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Research Article

Temperature and salt concentration behavior of a compact rectangular salinity gradient solar pond

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ABSTRACT

Design of economical and effective solar ponds which are useful thermal energy storage devices, remains a huge challenge. The present work aims at investigating the thermal performance of low cost mini salt gradient solar pond. The portable pond was fabricated as a rectangular configuration having a volume of $0.5m^3$. Polystyrene and high density polyethylene sheets were employed for insulating the walls. The top of the pond was covered with a slender glass so that the dust accumulation could be prevented without affecting the absorption of solar radiation. Sodium chloride salt was used as the medium and the three salt gradient regions namely lower convective, non-convective, and upper convective regions were established through injection filling technique. The temperature and salt gradient data were observed experimentally for a period of 20 days at Coimbatore, India. The pond could absorb significant amount of available radiation (around 65%) and the maximum temperature of the pond was observed to be 49°C. Frequent washing of the water surface is necessary to maintain stable salt gradient. Nevertheless, portable pond fabricated with low cost materials exhibited good potential of storing solar energy for solar thermal applications.

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INTRODUCTION

A salinity gradient solar pond (SGSP) is a pool having a mixture of salt and water that is heated by the sun's rays and can be used as an efficient and economical heat storage device that stores heat in a high-density salt solution [1]. A typical salt gradient can be established by using the injection filling technique, which makes highest salt gradient at the base layer and lowest at the top layer. Because of the

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salinity gradient, three dissimilar regions, namely upper convective region (UCR), non-convective region (NCR), and lower convective region (LCR) exist in the pond. UCR is formed at the pinnacle of the pond, with the thickness varying between 0.15m and 0.3m. Since this layer is in contact with the ambient air, the temperature is similar to that of the atmospheric air and the salt concentration is very close to that of potable water. The thickness of LCR varies between 1.0m and 2.0m, and it has the highest salt concentration. The temperature of this region remains higher than that of other regions due to the high concentration. In the NCR, which has the thickness in the range of 0.5m to 1.0m, the salt concentration increases with depth.

In the absence of salinity gradient, the temperature of entire pond would be almost the same as the stored solar energy would be lost due to natural convection. However, due to higher salt concentration at LCR, the water cannot move up towards UCR and the NCR suppresses the convection heat transfer. Hence, the UCR and NCR effectively act as insulators. This results in reduced thermal loss from LCR [2].

Among various cross sections, trapezoidal solar ponds are found to be widely employed one. Dineshkumar and Raja [3] investigated the thermal performance of a trapezoidal solar pond in Jordan. It was found that the trapezoidal pond exhibited higher thermal efficiency than a rectangular solar pond of the same size and depth as the trapezoidal shape allowed for a higher solar radiation absorption rate. The higher heat absorption rate by trapezoidal pond compared to rectangular pond is also reported by Meneses-Brassea et al. [4]. Besides higher heat absorption rate, trapezoidal pond is found to be less sensitive to changes in the atmospheric conditions according to Wu et al. [5]. In case of trapezoidal cross section, the geometrical parameters are found to be playing significant role in determining the thermal performance of pond. Prajapati et al. [6] found that a trapezoidal angle of 30 degrees resulted in the highest temperature difference between the bottom and the surface of the pond. On the other hand, Platikanov et al. [7] have suggested higher base lengths and the depths for the higher temperature differences between the bottom and the surface of the pond.

Although trapezoidal ponds seem to be better option than rectangular ponds from performance point of view, the reported research suggests that rectangular ponds too have good potential to provide sustainable energy and thermal storage solutions. Al-Iessa et al. [8] have highlighted that the rectangular pond is capable of producing fresh water at a low cost. Jayathunga et al. [9] could achieve 50% reduction in cost by employing low cost liner material (polyethylene) for the rectangular pond. Besides low cost fresh water production, 60% reduction in land use is reported by Yan et al. [10] when the salt concentration was low in the smaller size rectangular pond. Recently, Wang et al. [11] observed that a selective transparent cover could increase the temperature of the rectangular pond which resulted in improved efficiency. Recent review articles on rectangular solar ponds [12,13]. Perumal and Dharmalingam [14] have highlighted the areas for future research and development to improve the efficiency and expand its applications.

As discussed, it is necessary to enhance the performance of solar ponds by reducing heat losses through the use of insulators. Beiki and Soukhtanlou [15] investigated the effect of using different insulators on the thermal performance of a solar pond in various weather conditions. According to the results, expanded polystyrene material reduced heat losses through conduction and the aluminum foil layer reduced heat losses through radiation. Rghif et al. [16] employed a floating insulator made of polyethylene foam and found a higher temperature difference between the bottom and the surface of the pond compared to a pond without insulation. It was observed that floating insulator reduced both convection and evaporation heat losses. Abbood et al. [17] also used polystyrene foam as insulator. Although multiple options are available as far as insulating material is concerned, the choice depends upon the specific application, the local climate and more importantly, the cost and durability.

In SGSP, the selection of salt is critical and literature reveals the employment of various salts. The extensively studied salt is sodium chloride and the results have shown that it is an effective and low-cost heat storage medium [18-20]. However, Elmurodov et al. [21] found that magnesium chloride resulted in a higher temperature difference between the bottom and the surface of the pond compared to sodium chloride or potassium chloride. Apart from employing single salt, use of mixture of salts can also be found in the earlier works. Sodium chloride plus potassium nitrate [3], sodium chloride plus calcium chloride [22] are few salt mixtures attempted by various researchers.

From the above discussion, it seems solar ponds using sodium chloride are a low-cost and efficient way to store thermal energy. However, the earlier research works have considered sodium chloride salt for trapezoidal or square solar ponds which are all macro-size ponds. Hence, the present work focuses on investigating the thermal performance of micro-size rectangular shallow salt gradient solar pond (SSGSP) utilising sodium chloride. It can also be noted that the glass layers are crucial for preventing the dust accumulation and minimizing the convective and evaporative thermal energy losses from the upper region. However, usage of multiple glass layers severely affects the transmission of solar radiation [23,24]. Taking into account, a slender glass layer is employed so that transmission of solar radiation is not significantly affected.

Accordingly, the present work is a maiden attempt in which a micro-size rectangular SSGSP employs sodium chloride salt as storage medium, slender glass layer as cover and polystyrene + high density polyethylene (HDPE) as insulating materials. Considering the size of the pond and the cost of the materials, this research aims at investigating the thermal performance of a low cost SGSP.

MATERIALS AND METHODS

Experimentation

The proposed SGSP was fabricated as a rectangular tank made of steel. To avoid the heat loss, the inner walls were insulated with polystyrene and HDPE sheet. The outer walls were painted black. The top of the pond was covered with a slender glass. The pond contained sodium chloride salt and water as salt solution. Nine K-type thermocouples were placed along the depth of the pond at an equal intervals. The schematic and photographic views of the experimental setup are shown in Figure 1. The dimensions of the pond are presented in Table.1.

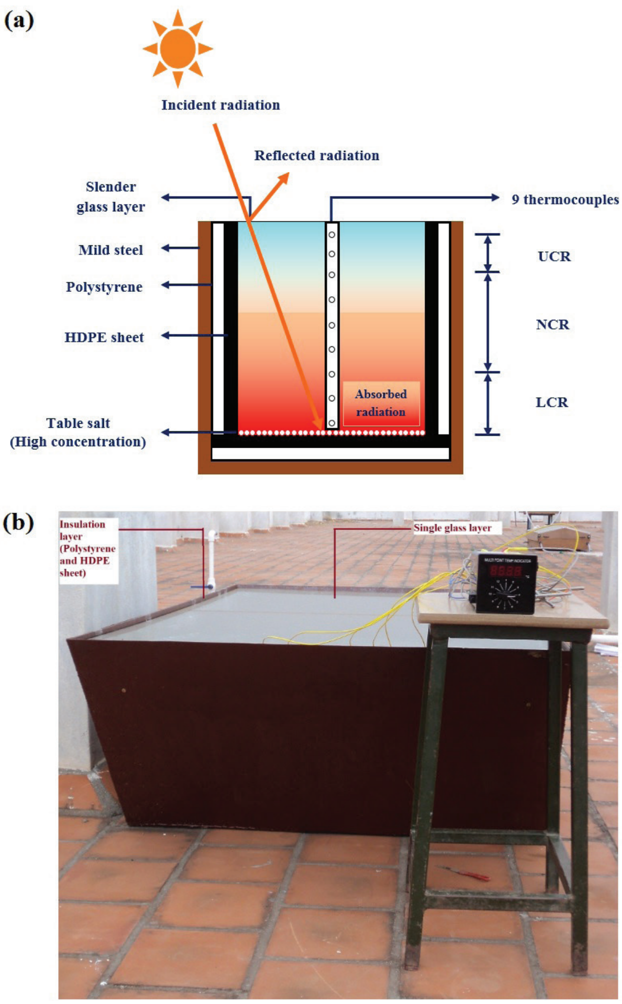

Figure 1. Experimental setup of the solar pond (a) Schematic view (b) Photographic view.

The fabricated solar pond was located in India at latitude of 11.10°N and longitude of 76.96°E. In the pond, the salt gradient was established by injecting NaCl slat solution (solubility 36gm/100ml of water) using a movable diffuser. First, the diffuser was placed at a height of 0.1m and the salt solution was injected. Then the diffuser was gradually moved up till the LCR was formed for a height of 0.2m. In the similar way, NCR was also formed. The salinity gradient was verified by measuring the density in all zoned using a hydrometer. It was found that, the density of salt varied from 1000 to 1050 kg/m^3 in the UCR; from 1050 to 1190 kg/m^3 in the NCR and from 1200 to 1250 kg/m^3 in the LCR. Further, salt solution replenishment has performed periodically to ensure constant volume of all the regions. The thermal conductivity and the specific heat values were also measured employing heat flow meter and calorimeter respectively. The thermal properties of the materials used in the work are shown in Table 2.

After establishing the salt gradient, the experimentation on solar pond was carried out for 20 days. During the experimentation the measurement of solar radiation was done using a hand held digital solar power meter. The K-type thermocouples were used to measure the temperature of all

Table 1. Dimensions of the solar pond.

Ponds' material	Mild steel (2mm thickness)
Height	0.5m
Width	1m
Length	1m
Volume of the pond	0.5m^3
Depth of UCR	0.1m
Depth of NCR	0.2m
Depth of LCR	0.15m
Insulators	Polystyrene and high density polyethylene sheet (20mm and 2mm thickness)
Glass	4mm thickness

Table 2. Thermal properties of materials used.

Properties	Water	Saline water	Polystyrene	HDPE Sheet	MS Steel
Density (kg/m^3)	1050	1250	960	950	7850
Thermal Conductivity (W/m-K)	0.599	0.56	0.033	0.45	40
Specific heat (J/kg-K)	4180	3985	1170	2400	486
Thermal Diffusivity (m^2/s)	0.143X10^{-6}	1.54x10^{-9}	2.93X10^{-8}	1.82X10^{-9}	2.49X10^{-2}

Table 3. Intruments specifications.

Instrument Name	Range	Accuracy	Minimum Value measured	Error in percentage
Solar power meter	0-2500 W m^{-2}	±1 W m^{-2}	30 W m^{-2}	3.33
Thermocouple	0-120°C	±0.75 °C	29 °C	2.58
12-point temperature indicator	0-300°C	±1 °C	29 °C	3.44
Heat flow meter	0 - 2.5 W m^{-1} K^{-1}	±0.0075W m^{-1} K^{-1}	0.03 W m^{-1} K^{-1}	25
Calorimeter	0 - 3000°C	±1°C	26°C	3.84

Table 4. Comparison between proposed system and earlier literature works.

Configuration	Maximum temperature of LCR (°C)	Ref.
Micro-size rectangular solar pons	49	Present work
Rectangular solar pond	40	[27]
Circular solar pond	49	[28]
Parallelipedic solar tank	48	[16]
Trapezoidal solar pond	65	[29]

the three regions. Table 3 presents the specifications of the instruments used in this work.

Besides experimentation, the present work focuses on mathematical approach to determine the salt concentrations. To evaluate the concentrations of LCR and UCR at any time, the analytical expressions proposed by Sayer et al. [25] are adopted. Hence, only the procedure and final expressions are explained here. For the derivation of the expressions, Ref. [25] can be referred to.

At any time '*t*', the concentrations of LCR or UCR can be expressed as a function of concentration at $t = 0$ and change in concentration at '*t*'. Accordingly, the concentration of LCR at anytime '*t*' is

$$C_L(t) = \frac{d_L C_U(t=0) + d_U C_U\,(t=0)}{d_L + d_U} + \frac{d_U C_L(t=0) - C_U\,(t=0)}{d_L + d_U}\left\{ e^{\frac{-D_C}{d_N}\left[\frac{d_L + d_U}{d_L d_U}\right]}\right\}^t \quad (1)$$

To use Eqn. (1), it is required to know the concentrations of UCR and LCR at $t = 0$ ($C_U(t = 0)$ and $C_L(t = 0)$), the salt diffusisivity (D_C), and the depths of the three regions (d_U, d_L, and d_N). The salt diffussivity of sodium choloride is taken as 0.00011 m^2 day^{-1} [25].

Following Eqn. (1), the change in concentration of LCR at '*t*' can be calculated using,

$$\Delta C_L(t) = C_L(t = 0) - C_L\,(t) \quad (2)$$

Now, the concentration of UCR at anytime '*t*' and the change in concentration of LCR at '*t*' are as follows.

$$C_U(t) = C_U(t = 0) + \Delta C_L(t)\frac{d_L}{d_U} \quad (3)$$

$$\Delta C_U(t) = \Delta C_L(t)\frac{d_L}{d_U} \quad (4)$$

RESULTS AND DISCUSSIONS

Impact of Solar Intensity and Atmosphere Temperature on Solar Pond

The solar radiation intensity and surrounding air temperature influence the temperature rise of solar pond. The hourwise variation of solar irradiation, ambient temperature and temperatures of inner and outer glass surfaces are presented in Figure 2 for representative days. It is obvious that surrounding air temperature, and the temperature of the glass varies in line with the solar radiation intensity. However, the inner and outer glass temperatures reach the peak values approximately 1 hout after the highest solar radiation intensity is recorded. This is because of the time required to warm up the water. It can be seen that solar radiation data recorded a maximum of 1050 W m^{-2} at 12.00 PM and a minimum of 150 W m^{-2} 7.00 PM. As can be seen from Figure 2, about 90% of the solar irrdaiance is absorbed between 10.00 AM and 03.00 PM. Owing to the quick rate of thermal energy transfer from top surface of water to inside glass, temperature of interior glass is greater than that of water and outer glass temperature. The higher inner glass temperature than the outer surface is also observed in trapezoidal pond by Bisht et al. [26]. Since the outside glass is exposed to the external environment, the thermal energy is transferred through convection mode.

Temperatures of the Inner Regions of SSGSP

To figure out the thermal losses from the regions of the SSGSP, the temperatures of all three regions were measured. To determine the daily mean temperature data at specified locations, region temperatures were recorded (20 days) throughout the day and the results are shown in Figure 3. It is clearly evident that the region temperatures vary with respect to the average solar energy received during a day. The UCR energy storage performance is creeping due to heat transfer from the region to the surrounding air. Small

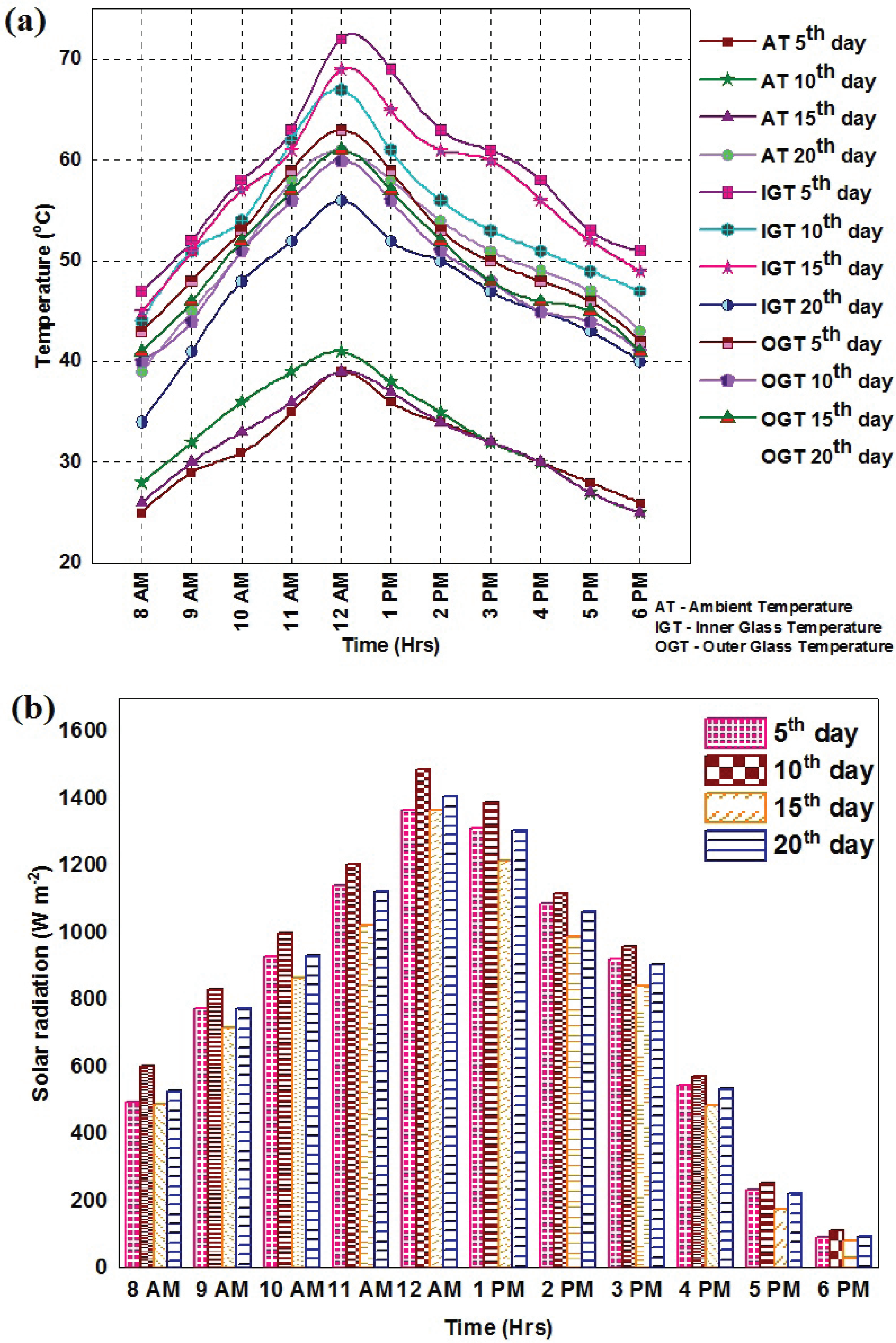

Figure 2. Time wise variation as measured data (a) Ambient temperature and temperatures of inner and outer glass (b) Solar radiation.

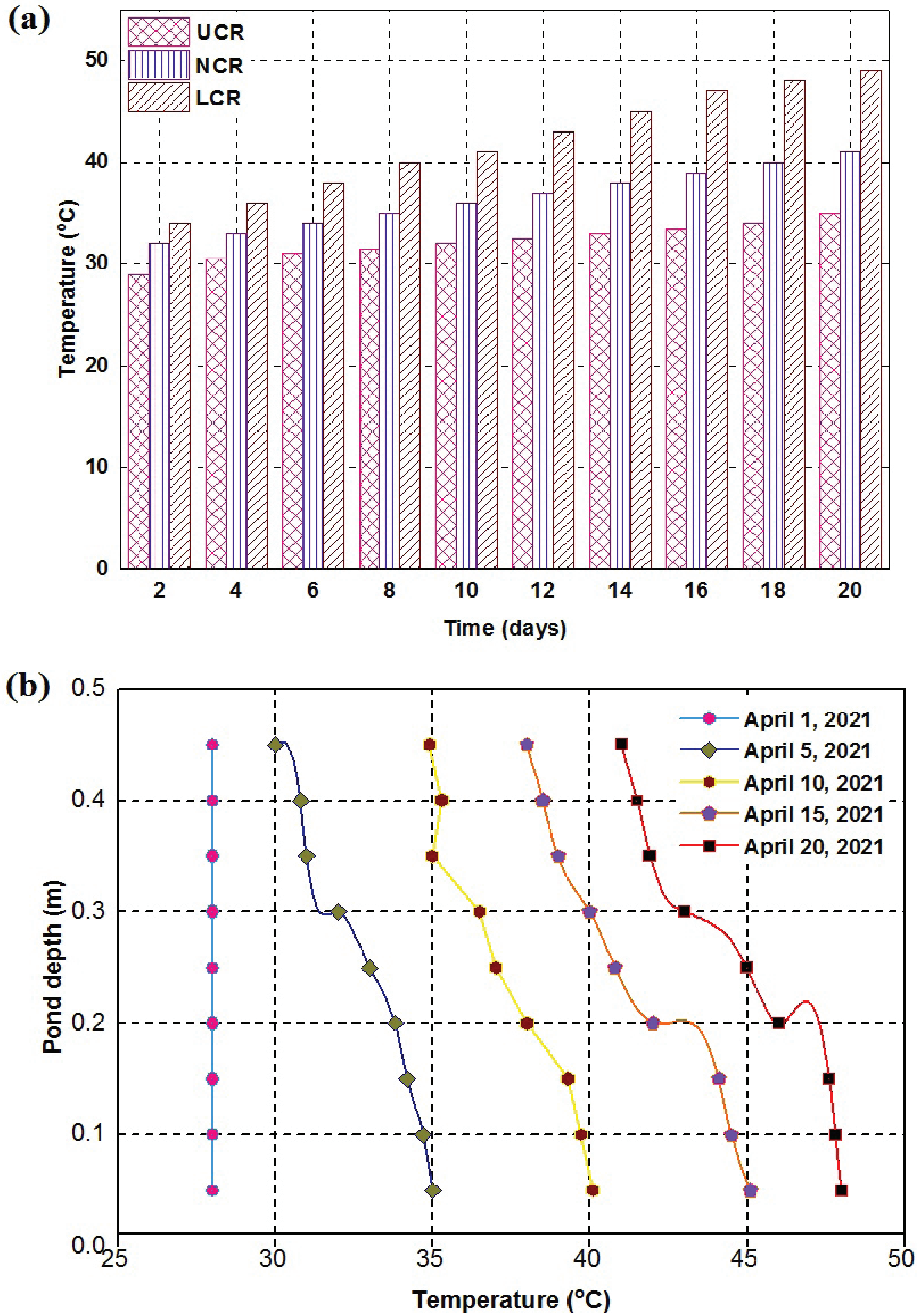

Figure 3. Temperature of three regions (a) Day wise variation of temperature (b) Temperatures variation along depth.

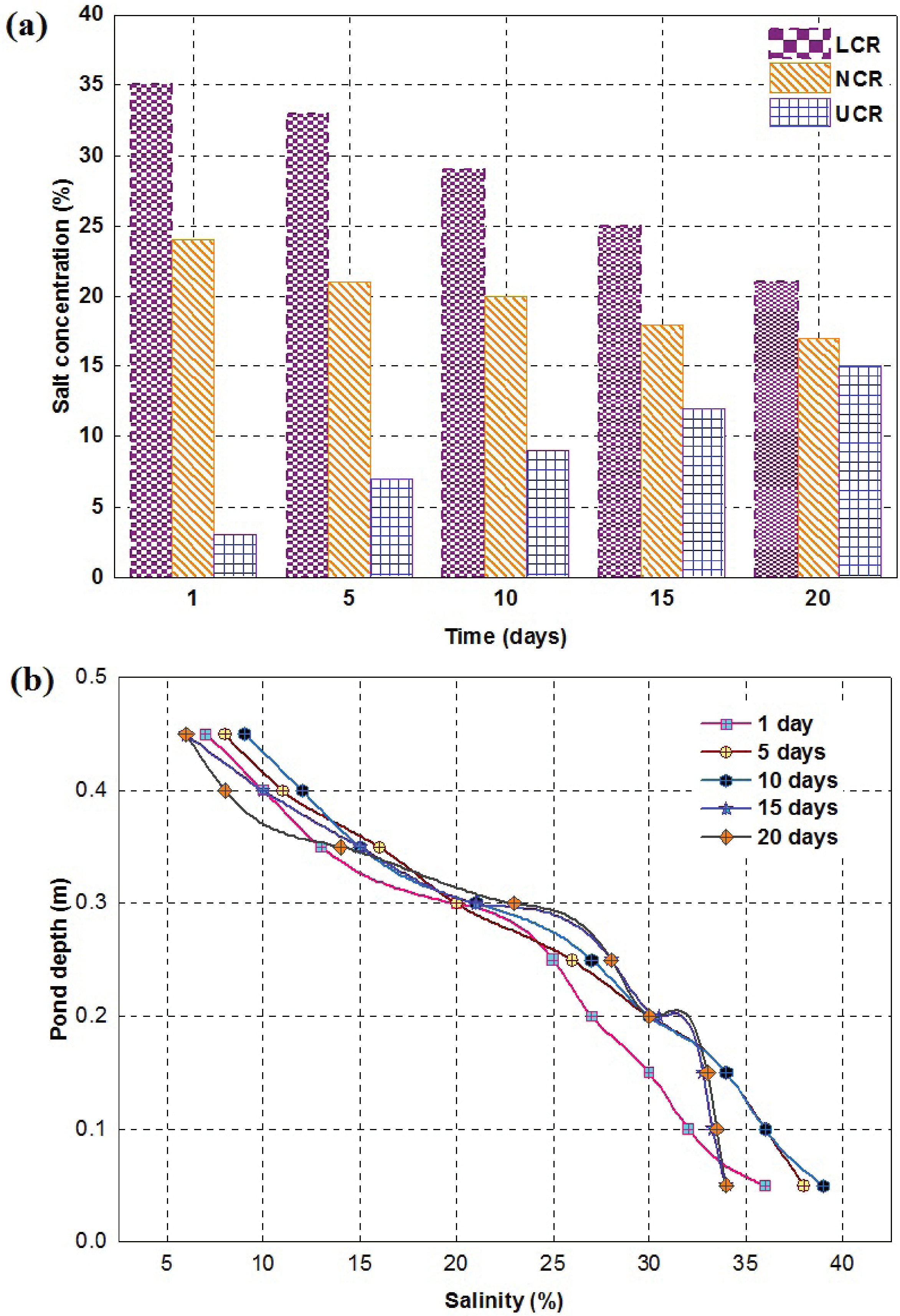

Figure 4. Variation of salt concentration (a) Day wise salinity variation (b) Salinity variation along depth.

portion (10%) of incident solar irradiance is stored in the UCR and remaining part is transmitted to the neighbour regions (NCR, and LCR). Almost 65% of solar radiation is absorbed by the LCR because of NCR which prevents the sallt molecules diffusion as it acts as an insulator. Hence, the tempeature of LCR remains higher than that of other regions which is true in all days (Figure 3a) The maximum and minimum temperatures of the UCR, NCR, and LCR were found to be 35°C and 29°C, 42°C and 32°C, 49°C and 34°C respectively. The maximum temperature acheived by the SSGSP of the present work is compared with the results of earlier works carried out on other types of ponds, i.e rectangular [27], circular [28], parallelipedic [16] and trapezoidal solar ponds [**29**]. The comparison is presented in Table 4 and it can seen that the present configuration exibits higher average tempearture than other configurations except the trapezoidal. This shows that the micro-size rectangular SSGSP has good potential for thermal storage applications.

For further understanding of the behaviour of the three regions, the temperature profiles are illustrated in Figure 3b. On the first day, it was noticed that there was no difference in temperatures of all regions throughout the day. In fact, the UCR contains only fresh water initially which gets evaporated easily and is retained inside the glass surface. This causes reduced transmission of solar radiation into the pond. Hence, all three regions remain at the same temperature during day 1.

From the second day of operation, it was observed that the temperature in the LCR linearly rises and remains higher than that of UCR and NCR. Fluid circulation in the heat storage region ensures that the temperature gradient is more homogeneous. The density variation in the NCR contributes to the stability of this condition. NCR functions as a translucent insulator and inhibits hot fluid from rising to the pond's surface. The stable temeprature gradient in the heat storage region of a simulated mini solar pond is highlighted by Ines et al. [29]. This work validates the same in the real time system. Further, Ines at al. [29] observed slight variation in the temperature of UCR during late hours. This is due to evaopration of water from the surface which requires periodical replenishment of salt and clean water.

Salt Concentration Profile

Stable salt concentration in all regions is critical in determining the performance of the pond. Hence, during the experimentation period, the salt concentration in all regions was monitored every day, and the results are given Figure 4. According to the data given in Figure 4a, initial day salt concentration in LCR was found to be 35% whereas it was 24% in NCR, and 3% in UCR. However, the UCR salt concentration steadily increased as the days passed on whereas, opposite trend was observed in case of NCR and LCR. This instability in salt concentration was due to rapid movement of salt molecules towards UCR and is expected to affect the performance. The possible reason could be uncleaned water surface. Hence, the experimentation was repeated and during this phase, frequent washing of the surface was performed. The new results obtained are presented in the form salinity gradient along the height of the pond in Figure 4b. In general, it is evident from Figure 4b that the variation in salt concentration in any region during the entire experimentation period is within the acceptable limit. Hence, it can be stated that frequent washing of the surface is vital in maintaining stable salinity gradient. The observed variation could be due to variation in the temperature of stored water. Nevertheless, the variation is insignificant. It can be observed from Figure 4, the lower UCR concentration value ensures that the water is close to freshwater which remains stable till the 20th day. This characteristics is also important for enhanced absorption of solar radiation.

CONCLUSION

In order to enhance the thermal performance of micro-size rectangular SSGSP, a slender glass layer along with low cost insulation materials is proposed. The SSGSP with sodium chloride as salt was fabricated in-house and the thermal performance enhancement was tested under the climatic conditions of Coimbatore, India for 20 days. The conclusions drawn from the research is summarized below:

- The proposed system is capable of absorbing about 90% of the available solar radiation.
- From energy storage perspective, the proposed system performs well as the LCR absorbs about 65% of solar radiation
- The tested module is capable of achieving homogeneous temperature distribution over a period of time
- It can be stated that the proposed compact SSGSP seems to be capable of exhibiting good thermal performance
- Regular cleaning of surface is required to avoid instability in the salt concentration so that enhanced thermal performance is ensured
- However, the proposed system is tested for only a limited period of 20 days. Hence, future works may focus on year round experimentation to expose the full potential of the compact system. Further, the frequency of surface washing during the year needs to be determined.

NOMENCLATURE

SGSP	Salinity gradient solar pond
UCR	Upper convective region
NCR	Non-convective region
LCR	Lower convective region
SSGSP	Shallow salt gradient solar pond
HDPE	High density polyethylene
d_L	Depth of LCR, m
d_U	Depth of UCR, m
D_C	Diffusion coefficient, m^2 day^{-1}
dN	Thickness of NCR, m

t Time, secs
C_U Concentration of UCR, g l^{-1}
C_L Concentration of LCR, g l^{-1}
ΔC Change in concentration, g l^{-1}

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [Sathish D], upon reasonable request.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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