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.

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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 ponds 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 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 m²). 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 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
that occur within solar ponds, this approach enables to investigate how different factors can affect solar pond efficiency in both short- or long-term time-periods, such as days, weeks, months or even for longer time-periods. Moreover, the approach presented in this study may be a promising tool for improving both efficiency and operation of solar ponds.

2. Materials and methods

2.1. Laboratory-scale solar pond

An experimental solar pond (Fig. 1) was constructed with a depth of ~1.0 m, a surface area of ~2.0 m², a bottom area of ~1.0 m², and a capacity of ~1.5 m³. The pond consists of one diagonal (45°) and three vertical sidewalls and one bottom wall. The pond is lined using a regular black-pond liner and insulated using polystyrene foam sheets. Three high-intensity discharge lamps (Super Grow 1000 W, Hydrofarm Inc., Petaluma, CA) were installed over the pond to mimic the sunlight spectrum. Air temperature and relative humidity were measured ~40 cm above the water surface using a shielded sensor (HPMC45-L, Campbell Sci., Logan, UT). Net radiation was measured ~10 cm above the water surface using a net radiometer (Q-7.1, Campbell Sci., Logan, UT). Incoming and reflected shortwave radiation were also measured ~10 cm above the water surface with two pyranometers (LP02, Hukseflux, Delft, The Netherlands). To estimate the incoming shortwave radiation at the water surface, before the experiments began, one pyranometer was located at the water surface while the other one was located ~10 cm above it. In this way, it was determined that 62.5% of the measured shortwave radiation at ~10 cm above the water surface reached the water surface itself. Electrical conductivity (EC) was used as a surrogate measurement for salt concentration. Electrical conductivity in the solar pond was measured at ten different depths using EC electrodes with automatic temperature compensation (SK23T, Van London-phoenix Company, Houston, TX). Temperature within the pond was measured using a vertical high-resolution DTS system (Fig. 1a). This DTS system measures temperature each 1.1 cm from ~20 cm above the water surface to a depth of ~95 cm, achieving a temperature resolution of less than 0.04 °C. All data were collected at 5-min intervals. Complete details on the pond’s instrumentation and DTS system are presented elsewhere [31,32].

The thickness of each layer of the experimental solar pond was scaled down from thicknesses utilized in other solar pond projects [33]: 10, 40, and 50 cm for the upper convective, non-convective, and lower convective zones, respectively. The filling of the solar pond was performed as follows: the lower 50 cm of the pond (the lower convective zone) were filled with a 20% by weight sodium chloride (NaCl) solution. Then, to construct the non-convective zone, layers of varying salt concentration (each 2.2% less than the previous layer) were added at 5-cm intervals until an elevation of ~90 cm, measured from the bottom of the solar pond, was reached. The final layer (the upper convective zone) had a thickness of ~10 cm and was filled with tap water. Although the thickness of the upper convective zone is within the range used in other solar ponds (10–40 cm) [33–36], maintaining such a thin layer in outdoor solar ponds may be challenging [33]. In this work, we selected a thin thickness only to increase the attainable operating temperature in the lower convective zone [29].

The actual water level in the pond varied from 0.98 to 1.03 m due to evaporation and freshwater injection, with an average water level of 1.01 m (measured from the bottom). The average water level was used to calculate depths within the solar pond throughout the experiment, disregarding the slight variance of the true water level.

The solar pond was covered tightly and allowed to sit for three days after filling to allow diffusion to create a more uniform salt gradient in the non-convective zone. After this, the pond was exposed to the artificial lights. The lights were typically turned on for 12 h per day from 6:00 a.m. to 6:00 p.m. with the exception of the first day (March 10, 2009) when they were on from 9:00 a.m. to 6:00 p.m. Because the experimental solar pond was constructed inside a laboratory, no direct sunlight reached the surface of the pond; thus, the main source of light was the artificial lights.

Samples were withdrawn every three days using ten sampling tubes (polypropylene, with an inner diameter of 3 mm) installed at ~10 cm intervals in one of the vertical sidewalls (Fig. 1b). After withdrawing the sample, density was measured using a portable density meter (DA-110M, Mettler Toledo, Columbus, OH), turbidity was measured using a portable turbidity meter (2100P, Hach, Loveland, CO) and EC was measured using an EC electrode (SK23T, Van London-phoenix Company, Houston, TX). Evaporation was measured periodically by reading the water level before and after freshwater was injected into the upper convective zone, and was on the order of 5 mm day⁻¹.

2.2. Numerical modeling

The two-dimensional fully coupled, transient double-diffusive convective model for salt-gradient solar ponds presented by Suárez...
et al. [3] was used to predict the response of a large-scale solar pond under the same meteorological conditions observed in the laboratory-scale solar pond experiment. Therefore, the temporal fluctuations of short- and long-wave radiation, air temperature, and relative humidity observed in the laboratory were utilized to drive the numerical simulations.

In the numerical model, mass conservation for water and species (NaCl), momentum, and energy conservation equations are coupled with the density of the fluid. These governing equations were solved using Fluent 6.3 [37], a commercial computational fluid dynamics code. This model was previously validated in a two-step process [3]. First, the transient momentum and heat transport were validated against limnological data from Mirror Lake (Storrs, Connecticut, USA), a shallow lake that shows diel stratification or mixing [38]. In the second validation process, double-diffusive convection was validated by comparing the results of steady-state simulations with experimental and numerical results published elsewhere [39,40]. To define boundary conditions and radiation absorption within the solar pond, we used the same calibration parameters presented by Suárez et al. [3]. These parameters are intended to be used in outdoor large-scale aquatic systems [38,41]. For further details regarding the validation of the numerical model the reader is referred to the work of Suárez et al. [3].

Simulations utilized a 1.01-m deep × 1.0-m wide section assumed to be in the middle of a large-scale solar pond. Therefore, boundary effects such as conductive heat losses across the sidewalls and potential radiation absorption on the sidewalls were neglected. This is a realistic assumption in large-scale solar ponds where the sidewalls area is much smaller than the area of the bottom of the pond [42]. Fig. 2a presents a comparison between the domains used in the numerical simulations and the laboratory-scale solar pond. Simulations were run for a 1-week time period using 5-min input data. Several grids were tested to ensure independence of numerical results with respect to spatial discretization. A uniform grid with cells of 0.02 × 0.02 m was found to be appropriate for the problem under investigation [3].

For simplicity, freshwater injections at the surface of the pond to account for the evaporated water were neglected. Thus, a constant-level water surface at 1.01 m elevation (measured from the bottom) was assumed, as was zero flux of salt across the top of the pond. Temperatures measured using the vertical high-resolution DTS system at the beginning of the experiment were used as thermal initial conditions in the numerical model. The measured initial density profile was used to define the initial thicknesses of the upper convective, non-convective, and lower convective zones, and the initial salinity profile. The measured temperature at the water surface was used as the top boundary condition. In addition, the measured short-wave radiation at the water surface was used to estimate the internal heat generation due to radiation absorption [1]. Both the initial and boundary conditions are presented in Fig. 2. The conductive heat losses through the bottom of the numerical domain were estimated using the thermal properties of the pond’s insulating material and the ambient temperature of the laboratory (because the bottom of the laboratory-scale solar pond is in contact with air).

3. Results and discussion

The measured and modeled thermal evolutions inside the solar pond are presented in Fig. 3. The modeled and experimental temperatures follow the same trend, verifying the model developed by Suárez et al. [3] with real solar pond data and without performing any parameter estimation. The good agreement between measured and modeled temperature evolutions suggests that high-resolution thermal observations combined with computational fluid dynamics can be a promising tool to improve both efficiency and operation of solar ponds. In this case, this approach was tested for one week but it can be easily expanded for longer time periods.

Although the results of the model represent very well the experimental results, the modeled temperatures slightly overestimate the temperatures measured by the DTS system in the upper and lower convective zones, and underestimate the temperatures in the non-convective zone. This can be observed more clearly in Figs. 4 and 5, which show the thermal evolution at different depths and the temperature profile inside the pond at different times of the experiment, respectively. The largest discrepancies between
measured and modeled temperatures are always less than 2 °C and occur in the non-convective zone, except for the discrepancies observed at 0.02 m depth from March 12 through 16 (Fig. 4). These discrepancies most likely occurred because during the first week of operation, the solar pond was not refilled with water to account for the evaporated water. This resulted in a lower water level than that used as a reference for the water surface (that was fixed at 1.01 m elevation for the DTS system and for the top of the numerical domain). Therefore, the temperatures measured at that elevation corresponded to air temperatures rather than the real temperature of the water surface, with the air temperatures being higher than the water surface temperatures. This also explains the discrepancies observed in the upper convective zone between March 12 and 16 shown in Fig. 4. The first freshwater injection to account for the evaporated water took place on March 16, where the temperature at 0.02 m depth decreased quickly. From Fig. 5 it also can be seen that the model represents the mixing in the different zones very well. For instance, the experimental data shows that the upper convective zone is typically stratified when the lights are on and completely mixed when the lights are off, and the model represents these two situations well.

At the end of the simulation (March 17 in Fig. 5), the modeled temperatures in the lower convective zone were approximately 0.8 °C higher than those measured by the DTS system. The main reason for this discrepancy is most likely the conductive heat losses, which were neglected on the sides of the modeled pond. In the laboratory-scale solar pond, conduction occurs across all sidewalls. The area of the walls surrounding the lower convective zone (including the 1 m² bottom) is approximately 3.0 m². Thus, in reality the laboratory-scale solar pond loses heat by conduction at a rate ~3 times greater than that represented in the model. Indeed, if the heat losses at the bottom of the numerical model are increased by three times, the modeled temperatures in the lower convective zone are in a better agreement with the experimental temperatures in this zone (data not shown). However, in this case the discrepancies observed in the non-convective zone remain unchanged (this is discussed below). In large-scale solar ponds, the area of the sidewalls is much smaller than the area of the bottom. Consequently, neglecting conductive heat losses through the sidewalls is more realistic only at larger scales.

The main reason for the model underestimation of the temperatures in the non-convective zone is likely the difference between the geometry of the laboratory-scale solar pond and the geometry of the domain in the numerical model, i.e., the boundary effects. In the model, to simulate the large-scale performance of a solar pond, the effect of the sloped sidewall was neglected. In the laboratory, because the sloped wall is lined with a regular black-pond liner, it absorbs energy along its entire length, i.e., energy is absorbed at different depths [43,44]. If energy is being absorbed at shallower depths than the lower convective zone, the experimental temperatures at shallow depths should be higher than those predicted by the model (that did not consider the sloped wall). Hence, larger temperature differences occurring at shallow depths, where radiation fluxes are high, are expected. This is supported by the experimental data, which show greater temperature differences in the non-convective zone between 0.2 and 0.5 m depth, e.g., see Fig. 4 at these depths and Fig. 5 after March 12. Following the previous interpretation, the largest discrepancy between the temperatures differences should occur in the upper convective zone, where one would expect experimental temperatures higher than the temperatures reported by the model. This did not occur in the simulations because the temperatures measured by the DTS system were used as the upper boundary condition. Thus, temperatures in the surface of the model are restricted and become closer to the experimental temperatures.

Another uncertainty that could cause differences between laboratory- and large-scale solar ponds is the way that shortwave radiation is absorbed inside the pond. In fact, previous investigations performed inside laboratories have shown that the thermal profile is affected by the type of lights used to warm the pond [14,15]. In the model used to predict large-scale solar pond performance, radiation absorption inside the pond was represented using the Rabl–Nielsen formula [1], which was developed for clean sea water data under natural solar radiation conditions. However, since artificial lights have a different light spectrum than natural solar radiation, it is expected to observe a different thermal performance between indoor and outdoor solar ponds. The data in Fig. 6 compare the relative intensity of a typical terrestrial solar spectrum distribution [45] with the artificial lights used in the small-scale laboratory solar pond. As shown in Fig. 6, the spectral distribution of the artificial light differs from the solar spectral distribution. Approximately 95% of the irradiance of the artificial lights is below 750 nm, while approximately 55% of the sun’s irradiance is in the 200–1200 nm spectral range. Radiation in the 200–1200 nm spectral range, especially at shorter wavelengths, penetrates deeper into the water column [46]. To be certain about how the shortwave radiation from the artificial lights absorbs into the water column, a correct description of the underwater light field is necessary (e.g., by measuring the underwater light field using spectrophotometers). Assuming that the Rabl–Nielsen formula [1] is correct to
represent the attenuation of the artificial lights, and ignoring the boundary effects of the inclined wall, the artificial lights should warm the lower convective zone more than sunlight will because all of the light radiation will reach the bottom of the pond. However, the radiation intensity of these lights is less than that of the sun. During the experiment, a daily average incoming radiation of $\approx 110 \text{ W m}^{-2}$ was delivered by the artificial lights. This irradiance is less than that observed in potential places where solar ponds can be built. For instance, the daily average radiation in arid regions such as the Dead Sea region of Israel, non-coastal regions of Australia, the desert of the western U.S., or the north of Chile is in the range of 220–260 W m$^{-2}$ [45,47]. Hence, even though these artificial lights have the potential to warm the lower convective zone more than sunlight, a solar pond under natural solar radiation conditions will achieve higher temperatures than a solar pond exposed to artificial lights. Temperatures higher than 80 °C have been observed in many large-scale solar ponds [9,42,36]. Even more, temperatures as high as 109 °C at a depth of 2.1 m below the surface were seen when the brine of a solar pond was boiling [48]. Therefore, even when the pond is subject to other heat losses, e.g., due to meteorological conditions, there is evidence that more energy can be collected and stored under ambient conditions in large-scale solar ponds compared to laboratory or indoor solar ponds.

The effect of salt diffusion on pond performance typically is neglected in small-scale solar pond experiments. This happens because the time scale in such experiments is shorter than the time scale required for observing significant changes in the salt or density profiles. However, salt diffusion is an important phenomena in
large-scale solar ponds, where the salt gradient needs to be maintained to achieve long-term operation [5,9,49]. In the experiments described in this study, no maintenance of the salt gradient was performed other than injecting freshwater at the surface of the pond. Fig. 7a shows the measured and modeled density profiles at the beginning (March 09, 2009 at 12:00 p.m.) and the end (March 16, 2009 at 10:00 a.m.) of the simulation period. As expected, density varies less than temperature within each zone. This is due to the diffusivity of NaCl being less than the thermal diffusivity of the brine. Measured and modeled densities agree fairly well. The differences observed in the upper convective zone at the end of the simulation (red points and line) occur because freshwater was injected in this zone to account for evaporation losses. Thus, near the surface of the pond the measured density is less
than the modeled density. Fig. 7a also shows that NaCl is being lost from the lower convective zone (as the effect of NaCl concentration on the density is larger than that of the temperature). Consequently, for long-term operation, injection of NaCl in the lower convective zone must take place to maintain a stable system for both small- and large-scale ponds.

Fig. 7b shows the measured turbidity at the beginning and at the end of the simulation period. The brine turbidity was very low, near the U.S. EPA standard for drinking water. This very clear brine has similar clarity to that of potable water. This confirms the previous hypothesis that the rays of light penetrate to the bottom of the pond. However, in large-scale solar ponds, clarity is an important issue. During pond operation, the pond surface is prone to dust, leaves, soil, and other particles that can deposit onto the water surface. These particles can either float on the surface, sink to the bottom of the pond, or in many cases, become suspended in the pond when the density of the particle reaches that same density in the gradient zone. This results in increased turbidity (decreased water clarity) during pond operation that reduces the water surface.

Turbidity on pond performance can be quantified using the empirical transmission function proposed by Wang and Seyed-Yagoobi [51]:

\[ h(\theta, z) = h(0.3, z)R(\theta, z) \]  

(1)

\[ h(0.3, z) = 0.58 - 0.076 \ln(100z) \]  

(2)

\[ R(\theta, z) = 1 - 0.1975(\theta - 0.3) + 0.0144(\theta - 0.3)^2 \]  

where \( h(\theta, z) \) is the non-dimensional transmission function at a depth \( z \) [m] with a turbidity of \( \theta \) [NTU]; \( h(0.3, z) \) is the reference non-dimensional transmission function based on a turbidity level of 0.3 NTU; and \( R(\theta, z) \) is the ratio between the non-dimensional transmission function at a given turbidity level and the reference non-dimensional transmission function. Eq. (1) is valid for \( 0 \, \text{m} < z < 1.34 \, \text{m} \) and for \( 0.3 \, \text{NTU} < \theta < 5.0 \, \text{NTU} \), and assumes a uniform turbidity throughout the pond. When the Wang and Seyed-Yagoobi [51] transmission function is implemented in the numerical model used in this work [3], and at the end of the one-week simulations, the temperatures in the lower convective zone decreased by approximately 0.4 and 2.3 °C when the turbidity levels increased from 0.3 to 1.0 NTU and from 0.3 to 5.0 NTU, respectively. This shows that turbidity is an important factor that affects pond performance. Outdoor solar ponds may also promote the growth of algae and bacteria due to the presence of organic nutrients, inorganic carbon, and other favorable conditions such as pH, temperature, or the presence of light. For example, in a solar pond located in Tibet, clarity decreased in a two-month period and algae growth in the non-convective and lower convective zones produced a red tint, which reduced penetration of solar radiation [34]. Previous investigations have shown that there are numerous ways to control algae growth in solar ponds. Treatment techniques to help control turbidity include the use of hydrochloric acid, sodium hypochlorite, copper sulfate, cupricide (a copper ethylamine complex), and other alums [30,49,52,53]. Dust, algae growth, and turbidity were not observed during laboratory testing, however, each of these would be expected in large-scale solar ponds and must be taken into account when modeling the performance of these ponds from laboratory studies.

4. Conclusions

This study investigated the main factors that result in differences between small- and large-scale solar pond performances by using a new approach that combines high-resolution DTS data with computational fluid dynamic simulations. In this paper, we showed that models based on laboratory-scale observations can be utilized to understand the expected performance of large-scale solar ponds. The main factors that result in differences between the two spatial scales of interest were investigated by comparing observations from a small-scale solar pond experiment with simulations that modeled the hydrodynamics within a large-scale solar pond as a density driven flow. These simulations were based on the laboratory-scale conditions (e.g., meteorology, temperature at the surface of the pond), but considered other conditions that are representative of large-scale solar ponds (e.g., natural solar radiation absorption within the pond, negligible boundary effects from the sidewalls of the pond).

Boundary effects, light radiation spectrum and intensity, and turbidity were found to be the main factors that result in differences between small- and large-scale solar pond performances.
Boundary effects such as pond geometry and conductive heat losses in small-scale solar ponds resulted in less energy collected than in large-scale solar ponds. The inclusion of a sloped wall in the small-scale solar pond modified the expected thermal profile within the pond. For instance, when comparing small- and large-scale solar ponds under the same conditions explored in this study, e.g., similar environments and duration of the experiments (one week), the sloped wall in a small-scale solar pond increased the non-convective zone temperature by approximately 1.5–2°C. On the other hand, conductive heat losses may become important in small-scale solar ponds that are not well insulated. In our experiments, an assessment of the conductive heat losses showed that temperatures in the lower convective zone can be approximately 1°C lower than those expected in large-scale solar ponds for a one-week time-period. Although this temperature difference is small, it must be pointed out that in large-scale solar ponds and for longer time-periods, this difference may become important.

The way that radiation is absorbed inside the pond is also important and depends on the radiation spectrum of the light. It was found that even when the spectrum of artificial lights allowed the light to reach the bottom of the pond, the light intensity was typically much smaller than that of the sun. In this study we observed daily average radiation of 110 W m⁻², which is much less than the irradiance of potential places where solar ponds can be built. For instance, in arid regions the daily average radiation can vary between 220 and 260 W m⁻². Therefore, large-scale solar ponds could collect more energy than small- or laboratory-scale solar ponds. This has been demonstrated in large-scale solar ponds that have achieved higher temperatures than 80°C.

Another important factor is how turbidity affects the pond’s thermal performance. Typically in small-scale solar ponds this is not an issue since the experiments are performed in a short time-scale and under controlled conditions. However, in outdoors large-scale solar ponds this an important issue that must be addressed. For example, our results showed that lower convective zone temperatures can be reduced by 2.3°C when turbidity levels increase from 0.3 to 5.0 NTU – demonstrating that turbidity is an important factor that affects pond performance. The combination of boundary effects, light radiation spectrum and intensity, and turbidity 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.

This investigation showed that experimental results from small-scale solar pond experiments can be used to investigate the expected performance of large-scale solar ponds, as well as the main issues that can decrease the thermal performance of solar ponds. Because the model results obtained in this investigation make clearer the physical processes that occur within solar ponds, the approach presented in this work enables to investigate how different factors can affect solar pond performance in both short- or long-term, and is seen as a promising tool for improving both efficiency and operation of solar ponds.

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