Investigation of thermal and electrical performance in a salt gradient solar pond

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Abstract. The performance of a salt gradient solar pond (SGSP) invariably depends on the properties across its various zones. This paper presents an experimental study of salt diffusion, electrical and thermal performance of a trapezoidal-shaped SGSP. The variations of various parameters such as salt concentration, temperature gain, electrical conductivity (EC), thermal conductivity, density, specific heat and total dissolved solids (TDS) are studied across different zones of SGSP. This study reveals that for a given level of solar insolation, the rate of temperature gain within the lower convective heat zone (LCHZ) is high during the initial stages of operation where the salt diffusion rate is slow. Temperature gain of 16.06 ° is observed during a month comprising both rainy and sunny days. Within LCHZ, it is found that thermal conductivity, density and specific heat depend strongly on the salinity and their dependence on the temperature is relatively weaker. However, the effect of temperature on these three parameters is observed in the upper convective cold zone (UCCZ). Additionally, in UCCZ and LCHZ, TDS and EC depend on both salinity and temperature. The present observations are proposed to be useful in applications related to solar pond based desalination and energy generation.

1. Introduction
A salt gradient solar pond (SGSP) is a solar thermal device used to heat water by suppressing the convective heat loss through a density difference created by a halocline effect [1]. Conventionally, an SGSP consists of three zones, namely, the lower convective heat zone (LCHZ), the non-convective insulated zone (NCIZ) and the upper convective cold zone (UCCZ). Solar ponds are widely used for water desalination [2], electricity generation [3], mechanical power generation [4] and many more [5]. In the past, many researchers studied the performance of various types of solar ponds. For instance, Angeli and Leonardi [6] numerically investigated the salt diffusion pattern in an SGSP and results were validated against analytical study. They concluded that the system never attains a true steady-state and the concentration profile oscillates in a periodic manner. A similar computational study considering the contribution of thermo-diffusion was further proposed by them [7]. Kurt et al. [8] highlighted the feasibility of sodium carbonate as a potential salt ingredient for a vertical-walled SGSP. In their study, density and temperature variations across the pond were highlighted. Jaefarzadeh [9] studied the concept of heat extraction from solar pond using heat exchangers. In their study, the thermal efficiency of the pond with 4 m² top area and depth 1.1 m was calculated nearly 10%. Liu et al. [10] presented the characteristics of a trapezoidal SGSP through experimental and numerical
analyses. Results were compared with the rectangular solar pond. For the studied environmental conditions, it was observed that a trapezoidal solar pond offers more temperature (51°C) than a rectangular one. Abdullah et al. [11] experimentally studied the thermal behavior of an SGSP on an annual basis and reported a maximum temperature of 94°C inside the LCHZ. Temperature gain of 1°C inside the LCHZ was observed after every three days. Khalilian [12] presented a lumped capacitance heat transfer model to compute the temperature within the LCHZ of an SGSP. Under their set of conditions, a maximum temperature of 64°C was achieved inside the LCHZ. Recently, Sayer et al. [13] provided analytical expressions to compute salt profiles inside the UCHZ and the LCHZ for vertical and trapezoidal SGSPs. It was highlighted that the salinity of the UCHZ increases, whereas that of the LCHZ decreases with time and ultimately they merge together.

It is found earlier that trapezoidal shape solar ponds yields better performance than rectangular ones. However, for such ponds, the physical behavior of important parameters such as electrical conductivity (EC), thermal conductivity, k, specific heat, \(c_p\), density, \(\rho\) and total dissolved solids (TDS) with salt concentration, \(c\) and temperature, \(T\) seem either missing or studied to a very limited extent. It is well-known that SGSPs can be eminently used for the generation of electric power [3, 14]. Evaluation of temperature, thermal conductivity, \(k\) and specific heat, \(c_p\) can provide useful insights related to such systems. Additionally, the determination of salinity and TDS is useful for desalination applications using solar ponds [2]. Furthermore, the assessment of \(EC\) is important in manufacturing processes based on brine-based electrolyte [15]. Based on the aforesaid reasons, the present study addresses the existing research gaps and studies the physics associated with various parameters in a solar pond. In the following section, the experimental setup along with the methodology is discussed.

2. Experimental setup

For the present analysis, an SGSP of trapezoidal shape (Fig. 1) has been fabricated with dimensions 1×1 m² at its bottom surface and 2×2 m² at the top. Figure 2 depicts the same pond involving two-phase thermosyphon for potential thermoelectric power generation. The total height of the pond is 1 m. The internal surface area of SGSP is covered with black colored Ethylene Propylene Diene Monomer (EPDM). EPDM serves two purposes including more absorption of solar thermal radiation and providing insulation. The outer surface area is covered with glass wool to make it perfectly insulated and reduce further heat loss from the SGSP. As discussed in the previous section that a heat storage SGSP consists of three zones, namely, LCHZ, NCIZ and UCCZ. Solar thermal energy is stored inside the LCHZ as sensible heat, whereas, NCIZ acts as a heat insulator between LCHZ and UCCZ. Therefore, a perfect salinity gradient or halocline within the NCIZ plays a key role to increase the heat storage capacity of LCHZ. In the present work, these layers are made by water diffuser. Salt concentration in the LCHZ under saturated condition was found as 20.04% by volume. In the present experiments, the NCIZ contained eight layers with continuously reducing salt concentration from the bottom layer to the top layer. The UCCZ contained normal water having very low salt concentration (0.38%). Since the heat loss by convection largely affects the heat storage capacity of LCHZ, thus, the present SGSP has been covered with the glass (fixed with the steel structure) at the top in order to prevent heat loss during night. Additionally, glass cover permits smooth operation of SGSP without disturbing the NCIZ during rains. A high quality-reflector is used to increase the temperature of LCHZ. National Instruments (NI) based data acquisition system and K-type thermocouples are used to measure the temperatures inside the three zones of SGSP. A total of fourteen thermocouples (out of which, eight were located inside the NCIZ and three each were placed inside the UCCZ and LCHZ) were placed inside the SGSP through a pipe. Salt concentration, EC, and TDS are measured by Salinometer (Horiba made Model no. LAQUAactEC120), whereas, the solar intensity is measured by solar radiation pyranometer (Sivara Systems and Solutions made Model no. PYRA300). Based on these data, thermal conductivity, density, and specific heat are implicitly determined from appropriate expressions. The experiments are conducted during the period of August-September 2018 in Rupnagar, Punjab (30.9659°N, 76.5230°E).
3. Calculation of parameters and efficiency

At first, thermal efficiency, \( \eta \) of the present SGSP is computed. Thermal efficiency describing the heat storage potential of LCHZ is expressed as,

\[
\eta = \frac{\text{Heat stored in LCHZ}, \ Q_{\text{LCHZ}} \ (J)}{\text{Average solar radiation incident on the SGSP}, \ I_0 A (W) \times \text{time of exposure (s)}} \times 100
\]

where, \( I_0 \ (W/m^2) \) is the radiative flux incident on the pond surface and \( A \ (m^2) \) is the pond’s top surface area. In Eq. (1), \( Q_{\text{LCHZ}} \) is calculated in the following manner,

\[
Q_{\text{LCHZ}} = c_{p_{\text{LCHZ}}} \times A_{\text{LCHZ}} \times H_{\text{LCHZ}} \times \rho_{\text{LCHZ}} \times \Delta T
\]

where, \( c_{p_{\text{LCHZ}}} = 3160 \ J/(kg-K) \) [11] is the specific heat of saturated salt water, \( H_{\text{LCHZ}} = 0.25 \ m \) is the height of the LCHZ and \( \Delta T \) is the temperature rise within it. In Eq. (2), the total surface area of LCHZ is evaluated as,

\[
A_{\text{LCHZ}} = 4 \left[ 2 \left( \frac{1}{2} x H_{\text{LCHZ}} \right) + a H_{\text{LCHZ}} \right]
\]

where, \( a = 1 \ m^2 \) represents the bottom surface area. Based on the data collected under the present set of experimental conditions, thermal efficiency of the present SGSP is calculated 6.06%. For the same top area of 4m², this value is somewhat lesser than 10% as determined in the literature [9]. The reason may be due to the solar radiation available along with some rainy days occurring during the month of September. Next, the density \( \rho \ (kg/m^3) \) of the salt water is computed in the following manner [16],

\[
\rho = \frac{c \rho_s + (100 - c) \rho_w}{100}
\]
where, \( c \) represents the percentage concentration of salt and subscripts indicate the respective components. In Eq. (4), densities of salt and water are considered as \( \rho_s = 2170 \, \text{kg/m}^3 \) [16] and \( \rho_w = 1000 \, \text{kg/m}^3 \) [16]. The salt concentration, \( c \) is determined using salinometer. However, it measures salinity up to a maximum of 10%. So, for measuring higher values than this limit, a 5 ml. sample is taken out from the pond and diluted with 95 ml. of distilled water. Thereafter, the obtained salinity value (salinometer reading) of the diluted solution is multiplied by a factor of 20 to determine the corresponding salt percentage of the strong/actual solution available within the solar pond. Finally, the thermal conductivity, \( k \) of salt water is related to the density according to the following relationship [17],

\[
k = k_w \left( \frac{c_p}{c_{pw}} \right)^{\frac{4}{3}} \left( \frac{\rho}{\rho_w} \right)^{\frac{1}{3}} \left( \frac{m_{sw}}{m} \right)^{\frac{1}{3}}
\]

(5)

where, \( k_w = 0.617 \, \text{W/(m-K)} \) is thermal conductivity of pure water, \( c_{pw} = 4186 \, \text{J/(kg-K)} \) denotes the specific heat of pure water and \( m_{sw} = 0.018 \, \text{kg/mol} \) is the corresponding molecular weight. In Eq. (5), salt water density, \( \rho \) is calculated using Eq. (4) and the specific heat of salt water, \( c_p \) is calculated based on its linear relationship with salinity as indicated below,

\[
\frac{c_p - 4186}{3160 - 4186} = \frac{c}{20.04}
\]

(6)

The molecular weight of salt water, \( m \) is computed in a similar manner as density, and an analogous expression indicated in Eq. (4) has been used for the same. For this, the molecular weight of salt is considered as \( m_s = 0.0584 \, \text{kg/mol} \) [18].

4. Results and discussion

In Fig. 3, the variations of average solar radiative intensity, maximum temperature acquired inside the LCHZ and ambient temperature are studied. Solar radiation during a day invariably depends upon the climate conditions and season. During the entire period of experiments, the minimum and maximum average solar radiation incident on the SGSIP was found 257.4 \( \text{W/m}^2 \) (on cloudy day) and 728.4 \( \text{W/m}^2 \) (on sunny day). The ambient temperature was almost constant during the experiment days and it varied between 30°C and 32°C as indicated in Fig. 3. The variations of maximum temperature gain inside the LCHZ corresponding to average solar radiation incident per day with different ambient conditions are also shown in the figure. Experiments were initiated at LCHZ temperature of 36.02°C that reached up to a maximum of 52.08°C after 28 days with a gain of total 16.06°C. During the initial phase, the rate of temperature gain is higher as compared to later phases of experimental analysis. This is attributed to the fact that the specific heat capacity of water decreases with salinity [19]. During the initial phases of operation, the diffusion of salt is very slow, whereas during the later phases the same is relatively faster. Consequently, for a given level of solar insolation, the specific heat capacity would be lesser during the initial phases that enable the LCHZ to attain higher temperatures than the later phases. The temperature in the UCCZ suddenly falls in the middle due to very low solar radiation during that point of time.

![Figure 3. Transient variation of temperatures and solar radiation](image-url)
Figure 4. Transient variation of salt concentration across SGSP

Figure 4 presents the variation of salt concentration, $c$ across the three zones of SGSP for various days. During the initial stage, saturated salt concentration in the $LCHZ$ was $c = 20.04\%$ and the same within the $UCCZ$ was $0.38\%$. The initial salt concentrations in the eight layers of $NCIZ$ were varied as 18.75%, 14.69%, 10.07%, 10.87%, 9.89%, 8.57%, 7.93%, and 4.92% from bottom to top layer. It is inferred that salinity within the $LCHZ$ gradually decreases, whereas the same within the $UCCZ$ increases with time. However, for a given time, the salinity across these zones remains constant. But, the salt concentrations with the $NCIZ$ yield a mixed trend.

The variation of $EC$ within the present SGSP is shown in Fig. 5. It is envisaged that the profile of $EC$ with $H$ is similar to the salt concentration. Furthermore, $EC$ remained almost constant with time within the $LCHZ$ and the $UCCZ$. This behaviour may be caused due to an increase in the $EC$ with increase in temperature [20] and nearly equal decrease in $EC$ with the decrease in salt concentration [21]. This ultimately cancels the effect of each other. However, for a particular height inside the $NCIZ$, the change of $EC$ from initial state is described by the change in salt concentration (diffusion to the upper layer and infusion from the lower layers) along with the temperature variation. The minimum and the maximum $EC$ were observed as $5.13 \times 10^{-1} \, S/m$ in the $UCCZ$ and $153.4 \times 10^{-1} \, S/m$ in the $LCHZ$.

Figure 5. Transient variation of electrical conductivity across SGSP

The variation of $TDS$ across the height of SGSP is studied in Fig. 6. It is highlighted that in case too, the trend of $TDS$ with $H$ is analogous to the salt concentration and $EC$. This is because $TDS$ is directly proportional to electrical conductivity [22]. Therefore, the same argument relating to Fig. 5 holds good in this case also.
Figure 7 presents the variation of thermal conductivity, $k$ across the height of SGSP, $H$. It is noticed that in this case, $k$ decreases with the depth of the solar pond (i.e. as $H$ attains smaller values) for all days of the month. This is an interesting observation, because at the given temperature range, salt possesses considerably high value of $k$ than water, so, the effective $k$ should intuitively increase. The decrease of effective $k$ is expected due to temperature decrement within the solution caused through endothermic reaction. Due to this, more heat is absorbed within the solution itself and cannot diffuse. However, at a given height, this variation is small. This leads to infer that thermal conductivity, $k$ is
strongly related to the salinity/salt concentration and its dependence on the temperature is relatively weak. A similar effect for density, $\rho$ and specific heat, $c_p$ is envisaged from Fig. 8 and Fig. 9, respectively. The variation of density is obvious. With increase in salinity, more heat is absorbed from the solution due to endothermic reaction. This decreases the temperature and internal degrees of freedom [23]. Consequently, less heat is needed to raise its temperature through a finite value, and specific heat decreases with salinity.

Even though the effect of temperature on thermal conductivity, $k$, density, $\rho$ and specific heat, $c_p$ of salt water is observed smaller than the corresponding effect of salt concentration, but its influence is subjective. On one hand, the values of $k$ and $c_p$ marginally increases with increase in temperature, whereas, on the other hand the value of $\rho$ reduces with rise in temperature. The finding is in line with the previous observations [24]. Due to this reason, within the UCCZ, almost constant values of $k$, $\rho$ and $c_p$ are observed at all time levels. With increase in temperature, the internal degrees of freedom of molecules present in the solution increases, therefore the heat storage capacity of molecules increases [23].

![Figure 9. Transient variation of specific heat across SGSP](image)

### 5. Conclusions

In the present work, thermal and electrical behaviours of a trapezoidal shape salt gradient solar pond (SGSP) are studied. In particular, the variations of temperature, salinity, thermal conductivity, electrical conductivity (EC), density, total dissolved solids (TDS) and specific heat capacity are shown along the height of the pond. Values of salinity, EC, TDS and temperatures are obtained from experiments, whereas, other parameters are computed using their appropriate relationships with the experimental data. For the present set of experimental conditions, the following conclusions are derived from the present work,

- Salinity inside the lower convective heat zone (LCHZ) always decreases, whereas the same within the upper convective cold zone (UCCZ) increases with time. However, inside the non-convective insulated zone (NCIZ) a mixed behavior is observed.
- Under similar incident solar insolation, higher rate of temperature increase during the initial stages of operation is directly related to slower rate of salt diffusion.
- The variations of EC and TDS across the height of SGSP are found similar to salinity. However, these two parameters are also found be affected by temperature, which makes these two parameters to attain nearly constant values in the LCHZ and UCCZ.
- Inside the LCHZ, thermal conductivity, density and specific heat are observed to vary more with salinity and insignificantly with temperature. However, the effect of temperature on these parameters is realized only within the UCCZ.
With increase in salt concentration, thermal conductivity of the solution decreases due to reduced effective conductivity caused by possible endothermic reaction that lowers the temperature of salt solution.

Specific heat of solution within the solar pond is observed to be governed by the internal degrees of freedom offered by salt and temperature variations.

The present results are concluded to be useful in solar pond-assisted water desalination and electric energy generation applications. In the near future, the present work can be extended to study the entropy generation and guidelines may be provided to minimize the irreversibilities within the solar pond-based systems.

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Acknowledgment
Financial support obtained through project EEQ/2016/000073 “Design and Development of a Solar Pond and Biomass Driven Thermoelectric Unit for Domestic Power Generation using Inverse Method” sponsored by Science and Engineering Research Board (SERB), Govt. of India is thankfully acknowledged. Authors are also grateful to IIT Ropar, Punjab for providing other facilities.