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Numerical Investigation of the Effect of Salt-Gradient Solar Pond Dimensions on the Pond Performance and Energy Storage

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Abstract

A numerical investigation on the non-convective salt-gradient solar pond was carried out to study the effect of different variables on the solar pond performance. A numerical computer program was performed to show the relations between the different pond variables. The investigation analysis was performed at selected days (1, 15, and 20th) of December 2012 at Jordan-Amman climate. The results of investigation show that the temperature of storage zone will increase by decreasing the depth of both UCZ and LCZ and increasing the depth of NCZ.

Keywords: solar pond, performance variables.

1. Introduction

A solar pond is a large reservoir of saline water, with the difference that a specific salinity (or density) profile is artificially created and maintained in the pond. A salinity-gradient solar pond (SGSP) is a body of water that collects and stores solar energy. A typical salinity-gradient solar pond has three regions: surface zone, main gradient zone, and bottom zone (figure 1). The surface zone, also called the upper convective zone (UCZ) is a homogeneous layer of low-salinity brine or fresh water. The bottom zone, also called the lower convective zone (LCZ) or storage zone, is a homogeneous layer of concentrated salt solution. Between the surface and bottom zones is the main gradient zone, which contains positive salinity and density gradients with depth and serves as a transparent insulating layer. Since there is no convection in the main gradient zone, the gradient zone is also called the non-convective zone (NCZ). Solar energy is collected and accumulated in the LCZ causing the temperature to increase. The insulating properties of the gradient zone, combined with the high heat capacity and large volume of water make the solar pond both a solar thermal collector and a long-term thermal storage device. There are many solar pond thermal energy storage schemes are already operating very successfully and several new systems are being constructed .It is the aim of the current investigation to investigate numerically the effect of different variables on the solar pond performance.

2. Concept of the Non-convective Salt Gradient Solar Pond

Non-convective solar pond shown in figure 1 is an ideal system that combines two functions, collection and storage of solar energy in one unit. This is available in large quantities, cheap, and has high specific heat capacity.

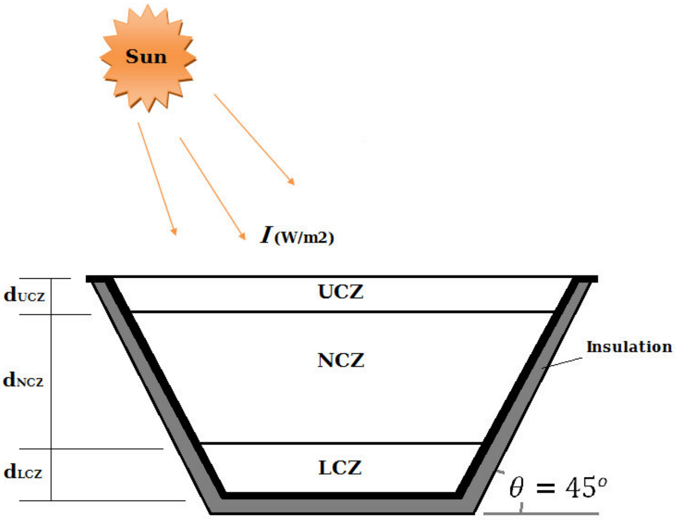

Figure 1. Typical Salt-Gradient pond

3. Pond Thermal Analysis

The following assumptions had been potted before making the theoretical analyses of the thermal behavior of the solar pond:

1) Uniform temperature and salt concentration in the lower convective layer (Fully mixed storage zone).
2) The temperature of the upper convective layer is always closed to the ambient temperature, i.e. mixing in the surface layer and LCZ, due to atmospheric agents or thermohaline convection, was assumed to maintain uniform temperature distributions in those regions.
3) Linear temperature profile in the non-convective zone.
4) Heat losses through the pond sidewalls and the ground are negligible (insulated walls).
5) The three distinct layers are fixed (i.e. no movement in the boundary of the three layers).
6) No heat extraction from the pond.

3.1 Energy Input to the Pond

The average solar radiation incident on the surface of the pond for each month of the year at Amman location is presented by the Energy Researches Center in the Royal Scientific Society. The body of the pond absorbs part of the incident solar energy while the other portion lost by reflecting. The amount of energy absorbed by the solar pond is calculated as:

$$Q_{abs} = A_c I(\alpha\tau) \quad [W] \tag{1}$$

Where:

A_c : The surface area of the solar pond [m^2]

I : The total solar radiation is incident on the solar pond unit surface area, [W/m^2]

ατ : The solar absorption transmittance product of the solar pond

3.2 Energy Lost from the Pond

It is assumed that heat losses through sidewalls and ground are to be negligible, the heat is lost from the pond only by conduction from LCZ (having temperature T_s) to UCZ (having temperature T_a) through non-convective gradient zone (NCZ). The mathematical representation of energy lost from the pond using Fourier low is given by:

$$Q_{loss} = K_w A\left(dT_w/dz\right) \quad at\ z = 1.0 \tag{2}$$

Where K_w is thermal conductivity of the water.

But the temperature profile is assumed to be liner in the NCZ, then:

$$Q_{loss} = A_c U_L(T_s - T_a) \quad [W] \tag{3}$$

Where:

U_L is the overall heat loss coefficient and is given by $U_L = (1 / \Sigma R) = (K / d_{NCZ})$.

d_{NCZ} is the thickness of the non-convective gradient zone.

3.3 Energy Stored in the Pond

Not all the input energy is gained as useful energy in the pond, some of it is stored (as useful energy) in the lower convective zone and some has been lost to the surrounding. The amount of thermal energy stored inside the body of the pond can be calculated as follow:

$$Q_u = mC_p \frac{dT_s}{dt} \quad [W] \tag{4}$$

Where

m	is the mass in LCZ which can be written as $(m = \rho V_{LCZ})$
ρ	is the density of water in the LCZ
V_{LCZ}	is the volume of water in the lower convective zone.
C_p	is the specific heat of water in the lower convective zone (storage zone)

Another way is to apply the first low of thermodynamic as follow:

$$Q_u = Q_{abs} - Q_{loss} \tag{5}$$

Substituting equation (1) and (2) into (5):

$$Q_u = A_c\left[I(\alpha\tau) - U_L(T_s - T_a)\right] \quad [W] \tag{6}$$

The (τα) product is related to the transmission function for radiation in the pond. For extremely clear ponds, the (τα) product is about 0.45 and for very dirty ponds, it can be as low as 0.2 [Kishore and Joshi, 1984].

And per unit surface area the energies can be calculated as follows:

$$q_{abs} = I(\tau\alpha) \quad \left[W/m^2\right] \tag{7}$$

$$q_L = U_L(T_s - T_a) \quad \left[W/m^2\right] \tag{8}$$

$$q_u = \left[I(\alpha\tau) - U_L(T_s - T_a)\right] \quad \left[W/m^2\right] \tag{9}$$

The rate of total energy that reaches the solar pond surface is given by:

$$Q_t = A_c I \quad [W] \tag{10}$$

And per unit area:

$$q_t = I \quad \left[W/m^2\right] \tag{11}$$

4. Pond Efficiency (Effectiveness)

A measure of solar pond performance is the pond effectiveness. The thermal collection effectiveness of the solar pond is simply defined as the ratio of useful energy gain in the pond (in the storage zone) to the amount of input solar energy. The net useful energy is the solar energy that stored in the lower convective zone of the pond and the input energy is the amount of insolation transmitted to the storage layer of the pond. Mathematically, the thermal effectiveness maybe represented as follow:

$$\eta_P = \frac{Q_u}{Q_t} = \frac{m\,C_p\,\Delta T}{A_c\,I} = \frac{\left[I(\alpha\tau) - U_L(T_s - T_a)\right]}{I} \tag{12}$$

5. Pond Dimensions and operation characteristics

The pond under investigation has the following dimensions and characteristics:
0.2 m width, 0.5 m height and 1.32 depth and inclined with Θ =45°
Then:

The pond volume: $V = Area \times depth = (1/2)[L_1 + L_2] \times d \times H = \frac{1}{2}[0.2 + 0.5] \times 0.15 \times 1.32 = 0.0693\ m^3$

The mass: $m = \rho V = 1150 \times 0.0693\ kg$

Where:
L_1 : solar pond width at the bottom [m]
L_2 : solar pond width at 0.15 height from the bottom [m]
d : height of the LCZ in solar pond [m]
H : depth of the solar pond [m]
V : volume of the brine in the LCZ [m^3]
P : the density of the brine =1150 [Kg/m^3] (20% sodium chloride at 20 °C)
C_p : specific heat of the brine =3110 [J/Kg.°C] (20% sodium chloride at 20 °C)
m : mass of the brine in the LCZ [Kg]

For extremely clear ponds, the (τα) product is about 0.45 and for very dirty ponds, it can be as low as 0.2 and the thermal conductivity of the solar pond solution is assumed to be 0.6 [W/m.°C], independent of salinity and temperature. Thus:

$U_L = 1 / \Sigma R$
$\Sigma R = (d_{NCZ} / K)$
$\Sigma R = (0.275 / 0.6) = 0.45$ [m^2.°C/W]
$U_L = (1 / 0.45) = 2.18$ [W/m^2. °C]

6. Sample of Calculations

Solar pond with no lost energy (assumed to be isolated) the useful energy equal the absorbed energy.
For the day 1/12/2012 at 15pm: I=362 [W/m^2], T_a=26 °C, T_{S1}=41.6 °C, (ατ) = 0.45, U_L=2.18 [W/m^2. °C]

Table 1. Sample of calculations

Quantity	without energy loss	with energy loss
$q_L = U_L(T_{s2} - T_a) \quad [W/m^2]$	0	$2.18 \times (43.95 - 26) = 39.13$
$q_{abs} = I\alpha\tau \quad [W/m^2]$	$362 \times 0.45 = 162.9$	$362 \times 0.45 = 162.9$
$q_u = q_{abs} - q_L \quad [W/m^2]$	$162.9 - 0 = 162.9$	$162.9 - 39.13 = 123.8$
$\eta_P = \frac{q_u}{I} \times 100\%$	$\frac{162.9}{362} \times 100\% = 45$	$\frac{123.8}{362} \times 100\% = 34.1\%$
$T_{s2} = T_{s1} + \Delta T = T_{s1} + \frac{q_u}{mC_p} \quad [^oC]$	$41.6 + 2.35 = 34.95$	

Where:
T_{S1}: temperature of lower convective zone at time t.
T_{S2} : temperature of lower convective zone at time (t+Δt).

7. Results and Discussion

The resulting graphs with the discussion of each effect are as follows:

Figure (3) illustrates the relation between the variations of the solar radiation with the time of the day, as it is shown, the radiation increases to be the maximum at 12:00, then it decreases to its minimum value at the sunset. This is because of the variation of the solar angle, which changes with time. Figure (8), (13), has the same behavior of figure (3).but deferent in each other by the duration of maximum radiation.

Figure (4) shows the relation between the variation of storage and ambient temperature with time. It can be seen that the ambient temperature increase until it reaches the maximum value at about 13:00pm then it will decrees until it reaches its minimum value at 16:00 pm. but storage temperature increase until it reaches it maximum temperature at 16:00 pm and then it become stable .the temperature difference appear Cleary between 15:00 and 16:00 pm since the ambient temperature decrease by the effect of sunset. Figure (9), (14) has the same behavior.

Figure (5) shows the relation between the variations of lost energy with the time. It can be seen that the lost energy increase until it reaches the maximum value at about 16:00pm. That is due to temperature difference between the ambient and storage that implies when the temperature defiance increase the lost energy will also increase so that the relation of lost energy is proportional with the time. The temperature difference appears Cleary between 15:00 and 16:00 pm since the ambient temperature decrease by the effect of sunset. Figure (10), (15) has the same behavior.

Figure (6) shows the relation between the variation of total and useful energies with the time of the day. It can be seen that the total energy and useful energy increase until it reaches the maximum value at about 12:00pm then it will decrees until it reaches its minimum value at 16:00 pm. When there is no losses the useful energy will be always equal to 0.45 of total energy depend on the assumption of that the solar pond is extremely clear. Figure (11), (16) has the same behavior.

Figure (7) demonstrates the relation between the efficiency of the solar pond and the time of day. The maximum efficiency occur at the about 9:00 am and then it will decrees slowly until it reaches 14:00pm (temperature difference will small) i.e. lost energy will be small the efficiency will decrease until reaches minimum value at 16:00 pm at the lost energy .figure (12),(17) have the same behavior .

Figure (18) shows one year prediction of storage temperature for the solar pond from this figure we can see the general trend of storage temperature variation during the period of prediction. It can be seen there is no big difference between the performance at the starting and the end of year .the maximum temperature achieved in the solar pond was 90 °C obtained in July(i.e. in phase with the month of maximum solar radiation) . The explanation of the periodic behavior of the storage energy may be due to the variation of the various parameters that have influence on the storage temperature such as solar radiation and ambient temperature.

Figure (19) shows one year prediction of effect of LCZ thickness on the storage zone temperature for the solar pond. When the amount of water in the storage zone decreases, the storage temperature will be higher. This variation in storage zone temperature with various storage zone thickness can be referred to the fact that for the same amount of solar energy reaches the bottom of the pond the temperature of the brine to be heated will be higher if the mass of the water is small .but if the mass of water in the storage zones is larger the temperature of that water due to heating from solar energy penetrating the bottom will be lower (i.e. the thinner LCZ thickness mean higher storage zone temperature)

Figure (20) shows the prediction the effect of the UCZ thickness on the storage zone temperature .the surface layer of the pond has no function since it reduces the fraction of solar radiation transmitted to the solar pond therefore, it should be as thin as possible. For different UCZ thickness with other parameters remains constant and ducz=0.15m .the results indicate that the higher storage temperature was found to be at lower UCZ thickness. That can be refereed to fact of lower thickness of surface layer and higher storage temperature obtained can referred to the increase of the solar radiation transmitted to the storage zone with lower UCZ thickness . Some of the incident solar radiation is absorbed by the water in surface layer resulting in raising its temperature above the ambient.

Figure (21) shows the prediction the effect of the NCZ thickness on the storage zone temperature. The results obtained for this pond indicate that it is better to increase the thickness of the NCZ. By doing this we decrease the losses from the storage zone and increasing the thickness of NCZ with constant surface layer thickness will reduce the thickness of storage zone hence, allow more increase in storage temperature. But , the NCZ has two vital function first it acts as an insulating layer to reduce losses from the storage zone and second its thickness control the amount of solar radiation penetrating the bottom of the pond . Thus there is an optimum thickness for this layer depending on the storage temperature required.

From the predicted results the average annual storage temperature is plotted against NCZ and LCZ thickness in figures (22) and (23). In general, one can say that the annual storage zone temperature for the proposed pond increase with increasing the NCZ thickness and decreasing the LCZ thickness for constant surface layer.

The boundaries of the three main layers (UCZ, NCZ, and LCZ) in the salt-gradient solar pond can be detected from the measured temperature profile within the pond as shown in figure (24). In this figure the measured temperature is plotted against different depths within the pond. The UCZ should be maintained free of salt by washing the surface with film of pure water from time to time to make sure that it is free of salt that will increased the amount of solar radiation transmitted through the pond

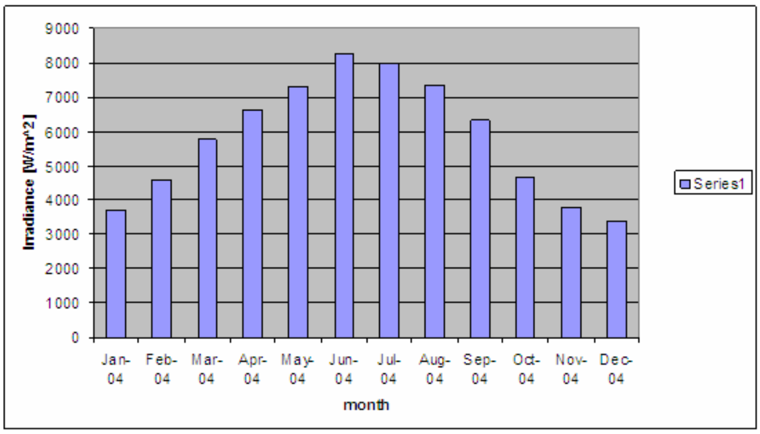

Figure 2. Total monthly irradiance [w\m^2]

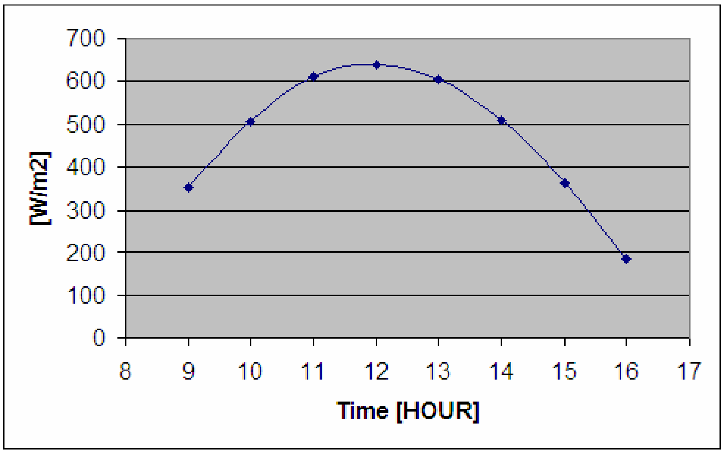

Figure 3. The variation of the solar radiation with the time of day for 1/12/2012

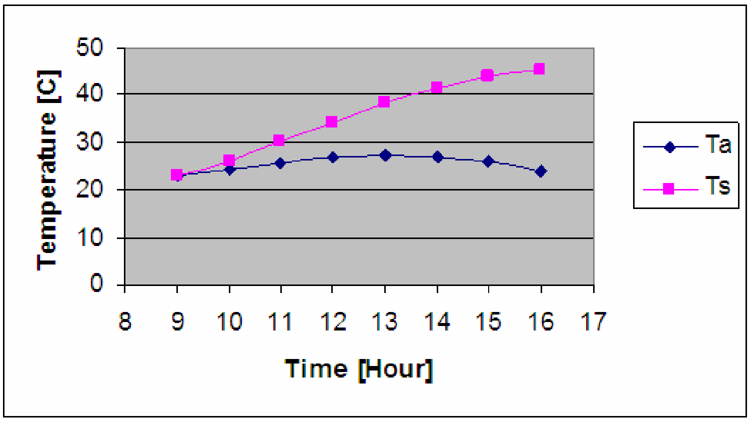

Figure 4. The variation of the Storage and ambient temperatures with the time of day for 1/12/2012

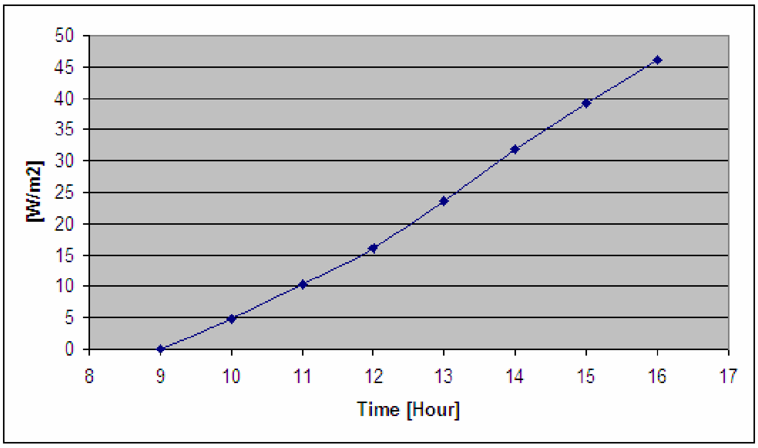

Figure 5. The variation of lost energy with the time of day for 1/12/2012

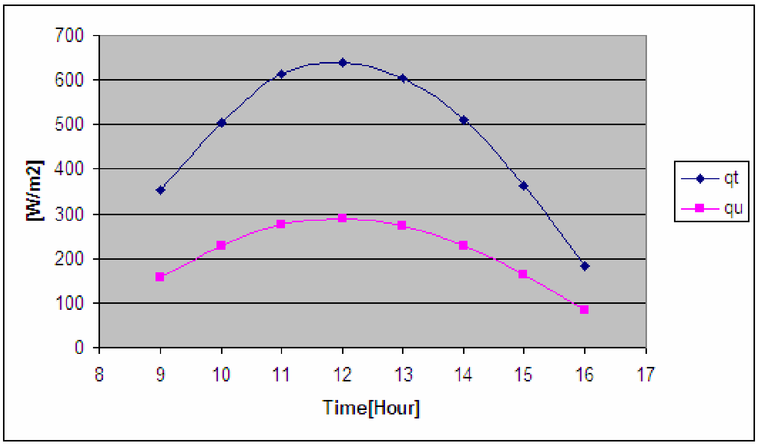

Figure 6. The relation between the total and useful energies and the time of day for 1/12/2012

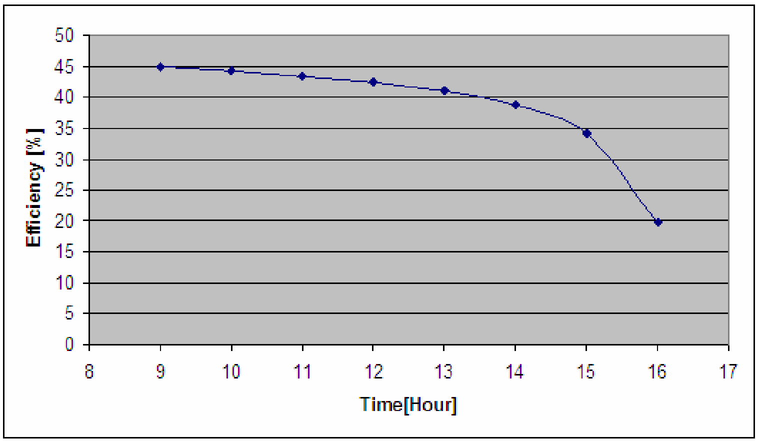

Figure 7. The relation between the efficiency of the pond and the time of day for 1/12/2012

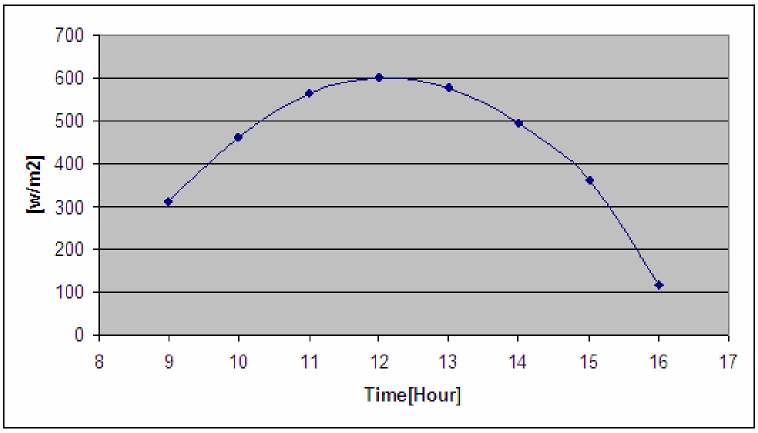

Figure 8. The variation of the solar radiation with the time of day for 15/12/2012

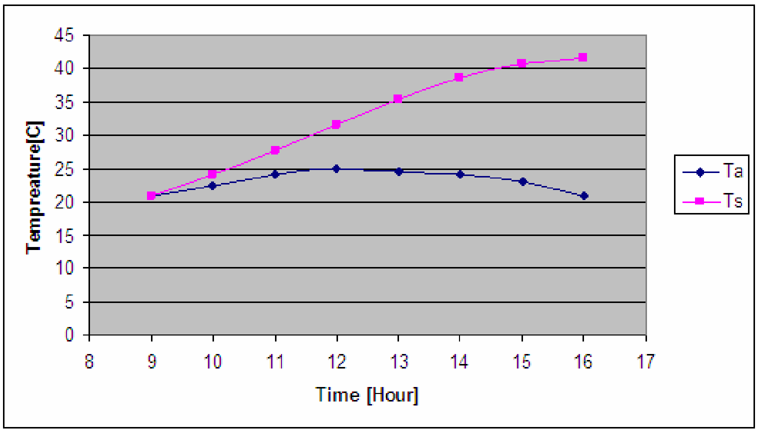

Figure 9. The variation of the Storage and ambient temperatures with the time of day for 15/12/2012

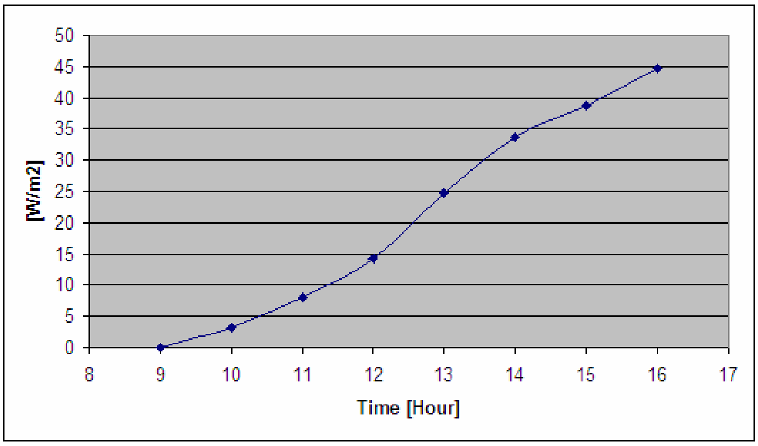

Figure 10. The variation of lost energy with the time of day for 15/12/2012

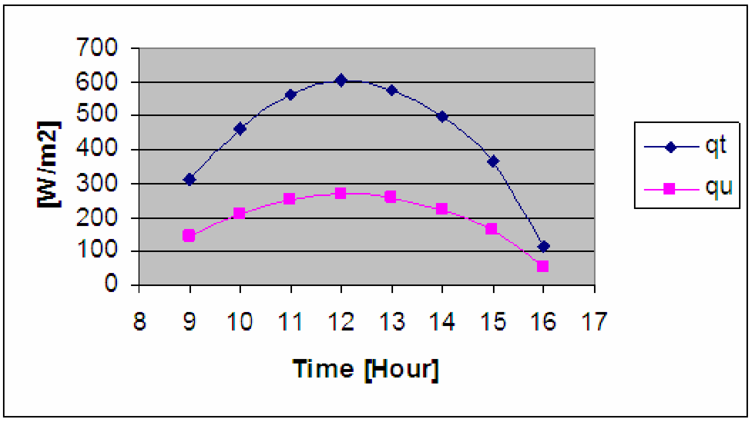

Figure 11. The relation between the total and useful energies and the time of day for 15/12/2012

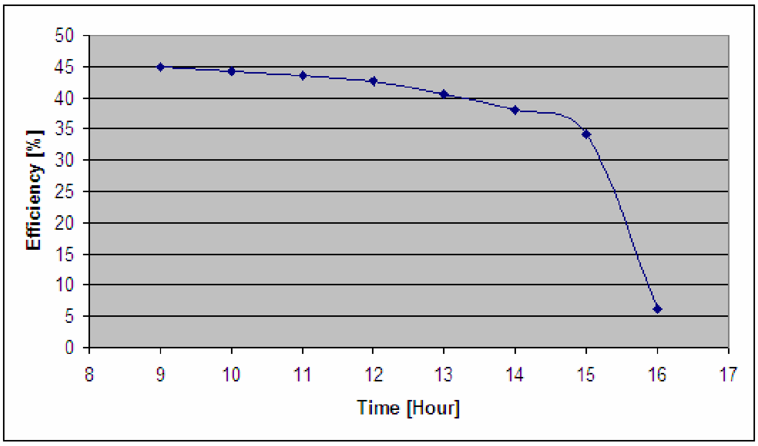

Figure 12. The relation between the efficiency of the pond and the time of day for 15/12/2012

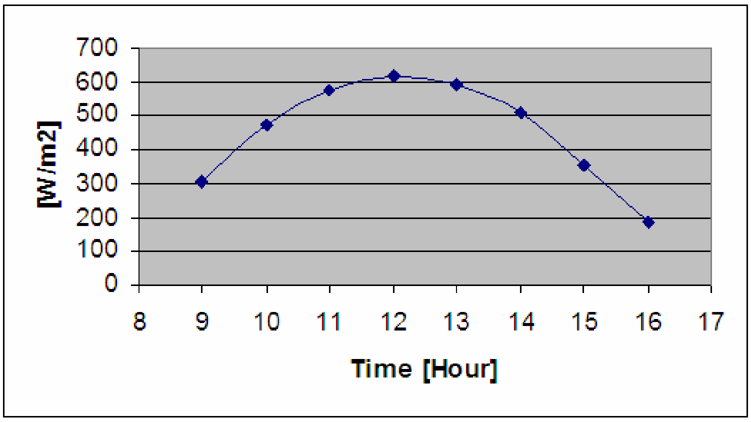

Figure 13. The variation of the solar radiation with the time of day for 20/12/2012

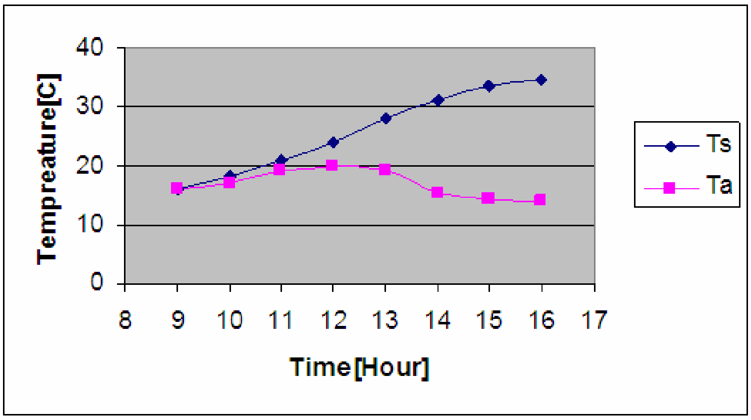

Figure 14. The variation of the Storage and ambient temperatures with the time of day for 20/12/2012

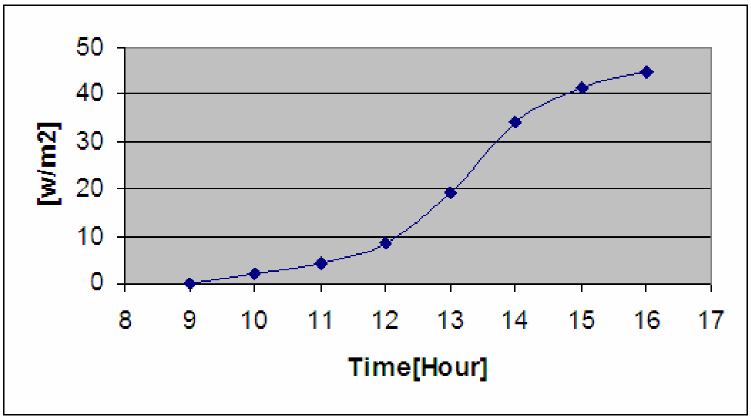

Figure (15): The variation of lost energy with the time of day for 20/12/2012

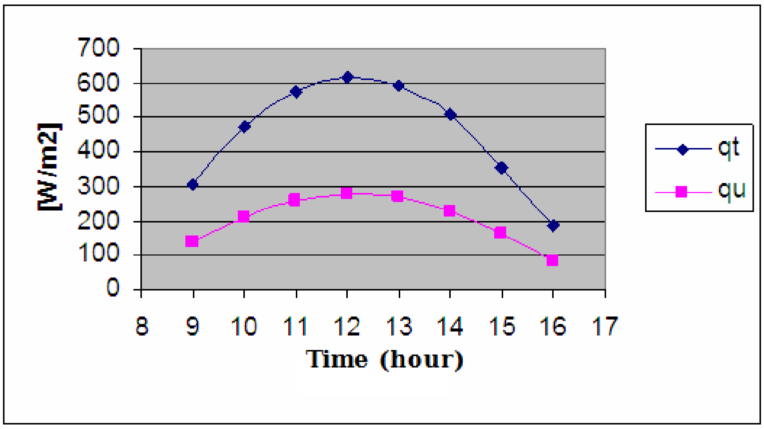

Figure 16. The relation between the total and useful energies and the time of day for 20/12/2012

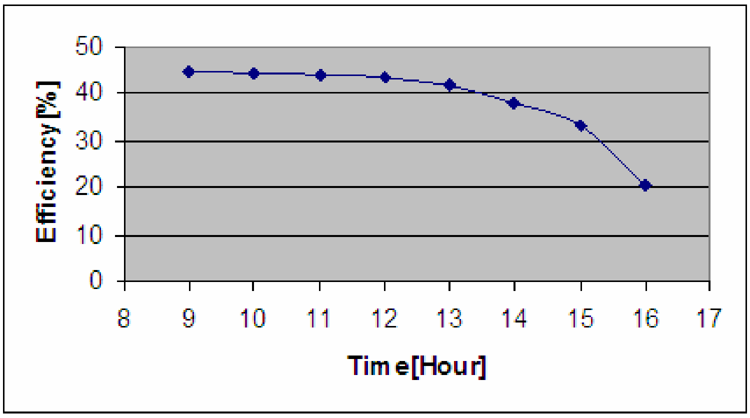

Figure 17. The relation between the efficiency of the pond and the time of day for 20/12/2012

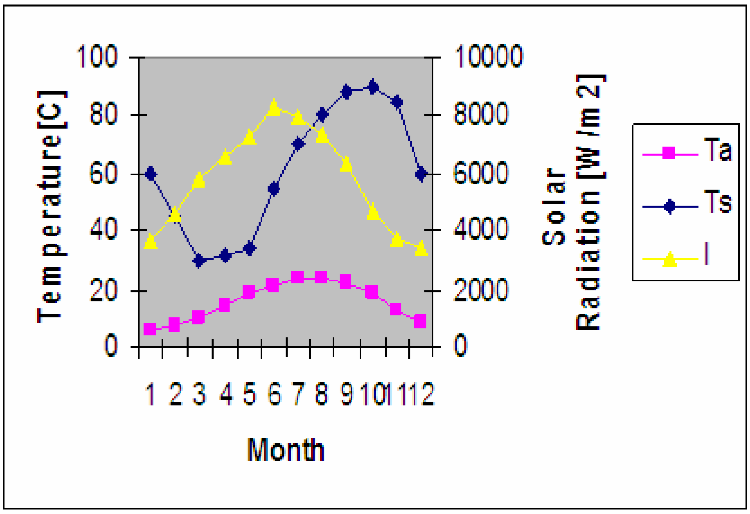

Figure 18. Mean ambient temperature, solar radiation (data of Amman) and one year prediction for the storage temperature. (D=0.5m, d_{ucz}=0.075, d_{lcz}=.015)

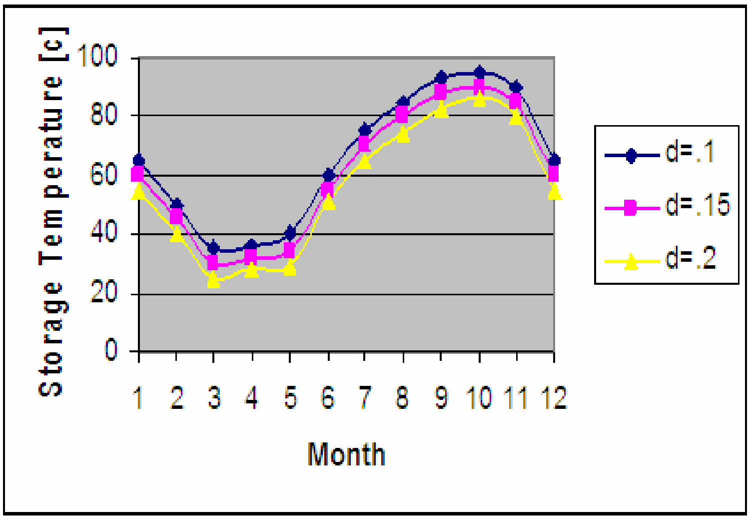

Figure 19. Prediction the effect of LCZ thickness on the storage zone temperature. (d=0.5m, d_{ucz}=.075m)

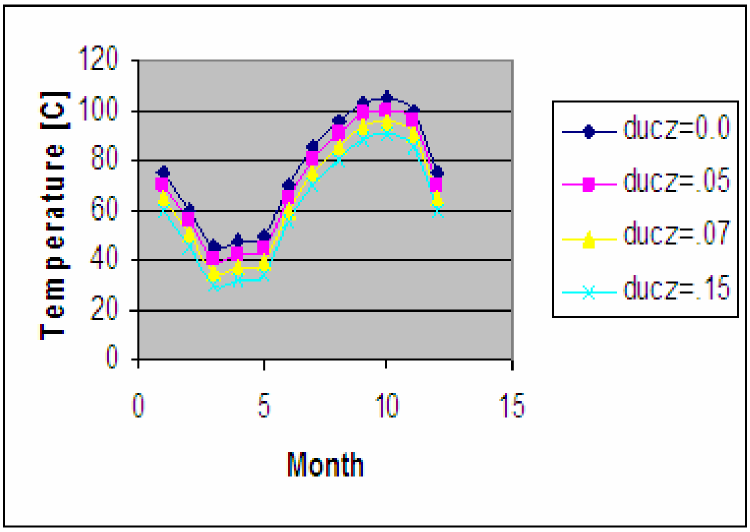

Figure 20. Prediction the effect of the UCZ thickness on the storage zone temperature (d=0.5, d_{lcz}=0.15)

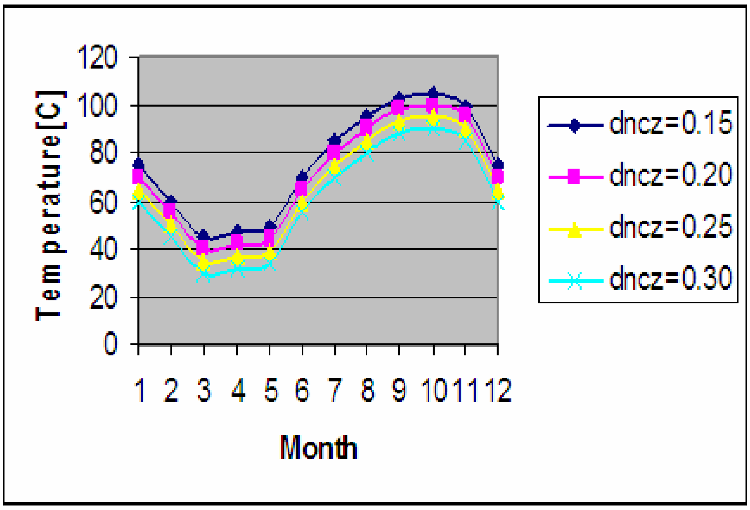

Figure 21. Prediction the effect of the NCZ thickness on the storage zone temperature (D=0.5, d_{lcz}=0.075).

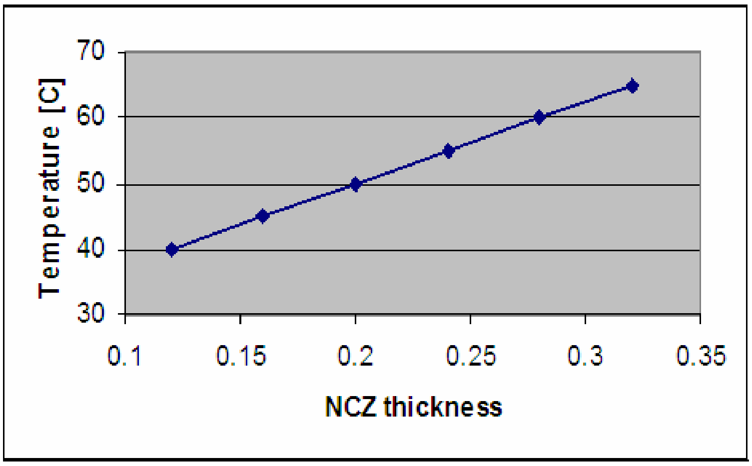

Figure 22. The average annual predicted storage zone temperature vs. the NCZ thickness (D=0.5m, d_{ucz}=0.075)

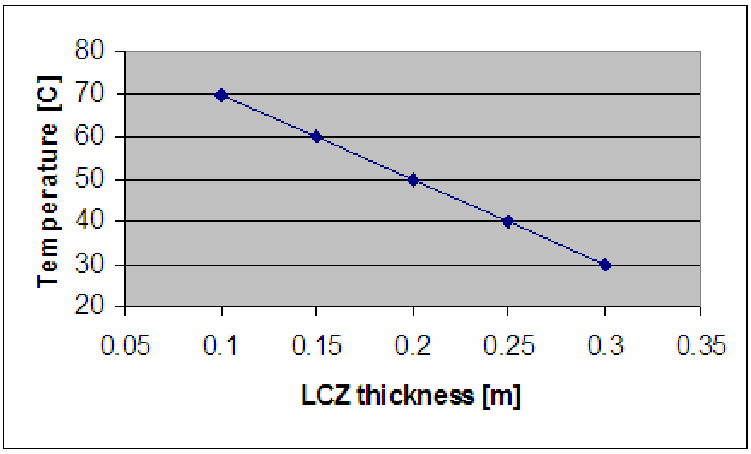

Figure 23. The average annual predicted storage zone temperature vs. the LCZ thickness (D=0.5m, d_{ucz}=0.075)

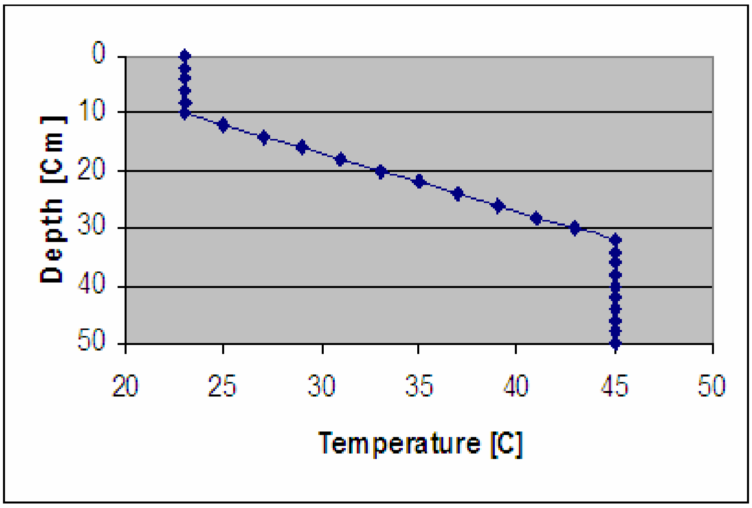

Figure 24. The temperature profile within the solar pond for day of 1/12/2012 (D=0.1m, d_{ncz}=0.225, d_{lcz}=0.175)

8. Conclusions

Based on the previous results the following may be concluded:

1) The performance of the salt-gradient solar pond depends mainly on the following parameters:

- The amount of solar radiation incident that reaches the surface of the solar pond.
- Density gradient inside the solar pond.
- Total thickness of the solar pond and the thickness of the UCZ, NCZ, LCZ.

2) The thickness of the lower convective zone determines the amount of thermal storage available (Proportional relation).
3) The thickness of the lower convective zone determines the maximum temperature of thermal storage available (Reversible relation).
4) The thickness of the gradient zone provides the solar ponds insulation, and reducing this thickness below optimum thickness will increase the heat loss.
5) Salt-gradient solar ponds are very much likely to be used in storing large amount of energy with relatively small temperature.
6) Wind affects strongly the behavior and performance of salt-gradient solar pond since it circulates the water, tends to lower the water temperature, and generates waves in a pond which can cause erosion of pond banks.
7) In General operating salt-gradient solar pond under climatic condition of Jordan especially in Dead Sea is encouraging due to good levels of solar radiation incident and availability of salts.
8) Salt –gradient solar pond have a low capital cost owing to the fact that they are based on low-cost materials like clay, plastic and salt.

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