MODELING AND OPTIMIZATION OF SALT- GRADIENT SOLAR POND LOCATED IN BAGHDAD

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ABSTRACT

The aim of this investigation is the detection of the ability of salt gradient solar pond the lake of shortfall in electric power in Iraq .This study Conducted using small model of solar pond for Weather conditions of Baghdad city, balance of power and distribution of saline was done through this model and the equations found was solved numerically using finite difference approach by Matlab program to study thermal behaviour of pond for all days of the year. Temperature and density profiles obtained twenty five days after filling for different months in year and it was noted that the temperature at the bottom of the pond in Baghdad is more than the temperatures in other places of the world which leads to increase in pond efficiency. The study stated that the solar pond can be used to produce electricity better in Iraq than in other countries because of Iraq's extant Geographic location, in addition this method is best used dusty weather in comparison with other methods of solar energy.

Keywords: Solar pond; Temperature distribution; Heat losses; Finite difference

نمذجة وتحسين بركة شمسية متدرجة الملوحة تقع في مدينة بغداد

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الخلاصة

يهدف هذا البحث إلى الكشف عن إمكانية استخدام البرك الشمسية متدرجة الملوحة لسد النقص الحاصل في الطاقة الكهربائية في العر اق.تمت الدراسة باستخدام نموذج لبركة شمسية صغيرة لظروف مدينة بغداد وقد أجريت موازنة للطاقة والتوزيع الملحي خلاله وتم حل المعادلات الناتجة عدديا باستخدام طريقة الفروق المحددة ببرنامج الماتلاب لدراسة السلوك الحراري للبركة في جميع أيام السنة. تم إيجاد منحنيات توزيع درجات الحرارة وتوزيع الكثافة بعد خمسة وعشرين يوم من بداية تشغيل البركة لأشهر مختلفة في السنة ولوحظ إن درجة حرارة قاع البركة في بغداد ترتفع عن درجات الحرارة المستخرجة لبرك في مناطق مختلفة من العالم مما ينتج عنه زيادة في كفاءة البركة . وإشارة الدراسة إلى إمكانية استخدام البرك الشمسية متدرجة الملوحة لتوليد الكهرباء في العراق بشكل أفضل مقارنة مع باقي الدول لما يتمتع به العراق من موقع جغرافي متميز ولأنها تناسب الجو كثير الغبار أفضل من غيرها من طرق استخدام الطاقة الشمسية الأخرى .

Nomenclature

C = Heat capacity of salt water $(w/m^2 °C)$

C_p = Specific heat of salt water $(J/kg°C)$

H = Incident solar radiation (w/m^2)

h_c = Convection heat transfer coefficient $(w/m^2 °C)$

k = Thermal conductivity of salt water $(w/m°C)$

LCZ = Lower Convective Zone

NCZ = Non Convective Zone

P_a = Atmosphere pressure (Pa)

P_s = Vapor pressure (Pa)

q_{ext} = Heat extracted from the LCZ (w/m^2)

q_g = Heat losses from LCZ to the ground (w/m^2)

q_{loss} = total heat losses from UCZ (w/m^2)

S = Salt concentration in the pond (%)

T = Temperature in the NCZ (˚C)

T_a = ambient temperature (˚C)

T_g = Ground temperature (˚C)

T_{max} = maximum ambient temperature (˚C)

T_{min} = minimum ambient temperature (˚C)

T_s = Surface temperature (˚C)

UCZ = Upper Convective Zone

U_g = ground heat loss coefficient $(w/m^2 °C)$

Greek symbols

α = Thermal diffusivity (m^2/s)

ε_w = emissivity of surface of salt water

θ = angle of penetration of radiation within pond (deg)

ϕ = relative humidity (%)

η = pond's efficiency (%)

λ =latent heat of vaporization (kj/kg)

ρ = Thermal diffusivity (kg/m^3)

ρ_f =the reflectivity of the bottom

φ = latitude (deg)

INTRODUCTION

Solar pond is an artificially constructed pond in which significant temperature rises are caused to occur in the lower regions by preventing convection. To prevent convection, salt water is used in then pond. those ponds are called ''salt- gradient solar pond'' (Velmurugan, 2008) [25]. Salt-Gradient solar ponds can be used to store large amounts of heat while operation at restively low temperature, and It has advantages of simple design, low cost and easily built over large years (Tahat,2000) [24].

In recent years, solar energy systems offer significant protection on the environment, and solar ponds received increasing attention in some thermal applications such power production, process in dairy plants, desalination, space heating and heating greenhouses(Banipal,2000) [3]. So far, many experimental investigations carried out to understanding thermal behavior of these ponds (Xiang,2001) [26], laboratory small –scale pond and middle-scale outdoor solar ponds were designed and built to provide both quantitative data and to study the dynamic processes in solar pond, including the behavior of gradient zone stability (Choubani,2010) [8] and test rig for solar pond simulation was developed to study the chosen fertilizer salt (Rmakrishna,2003) [21].A comparison between the temperature and salinity profile obtained in the model pond cylindrical plastic tank ,with 1m height , 0.9 m in diameter(Dah,2005) [9] .

Theoretical studies have concentrated on modeling and predicting solar pond performance, simple methods for estimation of radiation flux at various depth of salt-gradient solar pond is an integrated part of modeling its thermal performance (Husain,2004) [14]. governing equations of upper convective zone, non convective zone ,and lower convective zone of sat-gradient solar pond are deduced as a set of non-linear partial differential equation (Abdel-Dayem,2004) [2] .The basic equation governing heat flow in the non convective zone of solar pond is solved by finite difference approach using the Crank-Nicholsen (Husain,2003) [13].A finite difference method with a diffusion coefficient dependent on both temperature and salt concentration is used to solved the salt diffusion equation and studied salt diffusion and stability of the density gradient(Celestino,2004) [5] ,this model used for the study of the NaCl diffusion in solar pond take into account the effect of thermodiffusion and the possibility of injection of concentrated brine at the bottom of the gradient zone of the pond (Celestino,2005) [7].

In present work, numerical analysis of salt gradient solar pond behavior is conducted in one dimension transient heat transfer model solved using finite difference technique in Matlab program according to the rate of incident solar radiation in Baghdad city at a given latitude and longitude to study the effects of various configurationl and operational parameters on pond's performance .

THE SOLAR POND

The model of salt-gradient solar pond used consists of three thermally distinct zone of increasing salinity from the surface to the bottom **(Figure 1)**.The bottom layer (Lower Convective Zone, LCZ) of thickness 0.6m, which is hot and very salty. The intermediate or gradient zone (Non Convective Zone, NCZ), of thickness 2.0m, where salt content increases with depth .water in this layer cannot rise because less water above it has less salt content and is therefore lighter. Similarly, water cannot fall because the water below it has higher salt content and is heavier. The surface zone (Upper Convective Zone, UCZ) of thickness 0.4m of fresh or slightly saline water, it protects the rest of the pond from external influences such as rain and wind. The convection in UCZ is caused by wind mainly and the convection in LCZ is caused by the vertical temperature difference (Dah,2005) [9] and (Ouni, 1998) [20].The solar radiation that penetrates the pond's upper layers and reaches the lower convective zone heats the highly concentrated brine. The heated brine will not rise beyond the lower convective zone because the effect of salinity on density is greater than the effect of temperature (Francisco, 2010) [11].

THERMAL MODELING

ambient temperature

The ambient temperature is assumed to be sinusoidal function and variable values are obtained from analytical function (Karakilcik,2006) [16] and (Nalan,2008) [18]

$$T_{a(n,t)} = T_{av} + 8\sin\left[\left(\frac{360}{365}\right)n - 103\right] + 5\sin\left[\left(\frac{360}{24}\right)t\right] \quad (1)$$

Where t is any hour of the day varying from 1 to 24 and n is the number of the day varying from 1 to 365and T_{av} =average ambient temperature taken from **(table 1).**

Absorption of radiation in solar ponds:

When solar radiation was incident upon the solar pond, a part of the ray is reflected on the surface and most of incident ray transmits through working fluid. Also apart of transmitted ray is more absorbed by each thin layer of NCZ and LCZ and, the part of transmitted ray, which reached the LCZ, is changed into heat and stored in the LCZ. Absorptivity of the working fluid is changed with concentration of the salt-water (Xiang,2000) [27].

Extraction radiation H_o for the average hourly of the day on a horizontal surface can be calculated for each month using the following equations (Lana, 2010) [17] and (El-Sebaii, 2010) [10].

$$H_o = \frac{24\times 3600\times I_{sc}}{\pi}\left[1 + 0.033\cos\left(360\times\frac{n}{365}\right)\right]\times\left[\cos\varphi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\varphi\sin\delta\right] \quad (2)$$

Where I_{sc} =1353 (w/m^2) is the solar radiation and ω_s is the sunset hour angle given as:

$$\omega_s = -\tan\phi\tan\delta \quad (3)$$

δ is the solar declination angle defined as:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \quad (4)$$

The net radiation flux at a depth calculated from the following equations (Husain,2004) [14]:

$$H_x = H_o\left\{0.36 - 0.08\ln\left(\frac{x}{\cos\theta}\right)\right\} \quad (5)$$

Where:

H_o=radiation flux just within at the surface of the pond (w/m^2)

x=depth in meter

The radiation flux reaching the bottom can be obtained:

$$H_b = H_o \left\{ 0.36 - 0.08 \ln\left(\frac{L}{\cos\theta} \right) \right\}$$
(6)

H_b= radiation flux absorbed by the bottom (w/m^2)

L= total depth of bond (m)

The reflected part is assumed as equivalent to the beam radiation at θ=60˚ for the horizontal receivers, and calculated as:

$$H_{br} = H_o \times \rho_f \left\{ 0.36 - 0.08 \ln\left(\frac{(L-x)}{\cos\theta} \right) \right\} \quad (7)$$

The reflected radiation from bottom will travel towards the surface of the pond. At surface, apart will be reflected back down in the body of the bond and the remainder will cross the water-air interface. The surface reflects secularly and 47.7% is reflected back inside, and will reach to the depth level x traveling a distance x from surface.

The surface reflected part at depth x is

$$H_{sr} = 0.477 H_b \times \rho_f \left\{ 0.36 - 0.08 \ln\left(\frac{(L+x)}{\cos 60} \right) \right\} \quad (8)$$

The net radiation at depth x will be :

$$H_{xt} = H_x - H_{br} + H_{sr}$$
(9)

About 25% of solar radiation incident at the surface penetrates to the bottom of the pond and is absorbed there, causing the adjacent brine to heat up.

Energy balance of solar pond:

The energy balance equations for the different part of the salt gradient solar ponds used the following assumptions in the mathematical model developed to simulate the solar pond:

1- The pond consists of three zones:the upper convective zone ,the non convective zone and lower convective zone.
2- The temperature and salinity distributions within the pond are one dimension.
3- The temperature and density gradient in upper convective zone and in the lower convective zone are uniform and perfectly mixed.
4- The heat exchange through the side edges is negligible.
5- Heat loss occurs from the pond's surface due to convection, evaporation and radiation.
6-Heat loss includes: evaporation, convection, and radiation from the pond surface to air.

Upper Convective Zone

Due to convection, the upper convective zone is assumed to have a uniform temperature T_0. The energy balance of this zone can be written as:

$$q_{1\to 0} + q^{\circ} - q_{loss} = \rho C_p \left(\frac{\Delta x}{2}\right)\frac{\partial T}{\partial t} \tag{10}$$

Eq (10) in non differential form can be written as:

$$k\left[\frac{T_1^i - T_0^i}{\Delta x}\right] + \frac{1}{2}(H_o - H_1) - q_{loss} = \rho C_p \left(\frac{\Delta x}{2}\right)\left[\frac{T_0^{i+1} - T_0^i}{\Delta t}\right] \tag{11}$$

Dividing by k/2Δx and using the definitions of thermal diffusivity $\alpha = k/\rho C_p$ and the dimensionless mesh Fourier number $\tau = \alpha \Delta t/(\Delta x)^2$ gives (Cengel,2002) [7]:

$$T_0^{i+1} = \left[2\tau T_1^i + (1-2\tau)T_0^i + \frac{\tau \Delta x}{k}(H_o - H_1) - \frac{2\tau \Delta x}{k} q_{loss}\right] \tag{12}$$

At the water free surface, the heat losses by convection and vaporization into the ambient air combined to that between the surface and the sky have been considered .they are summarized as flows (Ridha,2006) [23]:

(i) The radiation heat loss to the sky is given by:

$$q_r = \varepsilon_w \sigma (T_s^4 - T_{sky}^4) \tag{13}$$

The sky temperature T_{skyt} is estimated as flows:

$$T_{sky} = T_a \left[0.55 + 0.61 P_a^{0.5}\right]^{0.25} \tag{14}$$

$$P_a = \phi \exp[18.403 - (3885/(T_a - 43.15))] \tag{15}$$

(ii) The convective heat losses is given by:

$$q_c = h_c (T_s - T_a) \tag{16}$$

With h_c, the wind convective heat transfer coefficient, which depends on the average velocity V of the wind as follows:

$$h_c = 5.7 + 3.8V \tag{17}$$

(iii) The heat losses due to evaporation:

The heat losses due to evaporation are proportional to the wind convective coefficient h_c and the difference between the vapor pressure of the water at the surface and the partial pressure of the water vapor in the atmosphere which is calculated as follows:

$$q_e = \frac{\lambda h_c}{1.6 C_s P_t}(P_s - P_a) \tag{18}$$

Where the P_s is the vapor pressure evaluated at the surface temperature:

$$P_s = \exp[18.403 - (3885/(T_s - 43.15))] \tag{19}$$

The total heat losses from UCZ can be calculated as:

$$q_{loss} = q_r + q_c + q_e \tag{20}$$

3-3-2 Non Convective Zone

The energy balance of non convective zone can be written as:

$$q_{(m-1)\to m} + q_{(m+1)\to m} + q^{\circ} = \rho C_p \Delta x \frac{\partial T}{\partial t} \tag{21}$$

Eq (21) in non differential form can be written as:

$$k\left[\frac{T^i_{(m-1)} - T^i_m}{\Delta x}\right] + k\left[\frac{T^i_{(m+1)} - T^i_m}{\Delta x}\right] + (H_{(m-1)} - H_{(m+1)}) = \rho C_p \Delta x \left[\frac{T^{i+1}_m - T^i_m}{\Delta t}\right] \tag{22}$$

Dividing by k/2Δx and using the definitions of thermal diffusivity $\alpha = k/\rho C_p$ and the dimensionless mesh Fourier number $\tau = \alpha \Delta t/(\Delta x)^2$ gives (Cengel,2002) [7]:

$$T^{i+1}_m = \left[\tau T^i_{(m-1)} + (1-2\tau)T^i_m + \tau T^i_{(m+1)} + \frac{\tau \Delta x}{k}(H_{(m-1)} - H_{(m+1)})\right] \tag{23}$$

Lower Convective Zone

The lower convective zone is assumed to have a uniform temperature T_3.the energy balance of this zone can be written as:

$$q_{2\to 3} + q^{\circ} - q_g - q_{ext} = \rho C_p (\frac{\Delta x}{2}) \frac{\partial T}{\partial t} \tag{24}$$

Where q_{ext} is the rate of heat extracted in the storage zone (LCZ).
Where q_{ext} is the rate of heat losses to the ground from the storage zone (LCZ).
Eq (24) in non differential form can be written as:

$$k\left[\frac{T^i_2 - T^i_3}{\Delta x}\right] + \frac{1}{2}(H_2 - H_3) - U_g(T^i_3 - T_g) - q_{ext} = \rho C_p \left(\frac{\Delta x}{2}\right)\left[\frac{T^{i+1}_3 - T^i_3}{\Delta t}\right] \tag{25}$$

Dividing by k/2Δx and using the definitions of thermal diffusivity $\alpha = k/\rho C_p$ and the dimensionless mesh Fourier number $\tau = \alpha \Delta t/(\Delta x)^2$ gives (Cengel,2002) [7]:

$$T^{i+1}_3 = \left[2\tau T^i_2 + (1 - 2\tau - 2\tau \Delta x/k)T^i_3 + \frac{\tau \Delta x}{k}(H_2 - H_3) + \frac{2\tau \Delta x}{k} T_g - \frac{2\tau \Delta x}{k} q_{ext}\right] \tag{26}$$

Salt diffusion within the solar pond

The salt diffusion within a solar pond is made up of two factors: molecular diffusion and thermodiffusion, which is the separation of the components of the liquid mixture induced by temperature gradients (Celestino, 2006) [6]. During the diffusion process the surface zone slowly becomes more salty and storage zone loses. Most solar pond operators to salt to date have maintained the convective zone concentration by disposing of some of the surface zone brine, replacing it with fresh water and adding new salt to the storage zone of the pond (Fynn,1983) [12].

The density ρ at any point (x, t) is a function of the temperature (T) and salinity (S) for a NaCl calculated by (Celestino, 2006) [6]:

$$\rho_{(x,t)} = 1000\left\{1 - \frac{T+a}{b(T+c)}(T-d)^2\right\} + e(T)S + f(T)S^{(3/2)} + gS^2 \qquad (27)$$

Where a=288.9414,b=508929.2,c=68.12963,d=3.9863,g=48314 and

$$e(T) = 8.24493*10^{-1} - 4.0899*10^{-3}*T + 7.6438*10^{-5}*T^2 - 8.2467*10^{-7}*T^3 + 5.3675*10^{-9}*T^4$$

$$f(T) = -5.724*10^{-3} + 1.0227*10^{-4}*T - 1.6546*10^{-6}*T^2$$

The best performance was obtained when both upper convective zone UCZ and lower convective zone LCZ where held at salinity of 0% and 25%, respectively (Jubran, 2004) [15].

Efficiency

The thermal efficiency of solar ponds, which is defined as the ratio of heat removal from the lower convective zone to solar energy incident on pond surface calculated by (Andrews,2005) [2]:

$$\eta = \frac{C[T_3 - T_a] + q_{ext}}{H} \qquad (28)$$

It is mainly affected by clarity of pond water, pond configuration and temperature differences between the LCZ and U CZ, there temperature differences between the layers are sufficient to drive an organic Rankine-cycle engine that uses a volatile organic substance as the working fluid instead of steam (Omar ,2010) [19]. The heat that is absorbed increases the temperature of a working fluid inside the copper tube heat exchanger and causes the working fluid to evaporate at an elevated pressure which is used for power generation system (Rajamohan, 2008) [22].

RESULTS AND DISCUSSION

In this part, numerical results will be presented and discussed for one dimension mathematical model salt gradient solar pond. The equations obtained for the model has been solved numerically by using finite difference technique in Matlab program to investigate the effect of the various parameter on transient thermal performance of solar pond.

The effect of Depth on the Solar Radiation

(Figure 3) show a series of radiation distribution at the full depth of solar pond for a few typical times of the day during the year, the long wavelength of simulator radiation is mostly absorbed by the UCZ and radiation reaches at all depth of pond decreases with increase the depth for all time.

The effect of Temperature profiles

The temperature profiles as a function of the pond's depth for a few typical days of year for [t=12, q_{exi} =60 (w/m^2) and C=1.2 $(w/m^2 °C)$] shown in **(Figure 4)**, it is observed that temperature increases with respect to depth of the gradient zone of the solar pond, After 15 days of simulation, the temperature profiles was established. The LCZ temperature increased on the day that the solar radiation was much higher for all days in year and the LCZ temperatures at 15-July higher than the LCZ temperatures at 15- March is a result to increase solar radiation at summer as shown in **(Figure 4-a)** and **(Figure 4-b)**. The LCZ temperature increases when heat capacity rate of salt water decreases as shown in **(Figure 5)**.

The effect of Depth on the Density

(Figure 6) shows solution density versus depth of the solar pond for [t=12, q_{exi} =60 (w/m^2) and C=1.2 $(w/m^2 °C)$], this variation of the density through the depth was attributed to the diffusion rate of the NaCl in water for three zones of pond, density of salt water with increases when depth of pond increases for all days in year and the densities at 15-July higher than the densities at 15- March is a result to increase solar radiation at summer as shown in **(Figure 6-a)** and **(Figure 6-b)**.

The effect of Temperature on the Density

The variation of density with temperature at different salinities is shown in **(Figure 7)**, results showed that the solution temperature increased as the density of the solution decreased and density increased as the salinity increased at the same temperature. The results are in very good agreement (about 98.5 %) with the previous results obtained by(Jubran ,2004) [15]for the same consideration as shown in **(Figure 8)**.

Efficiency of pond

The variation of efficiency of pond with perfect rang for temperature of LCZ at [15-Jan,t=12] shown in **(Figure 9)**, Efficiency increases when temperature of LCZ increase as a result of storage heat in lower convective zone. The variation of efficiency of pond with extraction heat rate from LCZ shown in **(Figure 10)**, Efficiency increases when extraction heat rate from LCZ increase but less than the increases with temperature of LCZ.

CONCLUSIONS

Numerical analysis of salt gradient solar pond behavior is conducted in one dimension transient heat transfer model in Baghdad city provides a reasonable approximate thermal performance for a solar pond compared to other studies. The solar radiation and the ambient temperature have greatly influence on the LCZ temperature. The temperature, salinity and density of UCZ and LCZ are almost constant. Whereas, in the NCZ they are increasing with depth. Solar pond efficiency improved by increasing heat extract from the LCZ and increasing the temperature of LCZ, increasing heat extract 1.666w/m2 has the same effect of increasing LCZ temperature by 1˚C.Solar ponds are the best way among different methods of generation electricity from solar energy because of the high amount of solar radiation which increases the solar storage for this pond thus increasing the solar efficiency for the ponds and because it is very suitable for dusty Iraqi weather.

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(Table 1) Metrological data for Baghdad based on the monthly average.

Month	T_{av} (˚C)	$T_{\min}$ (˚C)	$T_{\max}$ (˚C)	ϕ (%)
January	9.6	3.7	15.5	72
February	11.75	5.2	18.3	61
March	16.05	9.2	22.9	52
April	22.35	14.9	29.8	42
May	28	19.7	36.3	31
June	32	22.8	41.2	24
July	34.45	25.1	43.8	24
August	33.65	23.9	43.4	26
September	30.1	20.1	40.1	30
October	24.25	15.4	33.1	40
November	16.5	9.2	23.8	57
December	11.1	5.2	17.0	72

(Table 2) Simulation parameters of pond.

UCZ thickness X1	0.4 m
NCZ thickness X2	2 m
LCZ thickness X3	0.6 m
Velocity of air V	3.5 m / s
Ground temperature T_g	10 ˚C
Ground loss coefficient U_g	1 $(w/m^2 \,°C)$
Latitude for Baghdad	33.16°
Longitude for Baghdad	44. 6°
thermal conductivity of salt water k	0.6 $(w/m°C)$
emissivity of surface of salt water εw	0.83
heat capacity of salt water C	1-2 $(w/m^2 \,°C)$
heat extracted from the LCZ q_{ext}	20-60 (w/m^2)

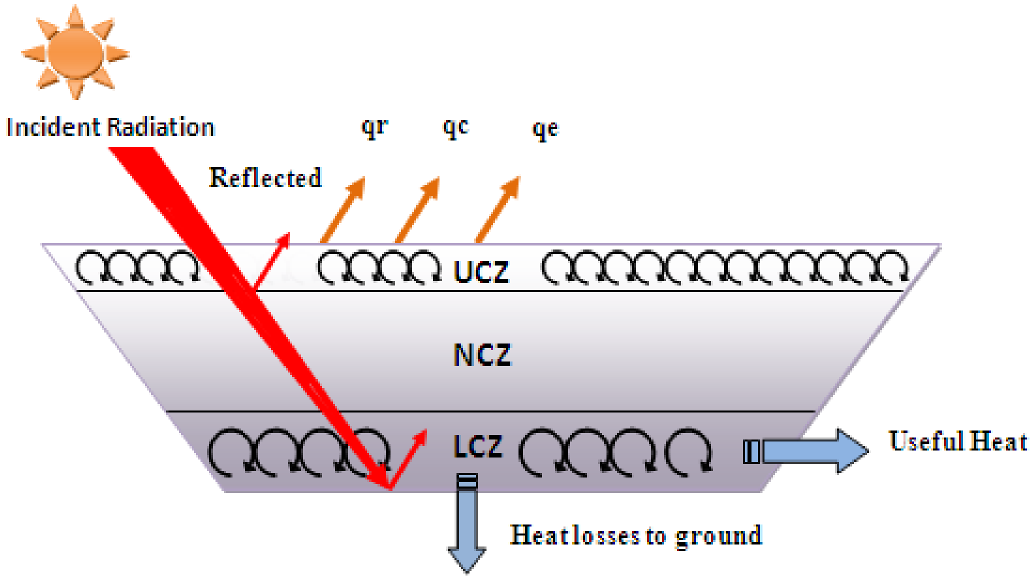

Figure 1. Schematic diagram of Salt Gradient Solar Pond

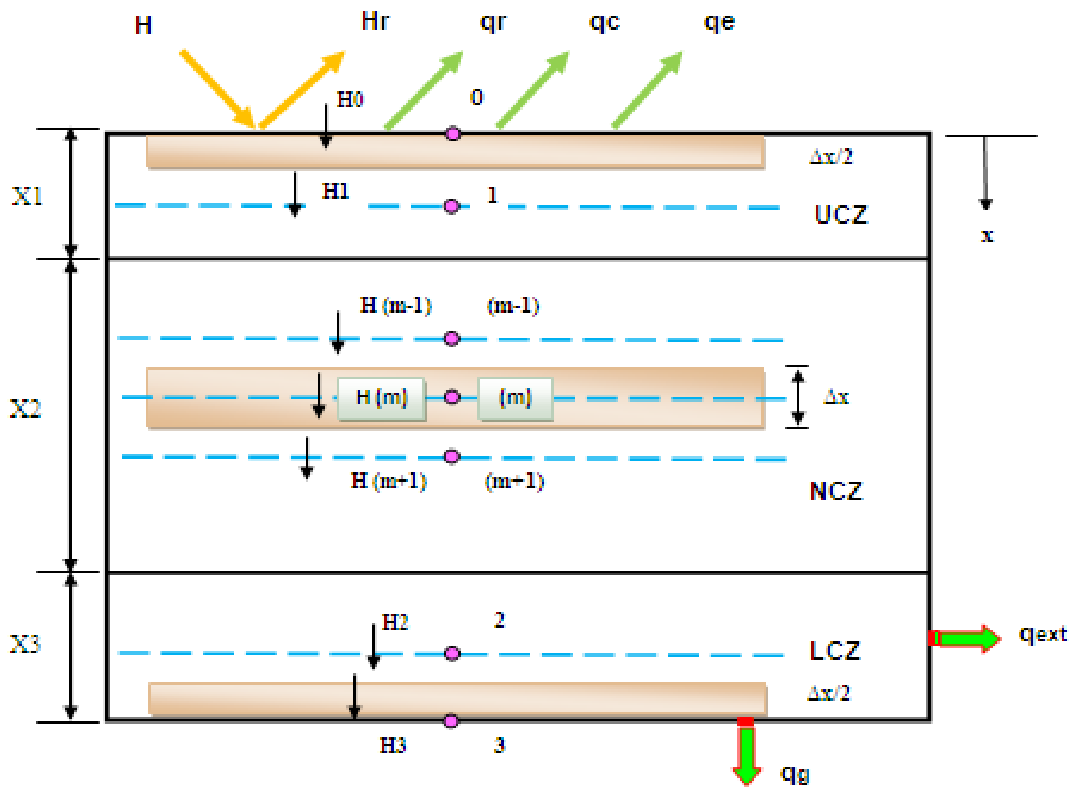

Figure 2. Solar pond model for configuration numerical analysis

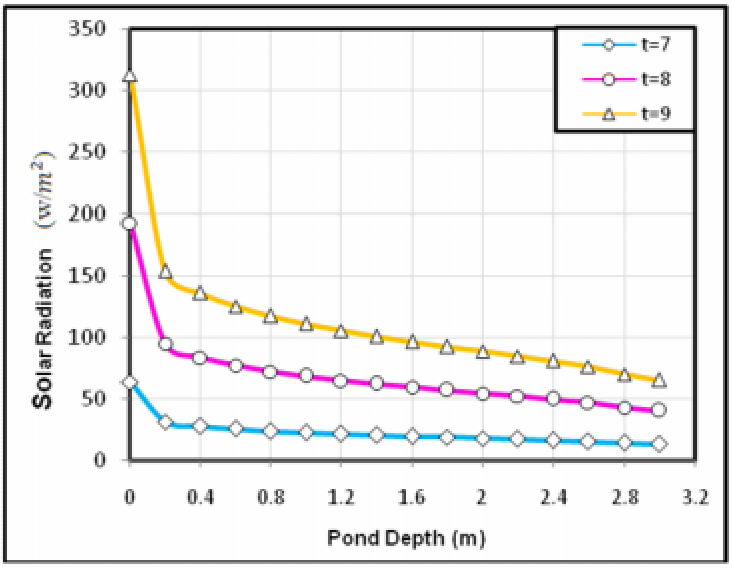

Figure 3-a. The effect of Depth on the Solar Radiation (15 - January)

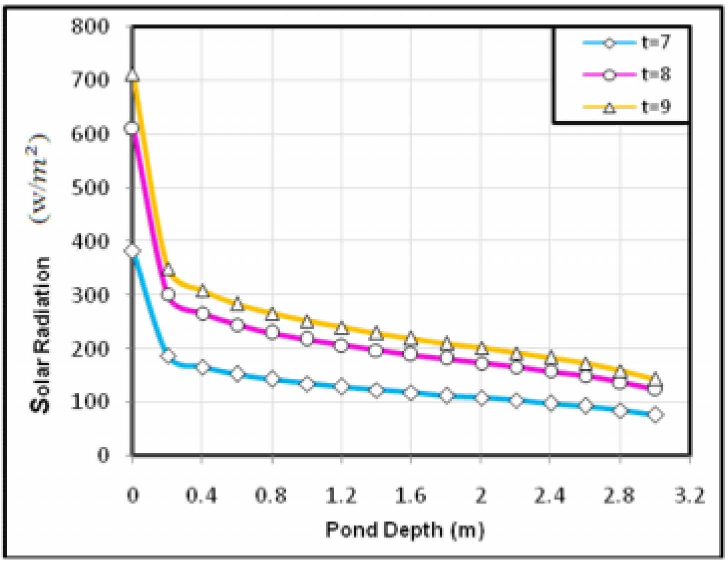

Figure 3-b. The effect of Depth on the Solar Radiation (15 - June)

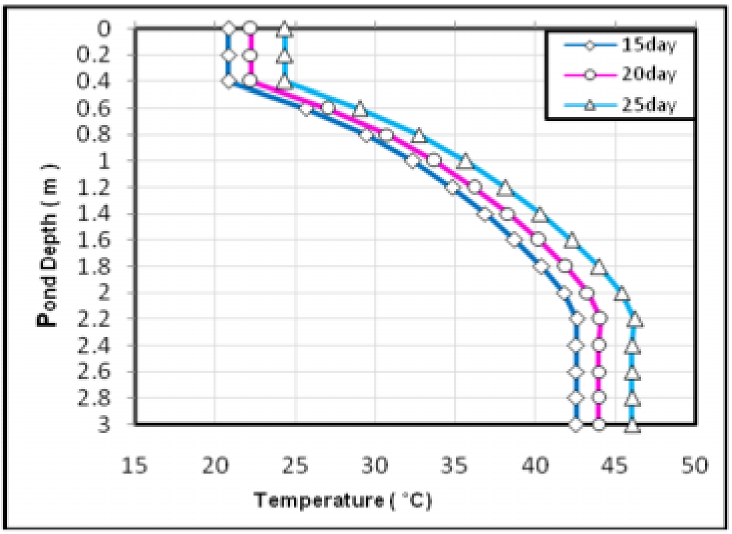

Figure 4-a. Solar pond temperature profile development (15 – March)

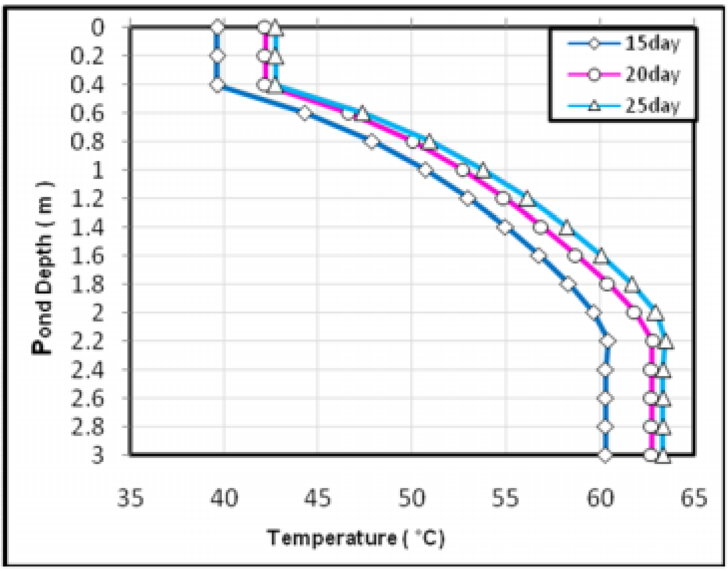

Figure 4-b. Solar pond temperature profile development (15 – July)

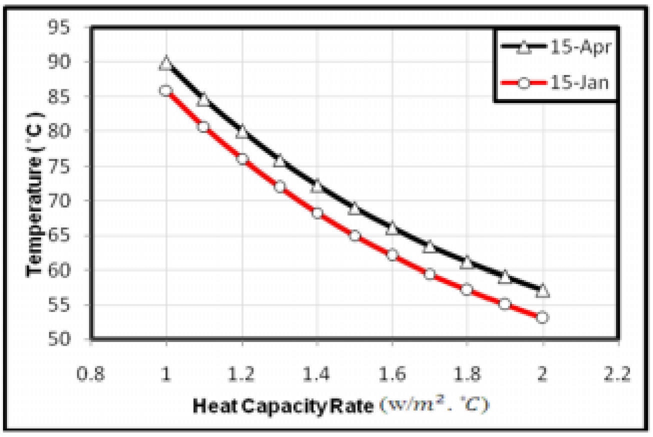

Figure 5. Temperature of LCZ versus Heat Capacity Rate

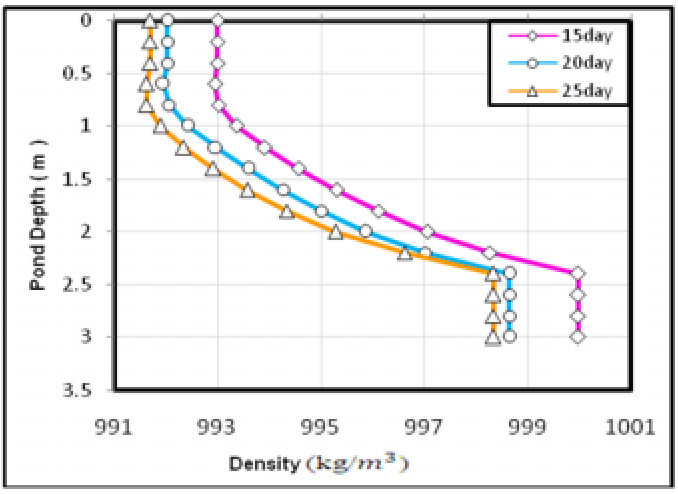

Figure 6-a. Solar pond Density profile development (15 - March)

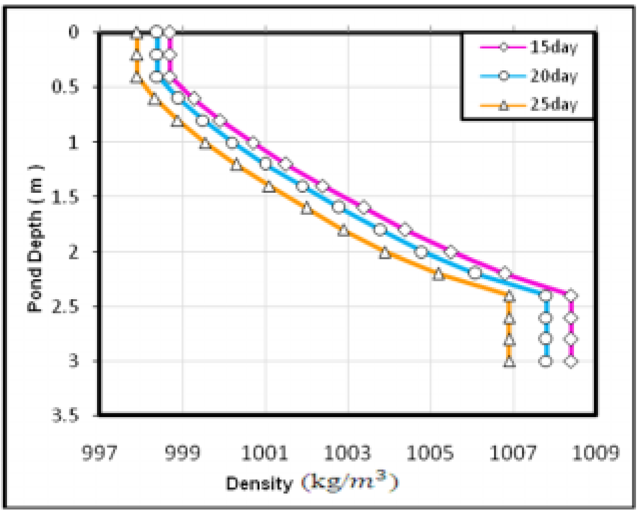

Figure 6-b. Solar pond Density profile development (15 - July)

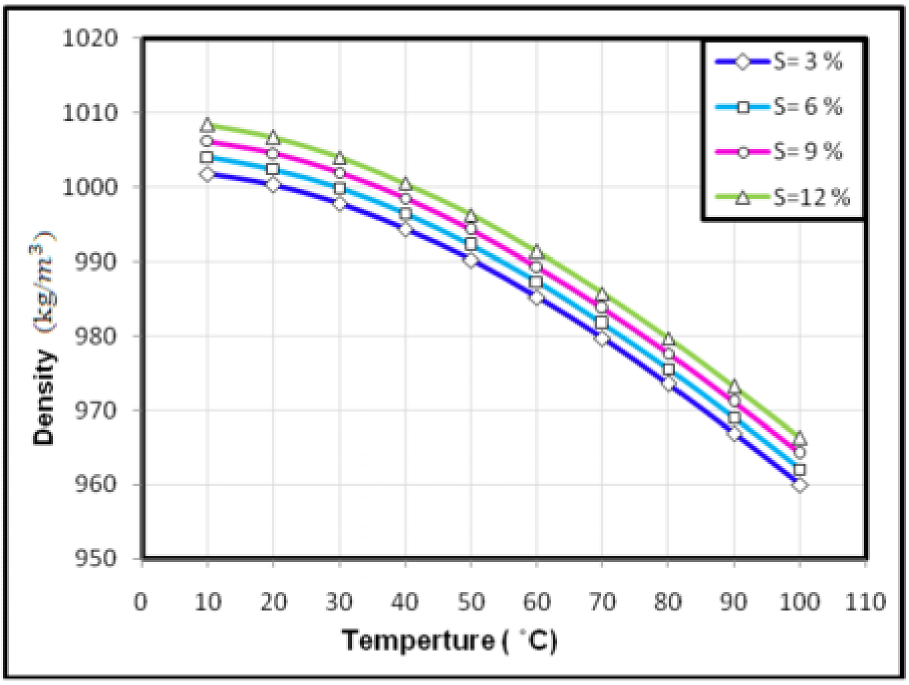

Figure 7. Density versus temperature at several salinities

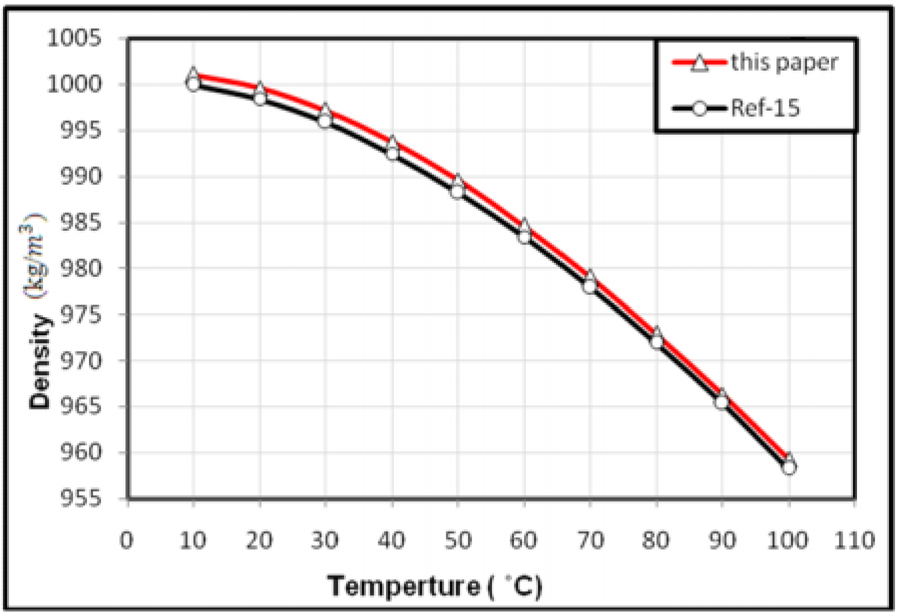

Figure 8. Comparison of Density versus temperature at 2 % salinity with reference [15]

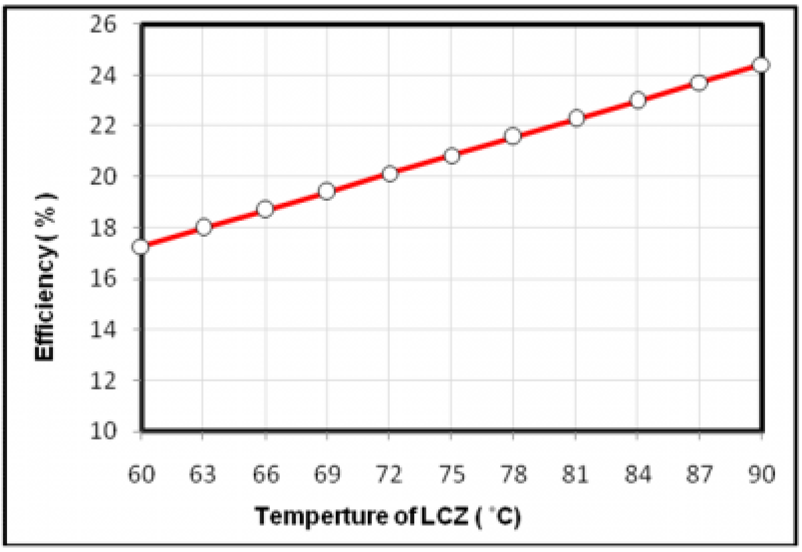

Figure 9. The effect of temperature of LCZ on the solar pond efficiency

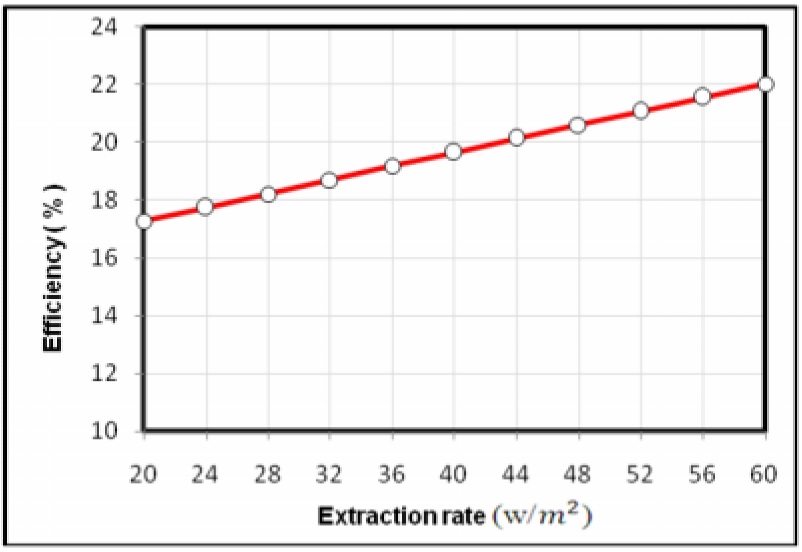

Figure 10. The effect of extraction rate on the solar pond efficiency