THERMAL ANALYSIS OF A MINI SOLAR POND OF SMALL SURFACE AREA WHILE EXTRACTING HEAT FROM LOWER CONVECTIVE LAYER

by

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Solar energy is major renewable energy resource which can potentially fulfill 100% energy demand of the world while releasing no polluting agents to the atmosphere in contrast to the conventional fossil fuels. However, due to its intermittent nature, solar energy requires effective storage of energy for utilizing during the night and cloudy weather. A solar pond is a promising solution because it has its own energy storage which is suitable for low temperature application like building heating and cooling. This paper presents a thermal analysis of a salt gradient solar pond while extracting heat from the lower convective zone. A mathematical model of surface area is developed. Efficiency analysis is performed numerically using a MATLAB code for steady temperature difference of 30 °C as well as 20 °C across the gradient layer for three different pond sizes of depths 1.5 m, 1.0 m, and 0.5 m. The thermal efficiency of first pond of 1.5 m depth varies from around 21% in summer to 11% in winter. Thermal efficiency of solar pond drops significantly by reducing its size and non-convective zone thickness. Annual average efficiencies are 21%, 19%, and 9.5% for the three ponds of 1.5 m, 1.0 m, and 0.5 m depths, respectively. So it is recommended to prefer a pond of 1.5 m over others. However, the efficiency of smaller the pond can be significantly improved by compromising on quality the of thermal energy, efficiency of 0.5 m pond rises to 17% when operating at temperature just 20 °C above ambient, compared with 9.5% for 30 °C above ambient. Solar pond therefore proves to be suitable for effectively utilizing solar energy and can present an effective solution for low temperature energy needs like space heating.

Key words*: mini solar pond, salt gradient, solar energy, thermal performance, energy storage and utilization, sensible heat based storage*

Introduction

With each passing day concerns on energy future of earth are increasing, since the fossil fuels conventionally used to fulfill a major part of energy demand are steadily depleting. Furthermore, their utilization is also polluting and causing global warming by emitting green-

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house gases. Renewable and clean energy conversion technologies are, therefore need of the time. Solar energy, being most abundant renewable energy can potentially fulfill all energy needs of planet earth [1, 2]. Solar energy conversion technologies can be divided into two major categories: *solar thermal* and *solar photovoltaic*. A recent study involved use of a low capacity solar tower for water heating application [3]. Another study investigated the performance of outdoor solar photovoltaic panels for summer conditions [4]. Solar technologies, like most other renewable technologies, are intermittent in nature and therefore need the use of a storage media to bridge the gap between supply and demand during the night and cloudy weather. Salinity gradient solar pond (SGSP) meets this need by providing a built-in energy storage in the lower convective zone (LCZ) of the pond.

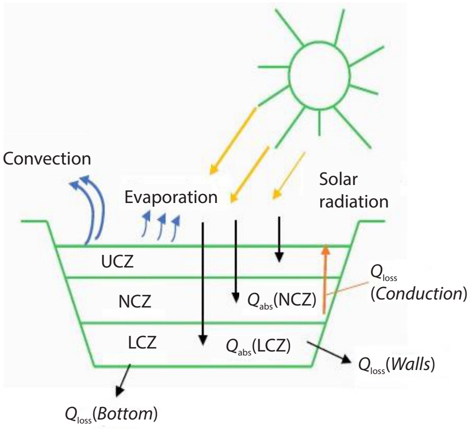


Figure 1. Solar pond

Solar pond consists of three layers, fig. 1, the top most layer is upper convective zone (UCZ), which is a mixed layer allowing convection within the layer as well as with the air above, and so it remains at ambient temperature. The second layer immediately below UCZ is non-convective zone (NCZ), it is unmixed layer and increases in salt concentration as well as density from top to bottom. The NCZ prevents free mixing and convection within itself, so it acts as a barrier to heat transfer, allowing only conduction heat transfer. The temperature of the NCZ, therefore, increases from top to bottom as heat is absorbed at the bottom of the pond in LCZ. The bottom layer is LCZ, it is also mixed layer allowing convection within this layer, so it maintains a uniform temperature, however, its temperature is always elevated from the UCZ and the ambient, this corresponds to the amount of sensible energy stored in LCZ of the pond.

Most of the recent research on solar ponds have been devoted to enhancing stability and thermal performance, mathematical modeling, integrated systems, power production and other applications. Valderrama *et al*. [5] presented construction and gradient control of a solar pond of 50 m^2 surface and 3 m depth, and proposed a diffuser design for mixing salt to the bottom of the pond. They also studied control of pH and turbidity by means of acidification for maintaining transparency for solar radiations. Akrour *et al*. [6] studied the effect of thermo-diffusion on the stability of non-convective layer of the solar pond. Hill and Carr [7] investigated the effect of the porous material on the stability of solar pond and observed that addition of 60% porous material in LCZ may optimize the maximum temperature that can be stored in LCZ if heat extraction ratio, *f*, at bottom of pond is kept fixed at 0.5. However, when *f* is increased above a critical value 0.6, the inclusion of porous material no more stabilizes the pond. Wang *et al*. [8] studied the effect of the addition of coal cinder, a porous material, to the bottom of LCZ on stabilizing LCZ temperature, and concluded that a higher temperature can be achieved in LCZ with coal cinder compared with a pebble. Wang *et al*. [9] also studied the effect of adding a porous material like coal cinder on the salinity diffusion under the LCZ, and found that addition of a porous material in pond bottom can delay upward diffusion of salt, making the requirement of salt replenishment less frequent. Leblance *et al*. [10] studied heat extraction methods in the solar pond for the El Paso and Pyramid Hill solar ponds: heat can be extracted from the LCZ of a solar pond either by placing the heat exchanger inside the LCZ, or by pumping hot brine to the heat exchanger outside the pond. A novel method of extracting heat from NCZ is also presented, this may result in an increase in the efficiency of the solar pond by 55% when compared with the conventional methods. Date *et al*. [11] studied the performance of solar pond under heat extraction from LCZ alone and heat extraction from both LCZ and NCZ together. They found that average annual efficiency increases by about 47% if heat is extracted from LCZ and NCZ together compared to that from LCZ alone. Karakilcik *et al*. [12] conducted an assessment of solar pond performance of a small rectangular solar pond with and without shading and found that the storage efficiency of the solar pond can be increased if the effect of shading area is eliminated. Dehghan *et al*. [13] investigated energy and exergy performance of solar pond for rectangular and circular cross-sections, for both NCZ and LCZ and found that the performance of circular pond is superior to that compared with rectangular pond. Liu, *et al*. [14] studied a mini solar pond of trapezoidal shape (top and bottom) and found that trapezoidal shape helps decrease losses from LCZ and increases the storage temperature of solar pond. Sogukpinar *et al.* [15] studied performance comparison of above ground and below ground solar pond and indicated that below ground solar ponds, if designed to be insulated with an appropriate insulating material, are more efficient compared to above ground solar ponds. Assari *et al*. [16] studied use the of phase change material (PCM) in LCZ, and found that PCM decreases the thermal efficiency of solar pond by reducing temperature of LCZ, however, if a certain application requires less temperature difference and more stable temperature, use of PCM is beneficial. Ziapour *et al.* [17] proposed that use of two-phase heat transfer by thermosyphon as well as heat exchanger to extract heat from solar pond would reduce the size requirement of heat exchanger compared with single-phase mode of heat transfer. Alcaraz *et al*. [18] studied use the of an in-pound heat exchanger installed laterally on side walls of pond, and found that this type of arrangement was more efficient than using either a bottom heat exchanger alone or using both heat exchangers simultaneously. Bozkurt and Karakilcik [19] investigated performance of solar pond integrated with flat plate collectors and found that the efficiency of integrated system increased from 21.3% to 26.5% when number of collectors were increased from 1 to 4.

Solar ponds can be utilized for applications like heating and cooling of buildings, refrigeration, power production, industrial process heat, and desalination [20, 21]. Singh *et al.* [22] studied the generation of low scale electric power from a solar pond using 16 thermoelectric generators. Date and Akbarzadeh [23] presented a theoretical prediction of using the solar pond for running a thermal pump for a solar pond located on a salt form at Pyramid Hill in North Victoria. Tundee *et al*. [24] studied electric power generation from the solar pond while drawing heat from LCZ using thermosyphon and delivering it to thermoelectric generators. Kanan *et al*. [25] studied the use of solar pond for providing energy to an absorption chiller for air conditioning. They used MATLAB model for a solar pond with TRANSYS simulation to predict the system performance. It was found that a solar pond of the area of approximately 400 m^2 can provide necessary cooling to a house of 125 m^2 floor area. Appadurai and Velmurugan [26] investigated the performance of fin-type single basin solar still with the fin-type mini solar pound and estimated the water collection gain to be 50%. Ding *et al*. [27] studied electric generation from the solar pond using a plate type power generation unit containing thermoelectric cells. The system was capable of producing 35.9 W power for hot water flow rate of 5.1 litre per minute at 81 °C. Ding *et al*. [28] proposed a passive thermoelectric generation unit for use with solar pond, to eliminate the need for a pump and involve no moving parts. Elsarrag *et al*. [29] studied liquid desiccant evaporative cooling system powered by a solar pond.

All these studies are concerned with different aspects of solar ponds for different configuration and sizes [5-29]. A study on optimizing the performance of a mini-solar pond, however, has not been conducted so far. A mini solar pond owes its importance because it may be portable and can be constructed on roof-tops. Since ground space may not be available in most cities or is costly, the further large building may be a hurdle to sunlight reaching the ground, a mini-solar pond can be the best option for such scenarios. The current study presents the effect of design parameters (sizes, the thickness of different layers) on thermal performance of mini-solar ponds while extracting heat from LCZ.

Mathematical model

A recent study on mathematical modeling has involved successive use of more accurate but complex equations, and including yet more complicated but less important factors affecting solar pond performance. Bernad *et al.* [30] developed a simulation tool for predicting solar pond performance and validated the results with experimental data obtained from operating a pilot plant in Martorell during 2009-2011. Giestas *et al*. [31] presented a numerical model for predicting dynamics of the solar pond in terms of velocity, pressure, temperature, and salt concentration using Navier-Stokes equation for an incompressible fluid and one-advection diffusion equations for temperature and salt concentration. Monjezi and Campbell [32] developed a comprehensive model of the solar pond to predict temperature distribution of solar pond under Mediterranean conditions. The model incorporates a finite difference method but treats LCZ as one-layer with uniform temperature. It, in addition to heat losses from the surface of the pond by convection and evaporation, also accounts the effect of makeup freshwater addition to the pond surface. Sayer *et al*. [33] presented a new model for heat transfer in the solar pond, writing non-linear first order differential equations for the energy balance of three different layers of solar pond and solving the model using the MATLAB ode45 function.

All these models of solar pond require rigorous simulation lasting days and weeks, using state-of-the-art computing technology. The use of these models, however, is not justified for a small project like a mini solar pond, because the cost of computing alone will supersede the cost of the whole project. Furthermore, many parameters affecting performance of larger solar ponds are easily managed in smaller ones, like side walls and bottom may be well insulated, surface evaporation may be controlled by installing transparent cover, and sunlight may be made to fall vertically on the pond surface, thereby eliminating the need to consider heat loss to surroundings, effect of surface evaporation and raindrops, angular incidence of sunlight, and effects of shading and sunny area ratios. Therefore, a simpler model developed to account other major factors like density and specific heat of saline water, transmittance and absorption of radiation with depth, and conductive losses from NCZ can be sufficient to account the thermal performance of a mini solar pond.

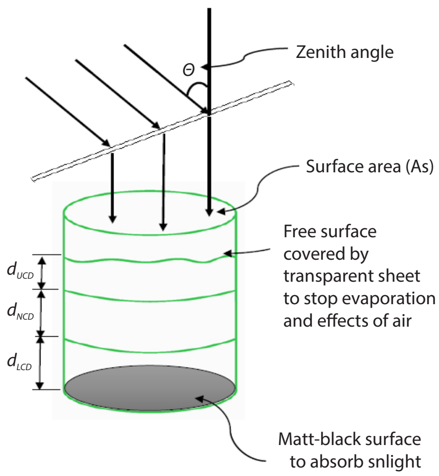


Figure 2. Cylindrical model solar pond with different storage zones

The solar pond selected for current investigation is the one constructed above ground in cylindrical shape having a circular surface area of 2 m^2 and depth varying as 0.5 m, 1.0 m, and 1.5 m and for three models under investigation, fig. 2. It is assumed that solar radiations are made to incident vertically on the pond's surface, which can be achieved practically using a reflector with an automatic motor to change position of reflector as per sunlight direction. This simplification eliminates effect of shading due to side walls. The sunlight gets partially absorbed, scattered, reflected and transmitted from different layers of brine water in the pond and only a fraction of it finally reaches the storage zone where it gets completely absorbed due to presence of absorbing media (mat-black surface) at the bottom. The following expression by Bryant and Colbeck [see in 34] may be used to find solar radiation at any depthfrom the pond surface:

$$I_x = I_o \left[0.36 - 0.08 \ln\left(\frac{x}{\cos\theta} \right) \right] = I_o\, h \tag{1}$$

where I_o is the solar radiation incident upon surface of pond, h – the fraction of radiation reaching depth x, and θ – the angle of incidence of solar radiations.

For a pond of smaller size, side walls and bottom of the pond may be effectively insulated using 50-100 mm thickness of glass wool or some other material. This would result in negligible heat loss from side walls and the bottom of pond, as found in a previous study, the fraction of heat losses from insulated walls are as small as 0.3% [30]. A stable density gradient in NCZ would eliminate chances of convection from storage zone. The only possibility of heat loss from the LCZ, also called storage zone to the UCZ is by conduction through the gradient layer, NCZ. The NCZ, therefore acts as a barrier to heat loss from the bottom of the pond. Due to available temperature difference between storage zone and ambient, a certain amount of energy may always be extracted as useful heat for desired application. Although recent development in solar pond technology have allowed extraction of heat from gradient layer enhancing thermal efficiency, however, effect of this method on performance and stability of a mini-solar pond is not investigated yet. It is therefore considered for the current discussion that heat may be extracted from LCZ alone.

Energy balance equation may, therefore, be written for LCZ of the solar pond:

Solar energy reaching LCZ = energy stored as sensible heat +
+ heat loss through the NCZ + useful energy extracted:

$$Q_{\text{in}} = Q_{\text{sto}} + Q_l + Q_{\text{ext}} \tag{2}$$

All terms of this equation may further be expressed in terms of measurable quantities for a time:

$$Q_{\text{in}} = h A_s I_o \Delta t \tag{3}$$

$$Q_{\text{sto}} = m c_p \left(T_{t+\Delta t} - T_t \right) \tag{4}$$

$$Q_l = \frac{k A_s \left(T_{t+\Delta t} - T_a \right)}{d_{\text{NCZ}} \Delta t} \tag{5}$$

where $T_{t+\Delta T}$ [°C] is the temperature of the LCZ at time $T_{t+\Delta T}$, T_t [°C] – the temperature of LCZ at time t, T_a [°C] – the ambient temperature/temperature of UCZ, h – the fraction of radiation reaching the LCZ, m [kg] – the mass of brine water in LCZ, c_p [Jkg^{-1}°C^{-1}] – the specific heat of brine in LCZ, k [Wm^{-2}°C^{-1}] – the average thermal conductivity of NCZ, A_s [m^2] – the surface area of pond, and d_{NCZ} [m]– thickness of NCZ.

The temperature, $T_{t+\Delta T}$, of the LCZ after a time Δt may then be calculated provided initial temperature, T_t, is known. In the current study, solar pond performance is analysed under heat extraction mode. Equations (1)-(5) are used to perform a numerical calculation over a year period using MATLAB software. Temperature difference across the NCZ is maintained at a minimum of 30 °C, extracting excess heat available. Efficiency is thus calculated based on this heat extraction and total incident solar energy on pond surface. The effect on yearly average efficiency of varying this fixed temperature difference across NCZ from 30 °C to 20 °C , is also studied.

Studies show that temperature in the UCZ remains essentially the same as the ambient temperature while that in the gradient zone or NCZ increases nearly linearly downwards until it reaches a value equal to that of storage zone or LCZ at the interface with LCZ. The temperature of LCZ is also uniform throughout due to convection currents [10]. The average temperature of NCZ, T_{NCZ}, at any instant may therefore be calculated by:

$$T_{\mathrm{NCZ}} = \frac{\left(T_a + T_{\mathrm{LCZ}}\right)}{2} \tag{6}$$

The average heat energy stored in storage zone or LCZ, available for the useful purpose, may then be expressed:

$$Q_{\mathrm{sto}}\left(\mathrm{LCZ}\right) = mc_p\left(T_{\mathrm{LCZ}} - T_a\right) \tag{7}$$

Methodology

The motivation for writing this paper is to investigate the performance of a mini solar pond under different design parameters, for real weather conditions. For this purpose, a MATLAB code has been developed to account the transient behaviour of the solar pond, based on energy balance equations discussed in preceding section. The theoretical study is divided into two categories: firstly, investigating solar pond performance under heat extraction mode for a fixed temperature difference of 30 °C across NCZ and secondly varying the temperature difference from 30 °C to 20 °C and observing the effect on the thermal performance of the pond. Three different sizes of the solar pond have been taken, tab. 1, and for each pond size, four different schemes are considered, to investigate the effect of design parameters (sizes of UCZ, NCZ, and LCZ) on pond's performance. Actual weather data *i. e.* solar insolation and ambient conditions, tab. 2, of Taxila, a city of Upper Punjab in Pakistan, have been used to carry out simulations for the proposed solar pond.

Table 1. Models of solar pond under investigation

Solar pond	Total depth	UCZ thickness	NCZ thickness [m] / LCZ thickness [m]
Model 1	1.5	0.3	0.6, 0.7, 0.8, 0.9 / 0.6, 0.5, 0.4, 0.3
Model 2	1.0	0.15	0.35, 0.45, 0.55, 0.65 / 0.5, 0.4, 0.3, 0.2
Model 3	0.5	0.075	0.15, 0.2, 0.25, 0.3 / 0.275, 0.225, 0.175, 0.125

Table 2. Monthly average weather data of Taxila city
(latitude 33.737 °N, longitude 72.799 °E, altitude 508 m above see level)

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
I_o [Wm^{-2}]	112	126	190	231	275	273	248	228	227	193	150	107	197
T_a [°C]	10.2	13.5	18.9	24.3	29.6	31.3	30.1	29.0	27.1	22.5	16.0	11.7	22.0

Validation of mathematical model

Validation of the current model has been performed by comparing with experimental solar pond developed by Karakilcik *et al*. [35], a mathematical model developed by Sogukpinar *et al*. [15] and another pond developed by Date *et al*. [11]. Although the surface areas are different, the depth of all these ponds is 1.5 m, furthermore, solar insolation is similar for these climates, and therefore similar performance is expected. Since, the climate in Melbourne, is offset by around half year – midwinter in Melbourne is in June while that in Taxila is in December – for being in opposite hemispheres, therefore Month 1 in fig. 3 would represent July for Melbourne and January for Taxila, to ensure convenience in comparing the performance of both ponds. It can be seen from figs. 3 and 4, that the average monthly efficiencies for the current mathematical model closely match with those of published results [11, 15, 35], thereby validating the model and giving confidence for further application.

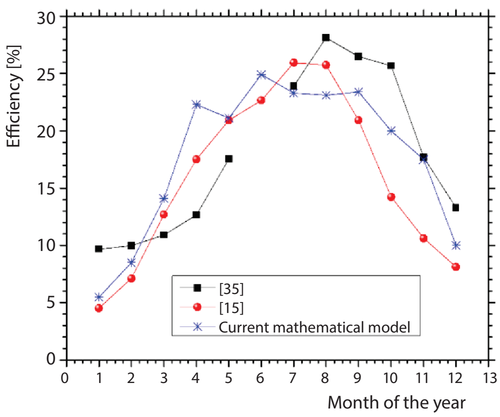


Figure 3. Comparison of results with experimental pond [35], and another mathematical model [15]

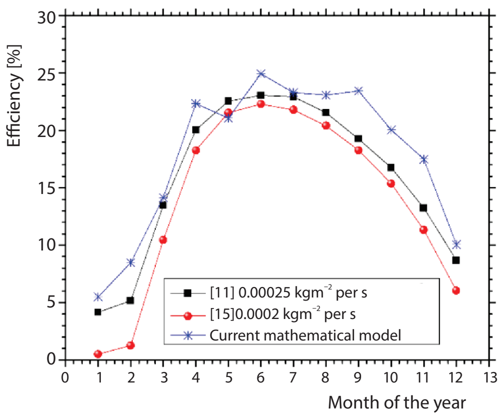


Figure 4. Comparison of results with experimental pond [11], for heat extraction at different flow rates of heat transfer fluid

Results and discussion

The three models of the solar pond, as discussed in preceding section on methodology, have been investigated in terms of thermal performance over one year of the operational period. Actual weather data (average of ten years' period 2000 to 2009) of Taxila city as summarized in tab. 2 taken by Meteonorm (website) have been used in this analysis. To study various phenomenon related to solar pond, the obtained plots are divided in three sets: first the history of temperatures over one year period, second energies involved and efficiency, and third comparison between average annual efficiencies between different cases of heat extraction.

Temperature history of solar ponds

The temperature history includes a transient variation of storage zone temperature along with local ambient temperature. Figures 5(a)-5(c), each represents different pond models of total depths 1.5 m, 1.0 m, and 0,5 m, respectively. Each figure further contains four curves, each for different configuration of thicknesses of NCZ and LCZ, fig. 5(a) for example consists of LCZ temperature history of four different ponds with NCZ thicknesses 0.8 m, 0.9 m, 1.0 m, and 1.1 m, each represented by different colours.

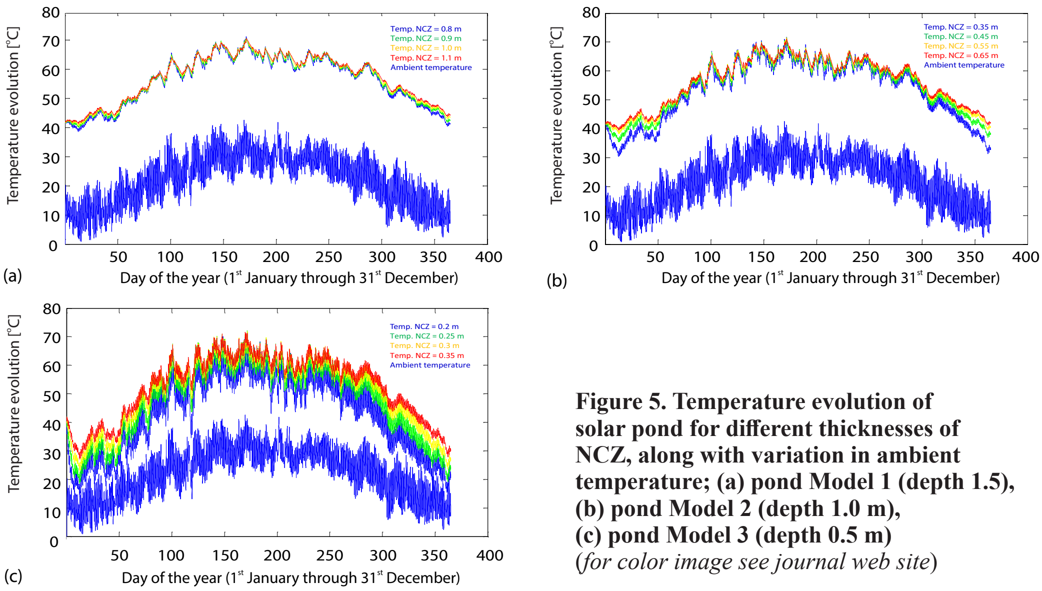


Figure 5. Temperature evolution of solar pond for different thicknesses of NCZ, along with variation in ambient temperature; (a) pond Model 1 (depth 1.5), (b) pond Model 2 (depth 1.0 m), (c) pond Model 3 (depth 0.5 m)
(*for color image see journal web site*)

Solar ponds operate under transient environmental conditions, in which solar insolation and ambient temperature play a major role. Solar insolation corresponds to the amount of energy available to be captured by the solar pond, while ambient temperature determines a datum for sensible energy stored in the solar pond as well as a sink for losses of energy from LCZ. In this work, a limit is put on minimum quality of energy being extracted from the solar pond *i. e*. heat extracted must be at 30 °C above ambient temperature. This is possible during the clear day because more solar energy is being added to the solar pond, which is available for being extracted by a heat exchanger. While during the night, since no more energy is added to the pond, it would be logical to think that any thermal energy extracted during the night would compromise the minimum quality of energy because energy extraction will result in a decrease in temperature of LCZ of the solar pond. However, the case is different, during night ambient temperature also drops and therefore more energy can be extracted without compromising the minimum quality of energy. It can be seen clearly in figs. 5(a)-5(c), that there are several local peaks and declines in temperatures of LCZ, which also correspond closely to the peaks and drops in ambient temperature. During daytime, the temperature is rising until reaching a maximum near noon, while temperature starts dropping in the evening until it reaches a minimum at midnight. For cloudy days, the temperature of the pond would not rise following the night, rather will continue to drop during the day, and because of losses even if no heat is extracted from the pond. This is represented by the extended decline in temperature curves. Similarly, clear sky and hot weather for consecutive days would result in an extended rise in temperature of the pond. It can also be observed from all figs. 5(a)-5(c), that rise and fall in ambient temperature during day and night are sharper, while the solar pond temperature is much more stable compared with that, giving reliability for long term storage of thermal energy.

It can also be seen that the temperature curve for greater NCZ thickness is always above others with lower thicknesses of NCZ. This is because more the thickness of NCZ, less will be conduction heat loss through NCZ, and greater temperature can be stabilized in LCZ under similar conditions. However, the decrease in stabilized temperature with decrease in NCZ thickness is more prominent for the smaller pond, fig. 5(b) and yet more significant for the smallest pond, fig. 5(b), because in small size pond any change in the size of layers casts greater effect on pond's performance. Furthermore, the solar pond will smaller size also faces greater fluctuations in temperature evolution of LCZ over the year. This may be attributed to smaller thermal mass and a smaller non-convective barrier to heat loss.

Energy and efficiency study

Figures 6-8, represent the thermal performance of solar pond Model 1, 2, and 3, respectively. Each figure has three parts: (a) contain monthly average efficiency of solar ponds, (b) contain monthly average values of heat losses and energy extracted per day, and (c) contains annual average values of incident solar energy, energy extracted and losses. A view of the plots in any of figs. 6(b), 7(b), and 8(b) reveals that for a given pond model, greater energy can be extracted from the solar pond in summer (4-6 MJ/m^2 per day in summer compared with only 1-2 MJ/m^2 per day for a pond of 1.5 m depth), this is because of greater amount of solar energy getting absorbed in the pond compared with winter. However, less effect on losses occurs from summer to winter, this is because losses in solar pond are majorly because of conduction heat loss through NCZ and provided nearly same temperature difference of 30 °C is maintained between LCZ and UCZ, these losses remain nearly same.

This results in greater extraction efficiency of solar pond in summer (25% for Mode l) compared with smaller efficiency in winter (10% for Model l). The average monthly efficiencies of three ponds can be observed in figs. 6(a)-8(a). By comparison of graphs 6(b), 7(b), and 8(b), it can be also be observed that losses significantly increase with decrease in pond depth, 2-3 MJ/m^2 per day for a pond of depth 1.5 m , to 3-5 MJ/m^2 per day, and 6-10 MJ/m^2 per day for ponds of depth 1.0 m, and 0.5 m, respectively, whereas reverse trend can be observed for values

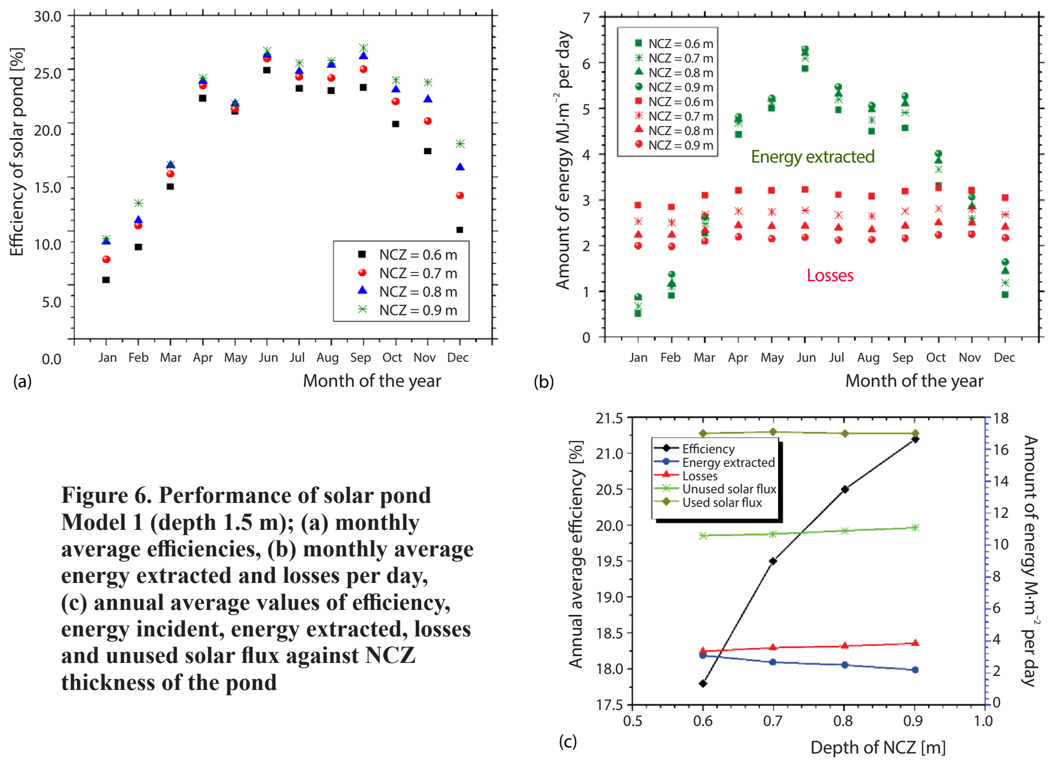
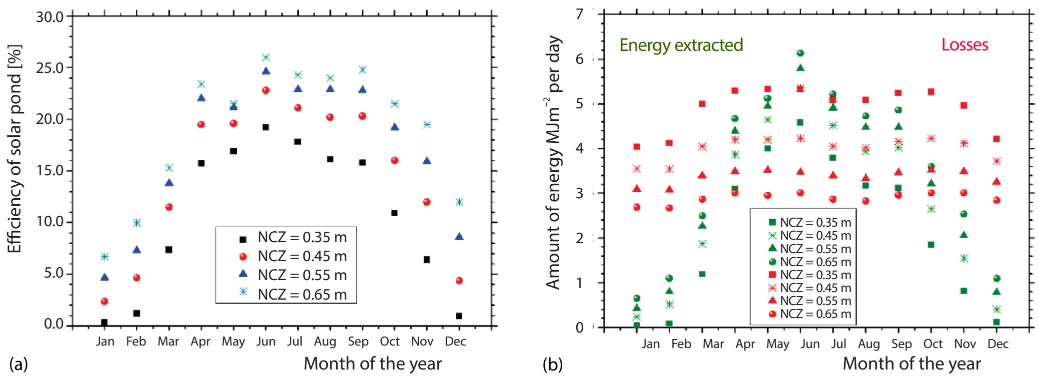


Figure 6. Performance of solar pond Model 1 (depth 1.5 m); (a) monthly average efficiencies, (b) monthly average energy extracted and losses per day, (c) annual average values of efficiency, energy incident, energy extracted, losses and unused solar flux against NCZ thickness of the pond



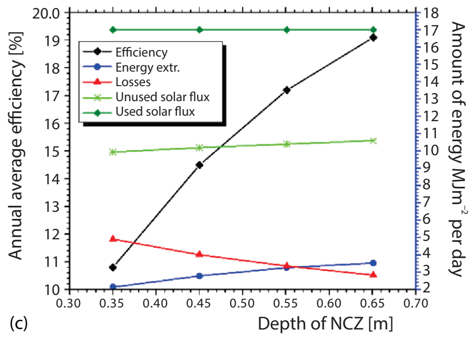


Figure 7. Performance of solar pond Model 2 (depth 1.0 m); (a) monthly average efficiencies, (b) monthly average energy extracted and losses per day, (c) annual average values of efficiency, energy incident, energy extracted, losses and unused solar flux against NCZ thickness of the pond

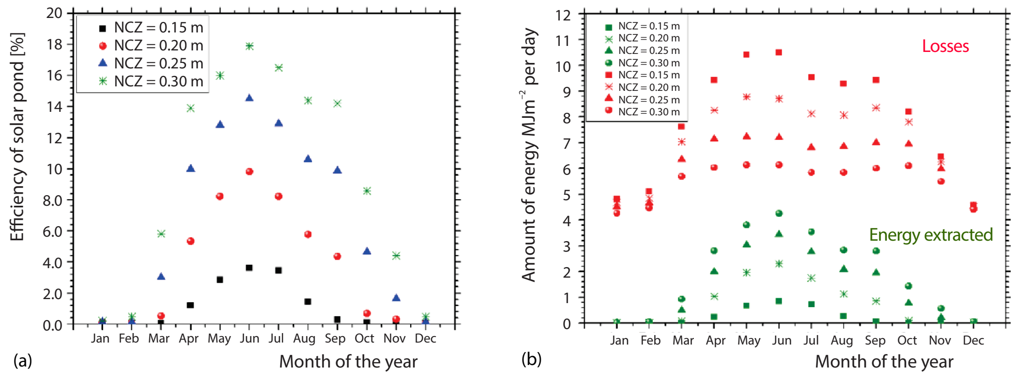
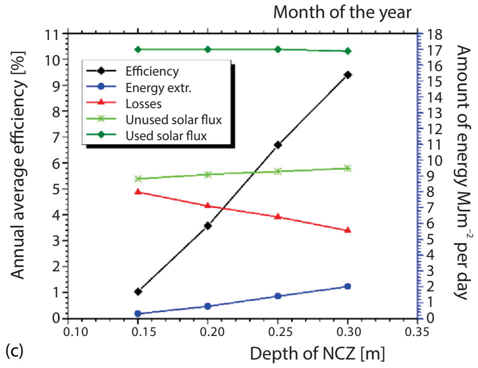


Figure 8. Performance of solar pond Model 3 (depth 0.5 m); (a) monthly average efficiencies, (b) monthly average energy extracted and losses per day, (c) annual average values of efficiency, energy incident, energy extracted, losses and unused solar flux against NCZ thickness of the pond



of energy extracted. In other words, efficiency significantly drops while moving from pond of 1.5 m depth to smaller ones. It is therefore recommended to use a solar pond of greater depth and a depth of 1.5 m can clearly be preferred over either 1.0 m or 0.5. However, increasing the depth of a mini-solar pond even further will require consideration of other factors. Firstly, with increase in depth, solar radiation incident on the pond are less likely to reach the LCZ and get absorbed in LCZ, so increasing depth can be of no more benefit. Secondly, increased depth is associated with greater pressure of water body on the rooftop or the place where it is placed and would require a stronger structure and foundation. It is therefore necessary to consider these two factors before selecting a pond of more depth.

Annual average efficiencies of the solar pond also vary significantly with change in pond depth, as well as the depth of NCZ, figs. 6(c)-8(c). For a pond of 1.5 m, annual average efficiency is 21% with NCZ thickness of 0.9 m, while this values drops to near 17.5% if NCZ thickness decreases to 0.6 m. For ponds of 1.0 m and 0.5 m depth, these values vary from 19% to 11%, and 9.5% to 1% for corresponding decrease in NCZ thickness from 0.65 m to 0.35 m and 0.3 m to 0.15 m. It is obvious that decrease in NCZ thickness also has detrimental effect on solar pond performance. Therefore, a greater NCZ thickness is desirable, however, this would mean decreasing the LCZ thickness, and a corresponding decrease in thermal energy storage capacity of the pond, for example a 50% drop in energy storage capacity would occur for change in LCZ thickness from 0.6 m to 0.3 m. But this matter can be handled with another technique, by placing a certain amount of PCM of suitable phase change temperature. A previous study on use of PCM the at bottom of solar pond has resulted in decrease in efficiency, but longer availability of thermal energy with less change in temperature because PCM can store much greater energy during phase change, compared with sensible energy [16]. The use of PCM in solar pond, can therefore provide a reserve of thermal energy for extended cloudy weathers. Furthermore, drop in efficiency of solar pond the due to PCM needs further investigation as far as mini solar the pond is concerned. Especially with a pond of smaller depth, like, it is possible that use of PCM may result in an enhancement of thermal efficiency of the pond due to two reasons. Firstly, PCM will restrict rise of temperature of solar pond above a certain value, this will help decrease losses, which otherwise may occur at higher rate a because of sharp rise in LCZ temperature of small thermal mass during the sunlight period. Secondly, the energy available in PCM can be utilized in addition to the sensible energy of LCZ.

Comparison of performance for heat extraction at different temperatures

The previous analysis is performed while trying to keep the storage zone temperature at least 30 °C elevated from ambient temperature. It is also important to discuss the effect of varying this temperature level to a lesser value (say 20 °C), especially for the pond of smaller depth, for which, lesser NCZ thickness results in greater heat losses, since these heat losses may be reduced by having a smaller temperature difference between LCZ and ambient. Figure 9 shows a comparison of two different levels of temperature difference 30 °C and 20 °C across the NCZ. This has result in a significant rise in thermal

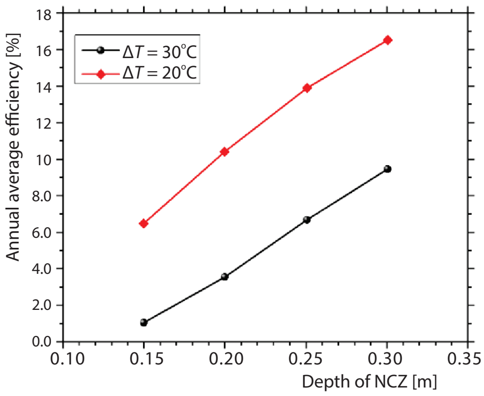


Figure 9. Comparison of efficiencies for 20 °C and 30 °C temperature difference across gradient zone (NCZ) for a pond of depth 0.5 m

efficiency of the solar pond of pond of thickness 0.5 m, making it at least double. Although this decrease in desired temperature has resulted in solar pond to work at greater efficiency, however, this is at cost of reduced quality of energy which now may be used for less useful purpose, for example for partial space heating only, adding some other energy source for fulfilling the complete requirement.

Conclusion

A theoretical model of a mini solar pond is presented. Numerical simulation is performed to evaluate the thermal performance of solar pond in heat extraction mode using actual climatic conditions of Taxila, Pakistan. Three pond models having a constant surface area of 2 m^2, but depths of 0.5 m, 1.0 m, and 1.5 m were investigated. The thermal performance of mini solar pond is affect by its size, especially the NCZ thickness. Although increasing NCZ thickness enhances thermal efficiency, however it also reduces thermal energy storage capacity of solar pond by reducing storage zone thickness. This drop in capacity can be handled by introducing PCM in LCZ which can provide greater energy storage density, however the, performance of mini solar pond while using PCM still needs to be investigated in future work. Thermal performance of smaller ponds of 0.5 m to 1.0 m depth may be significantly enhanced by extracting heat at a lower temperature, however this would limit the application of utilizing that heat.

Nomenclature

A_s – surface area, [m^2]
c_p – specific heat, [Jkg^{-1}K^{-1}]
d – thickness of different zones pond, [m]
h – fraction of radiation
I_x – solar radiation at depth of x, [Wm^{-2}]
I_o – incident solar radiation, [Wm^{-2}]
k – average thermal conductivity, [Jkg^{-1}K^{-1}]
$Q_{\rm in}$ – total solar energy, [Jkg^{-1}K^{-1}]
$Q_{\rm sto}$ – store solar energy, [Jkg^{-1}K^{-1}]
$Q_{\rm l}$ – energy loss, [Jkg^{-1}K^{-1}]
$Q_{\rm ext}$ – energy extracted, [Jkg^{-1}K^{-1}]
$T_{\rm a}$ – ambient temperature, [°C]
T_t – initial temperature of different zones at time t, [°C]
$T_{t+\Delta t}$ – temperature of different zones at after Δt, [°C]
t – time, [s]

Greek symbol

θ – angle of incidence, [°]

Acronyms

SGSP – salinity gradient solar pond
UCZ – upper convective zone
NCZ – non-convective zone
LCZ – lower convective zone

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