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Understanding the expected performance of large-scale solar ponds from laboratory-scale observations and numerical modeling

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HIGHLIGHTS

- Experiments and numerical models were analyzed to understand solar pond efficiency.
- Boundary effects typically reduce the efficiency of small-scale solar ponds.
- Artificial lighting affects the energy that reaches the lower convective zone.
- Turbidity is more important in large-scale solar ponds and decreases its efficiency.
- Large-scale solar ponds collect more energy than small-scale solar ponds.

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ABSTRACT

Solar ponds are low-cost, large-scale solar collectors with integrated storage that can be used as an energy source in many thermal systems. Experimental solar pond investigations at smaller scales have proven to be useful when trying to understand how different factors affect the pond's efficiency, but they do not necessarily represent the expected performance of large-scale solar ponds. Consequently, it is important to investigate how the results of small-scale solar pond experiments can be scaled up. In this work, we show how models based on laboratory-scale observations can be utilized to understand the expected performance of large-scale solar ponds. This paper presents an approach that combines high-resolution thermal observations with computational fluid dynamics to investigate how different physical processes affect solar pond performance at different scales. The main factors that result in differences between small- and large-scale solar pond performances are boundary effects, light radiation spectrum and intensity, and turbidity. Boundary effects (e.g., pond geometry, thermal insulation) reduce the energy that reaches the storage zone of small-scale solar ponds. Different types of lights result in different radiation spectrum and intensity, which affects the energy reaching the storage zone. Turbidity is typically not important in small-scale solar ponds subject to controlled environmental conditions. However, it is an important factor in outdoor solar ponds in which the pond is prone to particles that can deposit onto the water surface or become suspended in the gradient zone. In general, the combination of these factors results in less energy collected in small-scale solar ponds than in large-scale solar ponds, even though large-scale solar ponds are typically subject to more extreme environmental conditions. High-resolution thermal observations combined with numerical simulations to understand the expected performance of large-scale solar ponds seems to be a promising tool for improving both efficiency and operation of these solar energy systems.

1. Introduction

A salt-gradient solar pond is an artificially stratified water body that collects solar energy and stores it as thermal energy for long periods of time [1–3]. It normally consists of three layers: the upper convective zone, the non-convective zone, and the lower convective zone. The upper convective zone is a layer of cooler, less salty water. The non-convective zone is a layer where salinity increases with increasing depth. This is the most important layer in a solar pond because the salt gradient suppresses global circulation within the pond. This layer acts as a transparent insulator that permits solar radiation to penetrate to the bottom of the pond. The lower convective zone is a layer of high-salinity brine, which even when heated, remains so dense that it cannot rise to the surface of

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the pond. This maintained stratification allows the radiation that reaches the bottom of the pond to be stored as heat in the lower convective zone. While not as efficient as photovoltaic solar collectors, the costs of constructing and operating a solar pond are a fraction of the costs of photovoltaic cells [4]. In addition, the stored heat can easily be extracted from the pond via heat exchangers [5] and utilized for low-temperature thermal applications such as space heating [1], water heating in mines [6,7] or thermal desalination [8–10]. Thus, solar ponds are considered promising systems for solar energy conversion and storage [11], with the capability of storing massive amounts of energy [12].

There have been many investigations performed with small- or pilot-scale solar ponds [13–16], where more controlled conditions can be achieved (especially in indoor settings). Dah et al. [14] built a small-scale solar pond inside a laboratory to study the development of the temperature and salinity profiles in the absence of wind. In developing their experimental setup, the salinity distribution technique was utilized to establish the salt gradient in the non-convective zone. They observed temperatures as high as 45 °C in the lower convective zone, which was 23 °C higher than the upper-convective zone temperature. They also observed salt diffusion from the lower convective zone to the non-convective zone, pointing out the need for salt gradient maintenance. In more recent experiments, Dah et al. [12] observed 54 °C in the lower convective zone of a mini solar pond after only 20 days. This temperature was 27 °C higher than that in the upper convective zone. Kurt et al. [15] used a small-scale solar pond constructed inside a laboratory to investigate the feasibility of using sodium carbonate to suppress global convection inside the pond. Temperatures of 41 °C (10 °C higher than air temperature above the pond) were reached in the bottom of their pond when the salinity of the lower convective zone was 16% by weight. When the sodium carbonate solar pond was tested under field conditions, temperatures of 49 °C (21 °C higher than air temperature) were reached in the lower convective zone [17]. The small size of this experimental pond enabled the use of sodium carbonate, but it was noted that there was much difficulty in forming the salt gradient, which is expected to be increasingly difficult at larger scales [15,17]. Recently, Busquets et al. [18] found that the erosion of the non-convective zone of a solar pond prototype was accelerated by mass diffusion and convection in the lower convective zone, but no recommendations were provided to address this issue at larger scales.

Previous investigations also have tried to improve the efficiency of small-scale solar ponds. Shi et al. [19] improved the thermal efficiency of a small-scale solar pond by adding a porous media on the bottom of the pond. They observed that, in the presence of shallow groundwater tables or when the soils had a large thermal conductivity, the addition of a porous media in the bottom of the pond reduced ground heat losses, resulting in an improved solar pond thermal performance, reducing salt losses and costs, and maintaining the pond́s clarity. However, Shi et al. [19] did not study the effect of increasing solar pond size on heat losses through the ground or sidewalls, which is an issue that still needs to be addressed. In other investigation, Husain et al. [11] studied the inclusion of an additional salt-gradient zone between the non-convective zone and the upper convective zone. This additional layer had a thickness of 50 mm and comprised a sharper salt gradient than that used in typical non-convective zones [1,16]. Using an innovative design, Husain et al. [11] theoretically found that the temperatures in the lower convective zone should increase from 70 to 90 °C. However, they did not study the practical aspects that need to be considered when building these systems at larger scales. For instance, there is an increase in the difficulty of creating and maintaining the thin layer below the upper convective zone.

Many numerical investigations have also been carried out to examine the thermal behavior of solar ponds under different conditions [3,15,19–28]. In recent years, two-dimensional numerical investigations have become more common, but few researchers have modeled the hydrodynamics within the entire pond considering the phenomenon as a density driven flow and comparing their results with real solar pond experimental data [26]. More investigations are needed to verify these models and to confirm that the processes considered in these models are correct.

Other important aspect in solar ponds is heat extraction. Heat has been typically extracted from the lower convective zone [1,29]. However, in a recent investigation, Leblanc et al. [5] introduced a novel method for non-convective zone heat extraction. They tested this method in a small-scale solar pond and observed a 55% increase in the overall energy efficiency when compared to heat extraction from the lower convective zone. In addition, extracting heat from the non-convective zone did not change the density profile. This novel method of heat extraction worked at a small scale, but it is unknown what impacts could occur at larger scales. Dah et al. [12] evaluated a new method of heat extraction from the non-convective zone that improves the efficiency of a mini solar pond (0.64 m^2). Whereas heat extraction from the lower convective zone enhanced overall pond stability, heat extraction from the non-convective zone enhanced stability only above the heat extraction depth and decreased stability below this depth, i.e., their heat extraction method was found to reduce the stability of the interface between the non-convective and lower convective zone. The relationship between heat extraction and pond stability from this mini solar pond is not indicative of the effects of heat extraction from larger scale solar ponds, and must be further studied.

Investigations at smaller scales have proven to be useful when trying to improve the understanding of how different factors, such as ground heat losses, solar radiation, algae growth, heat extraction method, and salt type, affect solar pond efficiency [5,11–19,30], but these investigations do not necessarily enable prediction of large-scale solar pond performance. For example, heat losses through the sidewalls of large-scale solar ponds typically are negligible because the area of the sidewalls is small compared to the area of the bottom of the pond. In small-scale solar ponds, the area of the sidewalls and the bottom are often on the same order of magnitude, and consequently, the heat losses through the sidewalls could become important. Sidewall shading could also become important in small-scale solar ponds, where the effective sunshine hours are reduced [13]. Therefore, it is important to investigate how the results of small-scale solar pond experiments can be used to understand the expected performance of these solar energy systems at larger scales.

The general objective of this study is to investigate the main factors that result in differences between small- and large-scale solar pond performances. The understanding of these factors from laboratory-scale experiments enables prediction of solar pond performance at larger scales or under real environmental conditions. To achieve this objective, a new approach that combines high-resolution thermal observations with computational fluid dynamics is presented. In this study, for the first time, vertical high-resolution distributed temperature sensing (DTS) observations from a small-scale solar pond experiment [16,31] were compared to numerical simulations of a large-scale solar pond subject to the experimental environmental conditions. The simulations were carried out using a fully coupled double-diffusive convective model that considers the hydrodynamics within the solar pond as a density driven flow [3]. The differences between experimental and modeled results were explained and their impacts on large-scale solar pond were discussed. The approach utilized in this study allows real-time monitoring of solar pond performance at a wide range of spatial and temporal scales. Because the results obtained in this investigation make clearer the physical processes