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Use of fiber-optic distributed temperature sensing to investigate erosion of the non-convective zone in salt-gradient solar ponds

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ABSTRACT

Salt-gradient solar ponds (SGSPs) collect and store solar radiation as thermal energy. This thermal energy is stored in the pond's bottom because of the existence of the non-convective zone (NCZ), a layer comprised by a salinity gradient that results in a stable density profile, which suppresses global convection within the pond. As a consequence, the NCZ is the most important layer of an SGSP that must be maintained to sustain the internal structure of the pond and to allow successful thermal energy storage. The NCZ is characterized by a thermal gradient and thus, the internal structure of an SGSP can be inferred using temperature measurements. In this work, fiber-optic distributed temperature sensing (DTS) methods are systematically assessed in a laboratory-scale SGSP, and a simple interface tracking algorithm to determine the NCZ evolution – based on thermal measurements – is presented. To evaluate this algorithm, a DTS system and a discrete array of 14 point-in-space temperature loggers were used to record temperatures in the laboratory-scale SGSP. Acceptable results regarding the NCZ evolution were achieved with the discrete array of sensors. However, much better results were obtained with the DTS high-spatial resolution measurements, despite the presence of some artificial thermal oscillations in the DTS records. These oscillations did not affect the results of the interface tracking algorithm, but may be a concern on large-scale field installations. It was also found that the location of the NCZ boundaries can be determined even with low spatial resolution measurements. However, this determination can only be achieved using the proper interpolation method.

1. Introduction

A salt-gradient solar pond (SGSP) is a thermohaline water body artificially stratified with salts that operates as an energy collection and storage system (Suárez and Urtubia, 2016). It absorbs and stores solar radiation as thermal energy for long time periods (Amigo et al., 2017; Amigo and Suárez, 2018). An SGSP consists of three thermally distinct layers (Fig. 1): the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ). The UCZ is a relatively thin layer of cooler, less salty water that protects the NCZ from atmospheric processes. The non-convective (NCZ) zone has a salinity gradient that produces a density gradient, which prevents global convection within the pond and acts as insulator for the LCZ (also known as the thermal storage zone). The LCZ is a layer of high-salinity brine where most of the heat is stored and the highest temperatures in the pond are achieved (González et al., 2016). The solar radiation penetrates the SGSP upper layers and reaches the bottom, heating the LCZ. The heated brine cannot rise beyond the LCZ because the effect of salinity on density is greater than the effect of temperature. The stored thermal energy can be transported back to the atmosphere from the LCZ only by conduction through the NCZ. Hence, the stability and thickness of the NCZ is a critical operating parameter for an effective solar pond operation (Valderrama et al., 2011). Nonetheless, the convection fluxes above and below the NCZ can erode the salt gradient over time (Suárez et al., 2010a,b).

To maintain the NCZ salt gradient stable in time, different methods had been used. The most common approaches are the injection of highly concentrated brine at the SGSP bottom (Jaefarzadeh and

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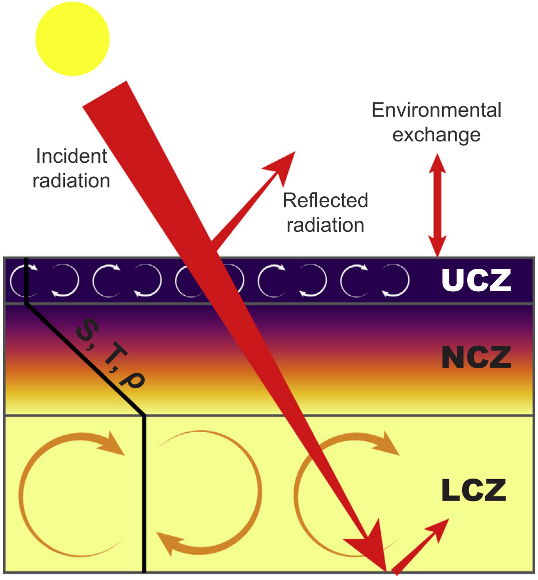

Fig. 1. Schematic of a salt-gradient solar pond (SGSP). A salinity (S) gradient maintains a stable density (ρ) gradient, despite the thermal (T) gradient that counteracts the salt gradient. UCZ is upper convective zone, NCZ is non-convective zone and LCZ is lower convective zone.

Akbarzadeh, 2002; Valderrama et al., 2011), and the flush of surface water with an overflow system combined with an injection of freshwater in the UCZ (Lu et al., 2004; Leblanc et al., 2011; Nie et al., 2011; Ruskowitz et al., 2014; Suárez et al., 2015). Other approaches try to reduce the impact of environmental factors, such as wind and waves, on the internal structure of the SGSP (Leblanc et al., 2011; Malik et al., 2011). In any of the previous methods, it is important to monitor the salinity, the density or the thermal gradient to ensure that the internal structure of the SGSP is correct.

To monitor the salinity gradient, samples are taken periodically and used together with instruments to measure either salinity, density or temperature (Jaefarzadeh and Akbarzadeh, 2002; Lu et al., 2004; Leblanc et al., 2011; Valderrama et al., 2011; Suárez et al., 2014). Temperature is usually measured continuously in time with arrays of ~10 to 20 sensors spatially distributed within the SGSP, for ponds with depths varying between 1 and 3 m (Leblanc et al., 2011; Silva et al., 2017). The measured thermal profile is usually represented using a linear interpolation between the sampled locations. Localized hydrodynamic instabilities can develop inside the NCZ, especially during heating, and can decrease the effective thickness of the NCZ (Jaefarzadeh and Akbarzadeh, 2002; Lu et al., 2004). These instabilities are typically repaired using a diffusor located at specific depths to supply brine with a specific concentration with the aim of redistributing the solute to maintain a stable density gradient (Lu et al., 2004). Nonetheless, to improve the effectiveness of this technique and thus the overall SGSP efficiency, the depth at which the instabilities occur must be detected to inject the brine at the correct depth. Therefore, the structure of the SGSP internal layers must be monitored with good spatial and temporal resolutions.

In the last decade, fiber-optic distributed temperature sensing (DTS) methods have gained ground among researches, and have been used to measure the thermal profile of natural water bodies (Selker et al., 2006; Arnon et al., 2014, 2016). The DTS technology is based on the scattering of light within an optical fiber for the thermal estimation along the entire fiber, with spatial resolution of 0.25–1.0 m, temporal resolution of 1–60 s, and an accuracy of ± 0.01 °C, along cables up to 10 km long (Tyler et al., 2009; Hausner et al., 2011; Suárez et al., 2011). This technology enables monitoring temperature at large extensions, offering an alternative for continuous measurements at a wide range of spatial scales. Recently, DTS methods have also been used in laboratory-scale SGSPs to monitor the thermal dynamics within the pond at high spatial and temporal resolutions (0.011 m and 5 min, respectively), with a thermal resolution on the order of ~0.035 °C (Suárez et al., 2010b, 2011, 2014, 2015; Ruskowitz et al., 2014; Amigo et al., 2017). However, DTS methods have not been used as an operating tool that can help to decide how to maintain the density gradient within an SGSP and thus, to improve the operation of these systems.

The general objective of this work is to investigate the temporal evolution of the NCZ by means of DTS methods, with the purpose of using this technology as a tool for solar pond efficient operation. The specific objectives are to perform a thorough assessment of the DTS data, and to develop a simple interface tracking algorithm. The purpose of this algorithm, which is based on thermal measurements, is to describe the erosion of the NCZ to support the salt gradient reconstruction, i.e., to improve solar pond maintenance. To achieve these objectives, a DTS setup and an array of independent point-in-space temperature loggers were used to monitor the thermal evolution of a laboratory-scale SGSP, and to assess the interface tracking algorithm. The structure of the remainder of this paper is as follows: Section 2 depicts the laboratory-scale solar pond and the experimental methods used in this investigation; Section 3 describes the data quality metrics used to assess the DTS and the point-in-space data; Section 4 presents the interface tracking algorithm developed to investigate the NCZ erosion; Section 5 shows the main results of this work and their discussion; and Section 6 delivers a summary and the main conclusions of this work.

2. Laboratory-scale solar pond and experiments

The laboratory-scale SGSP used by Amigo et al. (2017) was also utilized in this investigation (Fig. 2(a)). The SGSP has a depth of ~0.95 m and a surface area of 2.82 m^2 (1.2 m × 2.35 m), and was built inside a larger tank filled with sand. Thus, a homogeneous sand layer of ~0.5 m surrounded the pond. The walls of the pond were built with concrete and coated using a black epoxy resin. To mimic sunlight radiation, six 1000-W high-intensity discharge lamps (Dimmable MH/HPS Digital Grow Light, Virtual Sun, La Verne, CA, USA), with a spectral range between 350 and 770 nm, were installed over the solar pond. Incoming shortwave radiation was measured ~0.1 m above the water surface using an LP02 pyranometer (Hukseflux, Delft, The Netherlands) and the radiation data were collected in a CR10 datalogger (Campbell Sci., Logan, UT, USA). The incoming shortwave radiation at the water surface was determined in the same way as in Suárez et al. (2014). In our experiments, 75% of the radiation measured at ~0.1 m above the water surface reached the water surface itself. Air temperature and relative humidity were monitored ~0.05 m above the water surface using a HOBO Temp/RH Pro v2 Data Logger (Onset, Bourne, MA, USA).

Temperature inside the SGSP was measured using a series of 14 HOBO Water Temperature Pro v2 Data Loggers (Onset, Bourne, MA, USA) spaced at ~0.05 m that had a precision of ± 0.2 °C; and using a vertical high-resolution DTS, as shown in Fig. 2(a). The vertical high-resolution DTS system is similar to that presented by Suárez et al. (2011) and comprises a vertical high-resolution pole, a DTS instrument, two calibration sections at different temperatures, and an optical fiber that connects all the components. The total length of the optical fiber was ~240 m, with ~170 m used in the high-resolution pole, ~20 m used in each calibration section, and the remainder used to connect the DTS instrument with each component of the system.

The vertical high-resolution pole was constructed by wrapping a duplex (i.e., two optical fibers inside one cable) multi-mode fiber-optic cable (1.4 mm white polybutylene terephthalate tub with thixotropic gel, AFL Telecommunications, Spartanburg, SC, USA) around a 0.051 m diameter PVC pipe of ~2.0 m in length. This setup allowed 1 m of cable to occupy 0.011 m of pipe length. The two fibers were fused at the end