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Research Article

Optimization of thermal insulation of a small-scale experimental solar pond

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Abstract

A small-scale experimental salinity-gradient solar pond, which will be utilized for the research and development in harnessing solar energy for desalination of seawater and generation of electricity, has been constructed. The pond has effective length, width and depth of 3.0 m, 2.0 m and 2.0 m, respectively, covering a volume capacity of 12.0 m^3. Thermal insulation plays a major role for the successful operation of a salinity-gradient solar pond, especially when the dimensions of the pond are relatively small. The construction details of the solar pond, with particular attention to the methodologies adapted for the thermal insulation, are reported in the present work. The expected total rate of heat loss due to conduction through the thermally insulated boundary walls, assuming a bottom temperature of 90 ºC, has been calculated and found to be 106.3 W. Contribution from the bottom convective zone itself to this total rate of heat loss is 69 W, which corresponds to 65% of the total value. Based on this rate, the estimated temperature drop during the period with no solar radiation present in a typical day is only 0.3 ºC. With such a small temperature drop, it is possible to extract the thermal energy stored in the bottom convective zone during the day time, continuously, while maintaining the stability of the solar pond.

Keywords; Salinity-gradient solar pond, thermal insulation, desalination

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1. INTRODUCTION

Usage of solar ponds as a cost-effective method of collecting and storing solar energy at large scale has been an exciting field, particularly in improving renewable energy sources as a potential solution to meet the ever increasing energy demand of mankind. A pond filled with high-density salt water can develop itself eventually a salinity gradient when fresh water is added from top, either artificially or by rain, and behaves as a salinity-gradient solar pond.

A pioneering study of natural solar-heated lakes was reported in 1902 by Kalecsinsky[1]. However, studies of practical utilization of solar energy using solar ponds were first reported in Israel[2-4], several decades after the Kalecsinsky's paper. Research work on man-made solar ponds was reported in Israel where magnesium chloride salinity gradients were developed to retain heat. These results showed collection efficiencies of around 25 percent with bottom temperatures reaching almost boiling temperature[5]. Parameters involving the operation of a solar pond have to be optimized to achieve a maximum possible temperature in the bottom convective region of the pond. Close to boiling temperatures have been observed at the bottom region in several experimental ponds, and in fact one pond was reported as having its bottom temperature approaching the boiling point[6].

The present work is to report the results of methodologies adapted for the optimization of thermal insulation of a small-scale experimental tank for solar pond studies, with special endeavors to maximize bottom temperatures close to boiling point. Thermal performance of a natural-field solar pond depends heavily on environmental and physical conditions such as solar insolation at the site, rain and wind, density profile of brine, wall conditions and pond dimensions etc., which have to be optimized to achieve substantially high bottom temperatures. Thermal conductivity of the wall materials of a pond is an important parameter that varies according to soil type such as hard rock, clay, sand, mud, etc. With the optimization of these conditions, man-made solar ponds can generate higher bottom temperatures, and thus values even closer to the boiling point are possible. The ratio of wall area to brine volume is substantially higher in artificial small-scale solar ponds than that of naturally existing large-area solar ponds, and therefore, having walls with low thermal conductivity is an essential requirement to achieve higher thermal energy storage capacities, for the former case. Details of the construction of a thermally-insulated small-scale research solar pond which has been built at the Kelaniya University are discussed in the present work.

2. CONSTRUCTION DETAILS OF THE EXPERIMENTAL SOLAR POND

The tank was constructed with thermally insulated walls to investigate the performance of a small-scale experimental salinity-gradient solar pond, and is specially aimed at reaching the bottom temperatures close to the boiling point. The base of the tank is a concrete slab having a thickness of 0.125 m with a surface area of 3.65×3.25 m^2. The surrounding masonry walls have been constructed with a thickness of 0.225 m on this base up to a height of 2.1 m. A strong cement plaster was applied on the inner surface of tank, which was then covered with a commercially available water proofing material (Multilac Supreme Life Water Proofing Sealer) to avoid any possible water leakages through the walls. It was observed in a laboratory trial that a 0.1 m thick Styrofoam layer could retain a temperature difference of 60 ^{o}C between the two sides of the layer. These results reveal that a 0.1 m thick Styrofoam layer is good enough to maintain the bottom region close to boiling temperatures, above the outside ambient temperature of about 27 ^{o}C.

As a measure of thermal insulation, the inner surface of pond was covered with Styrofoam sheets having a thickness of 0.1 m. Two 1 mm thick layers of fiberglass coating were applied on top of the Styrofoam sheets to avoid contact of brine with Styrofoam. Inner surface of the base wall was strengthened by three such fiberglass layers to make sure that there will be no any leakages at a relatively higher liquid pressure at the bottom of the pond. Cross sections of the vertical surrounding walls and the horizontal base are shown in Figure 1. Finally, the inside effective length, width and height of the tank turned out to be 3.0 m, 2.0 m and 2.0 m, respectively, thus covering a volume capacity of 12.0 m^3. This tank will be utilized as a thermally-insulated small-scale experimental solar pond for research purposes. These include studies of theoretical aspects of salinity-gradient solar ponds, as well as practical applications such as desalination of seawater and electric power generation.

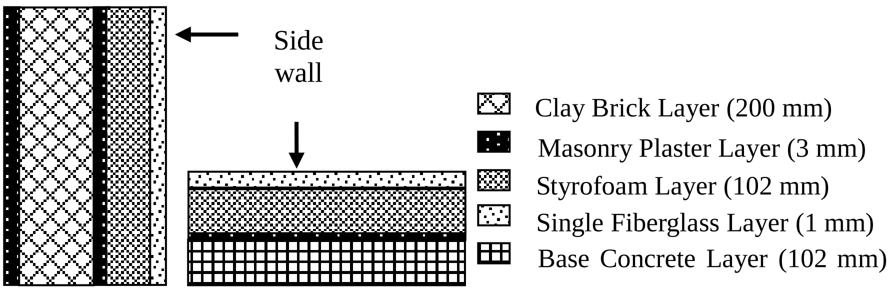

Figure 1: Cross sections of the vertical surrounding wall and the horizontal base wall of the thermally insulated pond. Thickness of each layer is given in parentheses.

3. THERMAL INSULATION PROCEDURE

Heat energy transmitted perpendicularly through a unit area of a composite wall structure of several media per unit time under a unit temperature difference between both sides of the wall is known as the coefficient of thermal transmission which is by convention taken as the *U* value or the overall heat transfer coefficient. The *U* value of a particular wall of composite structure is given by the reciprocal of the total thermal resistance or the *R* value of the wall. Consequently, the walls with high *R* values consist of high thermal resistance for the heat flow. Thus, high *R* values are desired for the low-thermal conductivity boundary walls of a solar pond, in order to improve retaining capability of thermal energy entrapped in the bottom convective zone for an extended period of time.

Thermal resistance of a material layer is equal to the ratio between the thickness of that layer and the product of cross sectional area and thermal conductivity of the material. The newly constructed model solar pond has two types of boundaries, namely the horizontal base at the bottom and the vertical surrounding walls, thus yielding two different *U* values. *U* value of the surrounding vertical walls is calculated from the expression,

$$U_{vertical\,walls} = \frac{1}{R^{total}_{vertical\,walls}} = \frac{1}{\sum_{i=1}^{4} R_i} = \left\{\sum_{i=1}^{4}\frac{t_i}{k_i A_i}\right\}^{-1} = A_{vertical}\left\{\sum_{i=1}^{4}\frac{t_i}{k_i}\right\}^{-1} \quad (1)$$

The index *I* takes the integer values from 1 to 5 for the corresponding five layers which constitute the vertical surrounding walls, and subsequently R_i represents the thermal resistance of i^{th} layer. Similarly, k_i and t_i denote the thermal conductivity and the thickness of i^{th} layer, respectively. The $A_{vertical}$ is considered as the total liquid-touching inner surface area of the vertical walls of the pond. Similarly, *U* value of the horizontal base is calculated using the expression,

$$U_{basewall} = \frac{1}{R^{total}_{basewall}} = \frac{1}{\sum_{j=1}^{4} R_j} = \left\{\sum_{j=1}^{4}\frac{t_j}{k_j A_j}\right\}^{-1} = A_{basewall}\left\{\sum_{j=1}^{4}\frac{t_j}{k_j}\right\}^{-1} \quad (2)$$

where, each parameter denotes the similar quantity as above. For the specific case of this model solar pond, the equations (1) and (2) take the form

$$U_{vertical\,walls} = \left\{R^{total}_{vertical\,walls}\right\}^{-1} = \left\{2R_{pl} + R_{br} + R_{st} + 2R_{fb}\right\}^{-1} = \left(A_{vertical\,walls}\right)\left\{2\frac{t_{pl}}{k_{pl}} + \frac{t_{br}}{k_{br}} + \frac{t_{st}}{k_{st}} + 2\frac{t_{fb}}{k_{fb}}\right\}^{-1}, \quad (3)$$

$$U_{basewall} = \left\{R^{total}_{basewall}\right\}^{-1} = \left\{R_{pl} + R_{st} + 3R_{fb} + R_{cc}\right\}^{-1} = \left(A_{basewall}\right)\left\{\frac{t_{cc}}{k_{cc}} + \frac{t_{pl}}{k_{pl}} + \frac{t_{st}}{k_{st}} + 3\frac{t_{fb}}{k_{fb}}\right\}^{-1}, \quad (4)$$

where the subscripts *pl, br, st, cc* and *fb* indicate the corresponding values for individual layers of cement plaster, brick wall, Styrofoam, concrete and fiberglass, respectively (see Figure 2.)

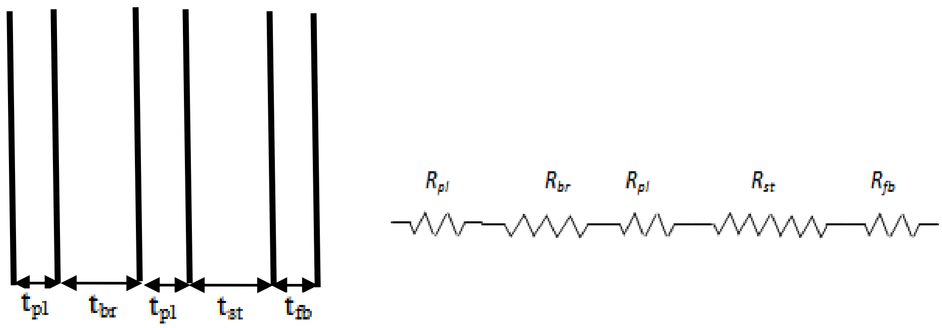

Figure 2: Composite structure of walls of the thermally insulated experimental pond.

4. THICKNESS TEST FOR THE THERMAL INSULATOR MEDIUM

Coefficient of thermal transmission of the composite wall structure depends predominantly on the thickness of Styrofoam layer because the thermal conductivity of this material is substantially low, and hence contributes a higher thermal resistance compared to those of other materials used for constructing walls. Therefore, a laboratory test was conducted to estimate the required Styrofoam thickness for this application. In this test, the temperature profile across a block of Styrofoam of which the two opposite surfaces were maintained, one at 100 ºC and the other at room temperature, was obtained. Four thermometers were placed inside the Styrofoam block at 1.25 cm, 3.75 cm, 6.25 cm and 8.75 cm from the hot surface, as shown in Figure 3, and the temperatures were measured at regular intervals.

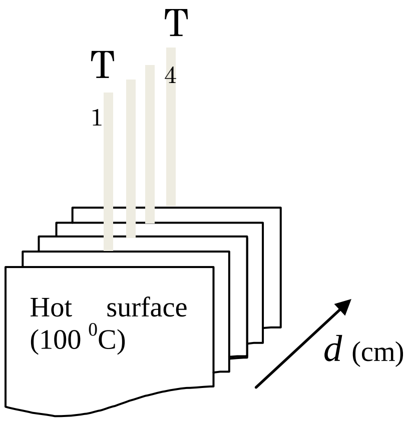

Figure 3: Experimental set up to measure the temperature profile of the Styrofoam medium.

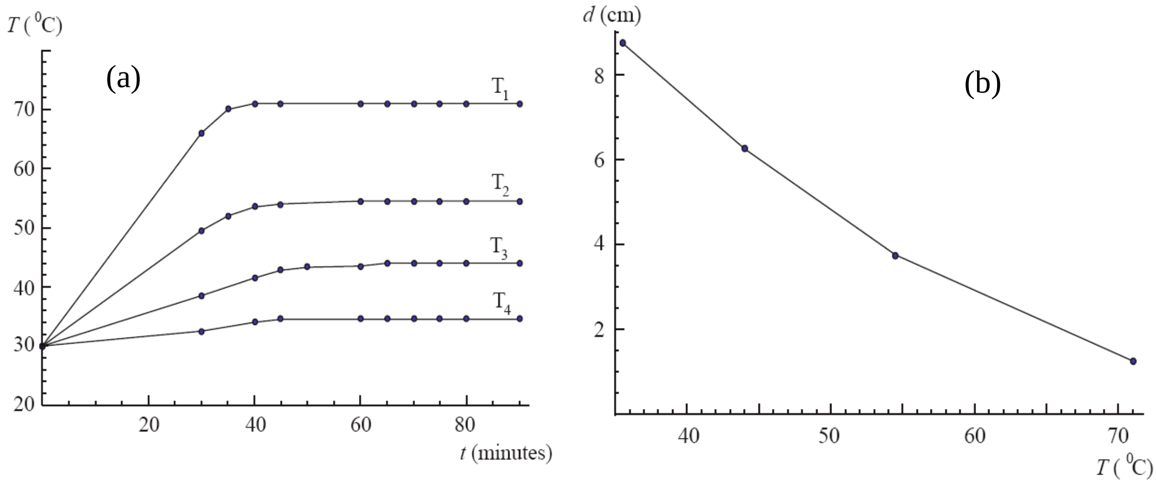

Figure 4: (a) Measured temperatures at different thicknesses inside the Styrofoam medium as shown in Figure 3. (b) Measured temperature profile inside Styrofoam medium at steady state with one end at 100 ^{o}C and the other at 27 ^{o}C.

The variations of measured temperature values with each thermometer, at different thicknesses inside the Styrofoam medium, with time are shown in Figure 4(a) which shows that the system reached the steady state after 65 minutes. Temperature profile thus extracted from the data, at the steady state, is shown in Figure 4(b). These results reveal that the temperature measured by the thermometer T_4, which was placed at a distance of 8.8 cm from the 100 ºC surface has reached a value that is very close to the room temperature.

The estimated total rate of heat loss via conduction as a function of thickness of the Styrofoam medium (with one end at 100 ^{o}C and the other at 27 ^{o}C) is shown in Figure 5 which suggests that a Styrofoam medium with a thickness of about 10 cm is adequate to minimize the expected heat loss through walls of the model pond. Therefore, considering the available thicknesses of Styrofoam sheets at the market, the pond was thermally insulated using Styrofoam sheets with a thickness of 10.2 cm.

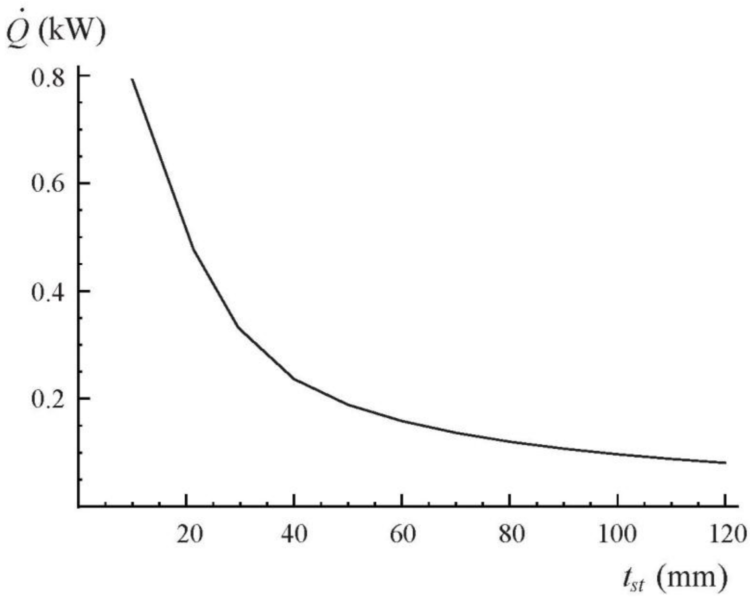

Figure 5: The estimated rate of heat loss $\dot{Q}$, at steady state as a function of Styrofoam thickness, t_{st}, with one end at 100 ^{o}C and the other at 27 ^{o}C.

The thickness of each insulation layer after the completion of the construction and the thermal conductivity are given in Table 1.

Table 1: Values of single layer thickness and thermal conductivity of different materials used for the construction of the thermally insulated model pond.

Material Medium	Thickness ($\times 10^{-3}$ m)	Thermal Conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Cement plaster	10	0.50
Clay brick	200	0.90
Glass fiber (single layer)	1	0.039
Sand/grave/concrete	102	2.16
Styrofoam	102	0.01

5. RESULTS AND DISCUSSION

A solar pond is operated as an environmental-friendly renewable energy source which has the ability to collect thermal energy transmitted by solar radiation, particularly with frequencies in infrared region of the electromagnetic spectrum. The solar pond, at its stable conditions, opens one-way path for the heat radiation through its upper convective and middle non-convective zones to the bottom convective region where the heat is trapped by the middle non-convective zone which acts as the thermal insulator. The buoyant force arising from the expansion of heated liquid mass inside the pond is readily compensated by the additional weight of the same due to the downward increment of liquid density – the so called salinity gradient of the middle non-convective zone.

The labels UCZ, NCZ and LCZ are used here to denote the upper convective zone, non-convective zone in the middle and the lower convective zone, respectively and the rates of heat loss from the pond have been estimated assuming thickness of UCZ with 10 cm, NCZ with 130 cm and LCZ with 60 cm having respective temperatures of 30 ^{o}C (considered as ambient), 60 ^{o}C (average temperature) and 90 ^{o}C (maximum bottom temperature) at expected stable conditions of operation of the experimental model pond, thus having a total liquid depth of 200 cm. The above thickness values have been selected based on the previous research studies done on the salinity gradient solar ponds [7-11].

The inner dimensions (3 m in length and 2 m in width) of horizontal cross section of the constructed pond, together with wall parameters and properties given in Table 1 are used to estimate the rates of heat loss through four different zonal walls of the pond due to thermal conduction. The subsequent results are given in Table 2 which also shows the total rate of heat loss from the pond. In this estimate, heat loss due to convection and water evaporation from the upper open liquid surface to the atmosphere has been neglected.

Table 2: Estimated rates of heat loss through different zonal walls and the total rate of heat loss of the model pond assuming a LCZ temperature of 90 ^{o}C.

Zonal Wall of the Pond	Wall Area (m^2)	Total Thermal Resistance (K/W)	Total Thermal Transmittance (W/K)	Temperature Difference (K)	Rate of heat Transfer (W)
UCZ(vertical)	1.00	10.5	0.095	2	0.2
NCZ(vertical)	13.0	0.81	1.236	30 (av.)	37.1
LCZ (vertical)	6.00	1.75	0.571	60	34.2
LCZ(horizontal)	6.00	1.72	0.580	60	34.8
Total *Rate of Heat Loss* through vertical and horizontal walls of the pond					**106.3**

The rate of heat loss through a certain wall due to thermal conduction is calculated as

$$\left(\frac{dQ}{dt}\right)_{wall} = U_{wall} \times \Delta\theta ,$$

where, $\Delta\theta$ is the temperature difference between two sides of the wall. The value of

U_{wall} for vertical walls is calculated from equation (3) and that for horizontal wall (the base) is calculated from equation (4) with relevant parameters given in Table 1 together with the respective liquid-touching wall areas.

The total rate of heat loss from all vertical and horizontal thermally insulated walls is estimated to be 106.3 W. These results suggest that the heat loss from walls of the UCZ is minimal when compared to those from walls of the NCZ and the LCZ. The estimated rate of heat loss from LCZ through the walls and base is 69 W, which is 65 % of the total rate of heat loss from the entire system, denoting a substantially high fraction, and hence the optimization of parameters of thermal insulation becomes vitally important for the successful operation of a solar pond of this type.

Usually, the thickness of the UCZ is low and that of the NCZ is the highest while the LCZ has a lower thickness than the middle region of the pond. Studies of the stability of salt-pan solar ponds for extended periods at salt productions sites in Sri Lanka report similar results where salinity and density profiles of large-area deep salt-pan solar ponds up to one-meter height were investigated[7-10]. The upper convective zone can develop a high-thick layer when the atmospheric winds are present which transfer kinetic energy to the liquid mass generating surface waves and eventually destroying the stability of solar pond. Suppressing surface waves is an essential requirement for the operation of solar ponds for longer periods especially when winds are present at the pond-site. On the other hand, rains add fresh water to the upper convective zone helping to strengthen the function of the middle non-convective zone, and hence increasing the effectiveness of collecting solar energy in the bottom region. The results of studies on rain and wind effects on the stability of large-area salt-pan solar ponds confirm that the stability is strengthened when the natural rain but no winds are present at the pond site[11]. As the generation of wind induced waves is minimal due to the small size of this model solar pond, more stable configuration than large area ponds is expected.

Insulating walls thermally helps bottom temperatures to rise even close to boiling point, particularly in small-scale experimental solar ponds. Once the bottom temperature exceeds 90 ^{o}C, small air bubbles start to form in the bottom, which then travel upward through the middle non-convective zone leading to a situation that destroys the entire zonal structure, and thus allowing the trapped heat to diffuse into the atmosphere through the upper convective zone. A comprehensive heat exchange mechanism is needed to extract the trapped heat energy from the bottom region to prevent the solar pond from becoming this extreme condition to maintain stability of the system.

The total rate of heat loss from the LCZ is 69 W. If this value is used together with the known values of density = 1200 $kg.m^{-3}$ (at 90 ºC) and specific heat = 3300 $J.kg^{-1}.K^{-1}$ of saturated brine to calculate the expected rate of temperature drop at LCZ, it turns out to be 4.8×10^{-6} $ºC.s^{-1}$. Site of this experimental pond receives a substantial solar flux throughout the day time thus enabling the pond collect solar energy at least during seven hours per day. During the remaining seventeen hours of the day, without the presence of direct solar radiation to the pond, the calculated total temperature drop at the above rate in the LCZ is 0.3 ºC. This situation implies that by employing an appropriate mechanism to extract thermal energy from LCZ, the energy stored during the day time can be extracted continuously while maintaining the temperature at around 90 ºC at LCZ.

The amount of extractable energy depends on the size of pond, in particular the liquid volume of the LCZ. Large-area solar ponds can produce substantial amounts of heat energy which can be utilized in practical applications such as sea-water desalination and electricity generation. The present project of optimizing parameters to increase the bottom temperature of a small-scale experimental solar pond to a maximum possible level is aimed to investigate the extreme bottom temperatures as well as developing a comprehensive heat exchange mechanism to extract thermal energy for the specific practical application of sea-water desalination.

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