day, respectively. Heat was extracted at a rate of 139 W from the solar pond, which corresponded to an efficiency of 29%. Stratification and mixing were clearly observed inside the solar pond using the vertical high-resolution DTS system.

Key words | distributed temperature sensing, renewable energy, salt-gradient solar pond

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INTRODUCTION

Climate change is one of many dynamic processes affecting the hydrological cycle that may have a large impact on world's water availability. A sustainable approach to increase water availability should consider several water-management or system-development options (Brekke *et al*. 2009). One source of freshwater supply is desalination, which will be sustainable only if it is powered using renewable energy (McGinnis & Elimelech 2008). Since solar energy is the most common source of renewable energy, it could be used as a substitute for fossil fuels to drive desalination in a sustainable way.

A salt-gradient solar pond (termed 'solar pond' for this work) is a low-cost, large-scale solar collector with integrated storage that is a potential alternative to flat collector systems in appropriate locations (Dah *et al*. 2005). A solar pond is an artificially stratified water body that is heated by the absorption of solar radiation and can provide long-term thermal storage and recovery for the collected energy. It consists of three distinctive zones (Figure 1): the upper convective zone, the non-convective zone and the lower convective zone. The upper convective zone is a thin layer of cooler and fresher water. The non-convective zone comprises a salt gradient that suppresses global circulation inside the pond. Therefore, this zone acts as insulation for the lower convective zone. The lower convective zone is the layer where the salinity and temperature are the highest. The solar radiation that reaches the bottom of the pond heats the highly concentrated brine, which will not rise beyond the lower convective zone because the effect of salinity on density is greater than the effect of temperature (Suárez *et al*. 2010*a*). The hot brine, which can reach temperatures greater than 90°C, may be used for low-temperature thermal applications, such as direct heating or thermal desalination (Rabl & Nielsen 1975; Kurt *et al*. 2000; Lu *et al*. 2001; Suárez *et al*. 2010*b*).

In the study of solar ponds, it is important to measure temperature on fine spatial and temporal scales to detect stratification, interface motion and the effect of heat extraction on the thermal behaviour of this solar collector. Fibre-optic distributed temperature sensing (DTS) is an approach that provides coverage in both space and time that can be used to continuously monitor real-time data in solar ponds

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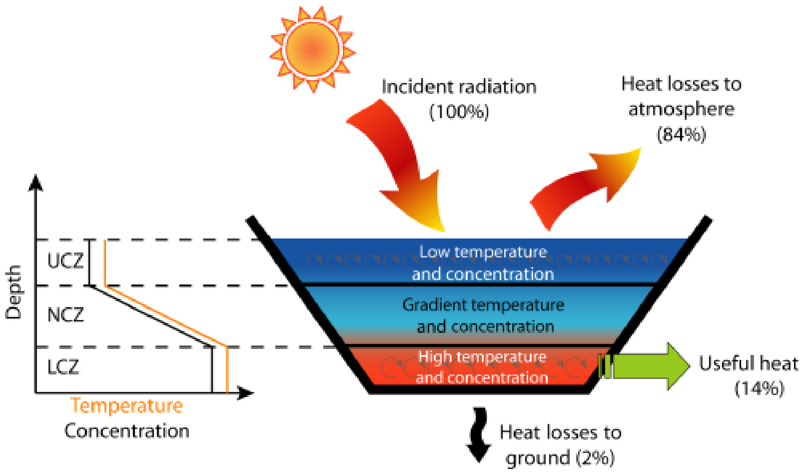

Figure 1 | Schematic of a salt-gradient solar pond; modified from Kurt et al. (2000).

(Suárez *et al.* 2009; Tyler *et al.* 2009). DTS technology uses Raman spectra scattering in an optical fibre to measure temperatures along its length, where spatial and temporal resolutions of 1 m and 10 s, respectively, for fibres up to 10 km can be achieved, with a temperature resolution as fine as $\pm 0.01^{\circ}$C (Selker *et al.* 2006). A detailed description of the theoretical basis and commercially available DTS system can be found in previous investigations (Rogers 1999; Selker *et al.* 2006). Because of the steep thermal gradients, and the need to monitor large temperature differences over short distances in time (Suárez *et al.* 2010*a*), DTS methods may have significant advantages over traditional measurement systems.

The objective of this work is to study the thermal evolution of an experimental solar pond using a vertical high-resolution DTS system. Both maturation time as well as heat extraction time periods are presented. This experimental solar pond is being used to deliver heat to a bench-scale thermal desalination system as described elsewhere (Suárez 2010).

METHODS

A 1.0-m depth experimental solar pond was constructed inside a laboratory (Figure 2). High-intensity discharge lamps were installed to mimic the sunlight spectrum. Meteorological data were measured above the water surface. Temperature every 1.1 cm within the water column was measured using a vertical high-resolution DTS system. This system achieved a temperature resolution smaller than 0.04°C when the data were collected at 5-min intervals. More details on the experimental installation and the DTS system are presented by Suárez (2010).

A long-term experiment was performed to study the thermal evolution inside the experimental solar pond. The lower 50 cm of the pond – the lower convective zone – were filled using a sodium chloride (NaCl) solution with a concentration of 20% (in weight). To create the non-convective zone, layers of 5 cm were added up to an elevation of 90 cm (measured from the bottom). Each layer had a NaCl concentration that was 2.2% lower than that of the previous layer. The upper convective zone consisted of 10 cm filled with pure water. The solar pond was covered after filling it to

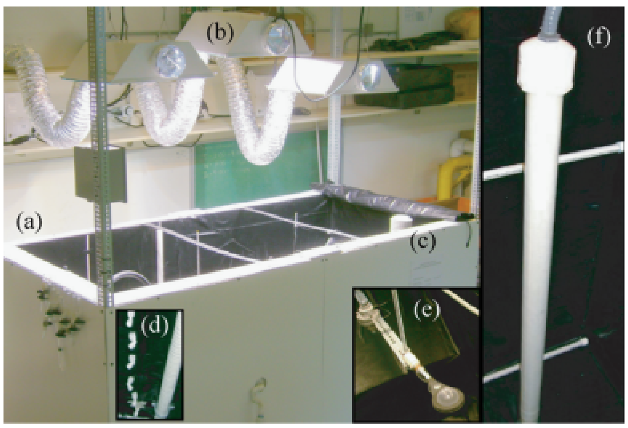

Figure 2 | (a) Experimental solar pond; (b) high-intensity discharge lamps; (c) air temperature and relative humidity sensor; (d) manual sampling system; (e) net radiometer and pyranometers; (f) vertical high-resolution DTS pole.

create a uniform NaCl gradient in the non-convective zone. After 3 days the pond was exposed to the artificial lights. The lights were turned on for 12 hours per day yielding a daily-average radiation of 110 W m^{-2}. After reaching a thermal quasi-steady-state, the lights were turned on for 24 hours per day. When a thermal steady-state was reached, brine was extracted at one side of the pond, passed through a heat exchanger, and then returned at the other side of the pond. The brine was extracted and returned at approximately 50 cm depth. The heat extraction experiment was performed for approximately 45 hours.

RESULTS AND DISCUSSION

The thermal evolution for the maturation period at different depths inside the solar pond is shown in Figure 3. The initial time (0 days) corresponds to midnight. The temperature in the upper convective zone (shallow depths) is strongly dependent on the meteorological conditions. During the first 6 days of the experiment, the upper convective zone is stratified during the day. During the night, because of penetrative convective mixing, it becomes a completely mixed zone. After the sixth day, because of the higher temperature in the non-convective zone, the upper convective zone is always a completely mixed zone. After 10 days, the temperature in the upper convective zone fluctuates between 18 and 28°C with an average of 23°C. The unusual temperature peak observed on the sixth day corresponds to an air temperature measurement. This occurred because no water was added to replace the water that evaporated from the solar pond. The rapid decrease of that unusual peak occurred because water was injected to correct the water level in the pond. Water injection in the upper convective zone is also observed on the 8th, 9th, 10th and 13th days. In the non-convective zone, the temperature stratification is clearly observed, and larger daily fluctuations are observed closer to the upper convective zone, where temperature variations are larger. The lower convective zone is a completely mixed zone during the day. This occurs because the radiation that reaches the bottom of the solar pond is absorbed at this depth in a black liner (see Figure 2). The black liner warms and increases the temperature of the highly concentrated brine. The warmer brine rises by buoyancy and creates the circulation inside the lower convective zone. During the night, the lower convective zone stratifies. Heat is lost through the non-convective zone as well as through the bottom and sides of the pond. After 15 days, the lower convective zone reached a temperature of approximately 34°C, which corresponded to the thermal quasi-steady state.

Figure 4 shows the temperature profile for different times during the maturation period. The day before the

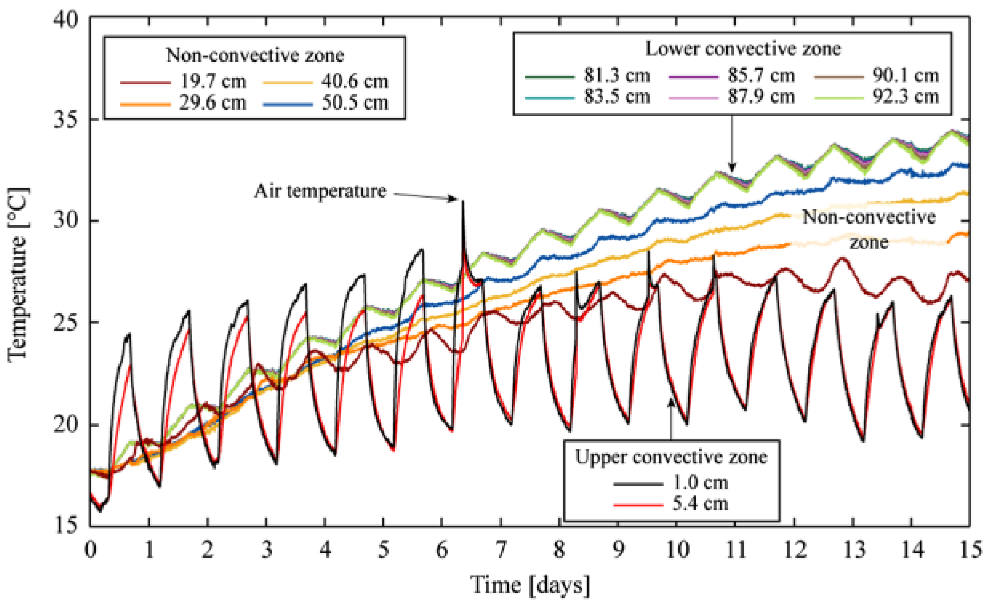

Figure 3 | Thermal evolution at different depths inside the solar pond.

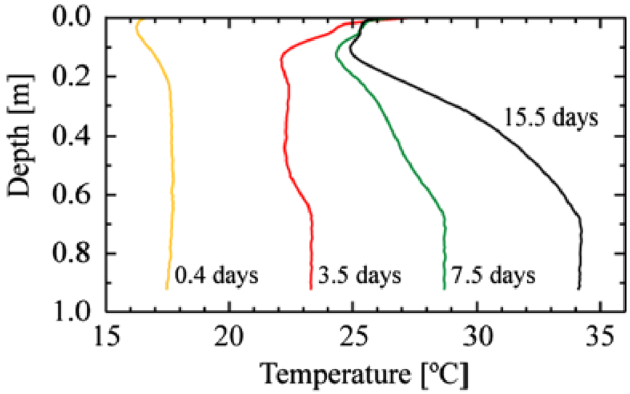

Figure 4 | Thermal profile for different times during the experiment.

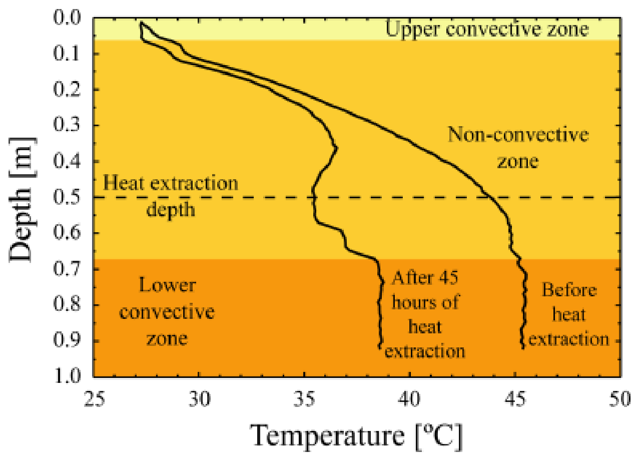

Figure 5 | Temperature profile inside the solar pond at the beginning and at the end of a heat extraction experiment.

experiment started, the pond was left uncovered during the night and the experiments started at 9:00. Before turning on the lights for the first time (at 0.4 days), the effect of surface cooling at night is clearly visible. At 3.5 days, the vertical high-resolution DTS system already shows that the lower convective zone is completely mixed. Additionally, the DTS system shows that the interface between the non-convective and lower convective zones is located at ~0.65 m depth, which is deeper than the desired level (0.50 m depth). Thus, an unwanted reduction of the lower convective zone occurred due to turbulent mixing when constructing the salt gradient. At 15.5 days, the DTS system shows that the location of the interface between the non-convective and lower convective zones is now closer to 0.7 m depth. This erosion of the lower convective zone is likely due to salt diffusion.

After reaching the thermal quasi-steady-state, the lights were turned on for 24 hours per day. When a new thermal steady-sate was reached, brine was extracted from the solar pond. The temperature profiles inside the solar pond, before and after heat extraction, are presented in Figure 5. The temperature in the lower convective zone at the new thermal steady-state was approximately 45°C. Note that the lower portion of the non-convective zone (between 0.55 and 0.65 m depth) became a completely mixed zone. As a result, there is a temperature step change of 0.5°C in the interface between the non-convective and lower convective zones. The mixing in the lower portion of the non-convective zone was not observed when the solar pond was operating at lower temperatures because the effect of salinity on density was greater than the effect of temperature. Thus, it behaved as a stable zone where transport occurred by diffusion alone. However, when the lower convective zone had a higher temperature, the lower portion of the non-convective zone became unstable and transport occurred by double-diffusive convection (Turner 1974).

Heat was extracted from the non-convective zone. As can be seen in Figure 5, as energy was extracted, the temperature at the heat extraction depth decreased. When these temperatures were cooler than a threshold, the fluid at this depth became heavier and thus sank to the bottom of the pond, which produced a rise of the warmer brine. Therefore, energy was indirectly extracted from the lower convective zone. After heat was extracted, below the heat extraction depth, the temperature profile shows a staircase shape, typical of double-diffusive convective systems (Kelley *et al.* 2003). This staircase is the result of the method used to create the salt gradient within the pond. The temperature profiles presented in Figure 5 were used to determine the heat content inside the solar pond (Wetzel & Likens 1991). The change in the heat content permitted estimation of the energy extracted from the pond. An average of 139 W was extracted from the solar pond during the 45 hours of heat extraction. This corresponds to an efficiency of 29%. Efficiencies between 4 and 35% have been reported in other solar pond studies (Beniwal & Singh 1987; Lodhi 1996; Karakilcik & Dincer 2008). In this estimation, only the heat content below 0.20 m depth was considered as heat used for extraction. Changes in the heat content at shallow depths could have been the result of changes at the surface of the pond (e.g. due to freshwater injection to account for evaporation) and, consequently, changes in temperature at shallow depths were not considered as heat extracted from the solar pond.

CONCLUSIONS

The thermal evolution of an experimental solar pond, for both maturation and heat extraction time periods, was studied using a vertical high-resolution DTS system. Temperatures of 34 and 45°C were achieved in the lower convective zone when the lights over the pond were on for 12 and 24 hours per day, respectively. When heat was extracted, the solar pond operated with an efficiency of 29%. The vertical high-resolution DTS system detected stratification and mixing inside the solar pond. Even more, the DTS system was able to detect stratification inside the convective zones and mixing inside the non-convective zone.

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