A Simple Heat and Mass Transfer Model for Salt Gradient Solar Ponds

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Safwan Kanan, Jonathan Dewsbury, Gregory Lane-Serff

Abstract—A salinity gradient solar pond is a free energy source system for collecting, converting and storing solar energy as heat. In this paper, the principles of solar pond are explained. A mathematical model is developed to describe and simulate heat and mass transfer behaviour of salinity gradient solar pond. MATLAB codes are programmed to solve the one dimensional finite difference method for heat and mass transfer equations. Temperature profiles and concentration distributions are calculated. The numerical results are validated with experimental data and the results are found to be in good agreement.

Keywords—Finite Difference method, Salt-gradient solar-pond, Solar energy, Transient heat and mass transfer.

I. INTRODUCTION

THE solar pond is described as an artificial large body of water reservoir that collects and stores solar energy. It is about 1 to 3 meters deep, and the bottom of the pond is usually painted black. The solar radiation landing on the surface of the pond penetrates the liquid and falls on the blackened bottom which is thereby heated. If the liquid is homogeneous which means no density gradient, convection currents will be set up and the heated liquid being lighter will travel towards the surface and dissipate its heat to the atmosphere. In a solar pond these convection currents are prevented by having a concentration gradient of salt, the solution's concentration and density being highest at the bottom and lowest at the top. Typically ponds are composed of three zones as shown in Fig.1. The first zone is Upper Convective Zone (UCZ), which is cold, close to the ambient temperature; and has low salt concentration (almost fresh water).The thickness of this surface layer varies from 0.1 to 0.4m. The second zone is Non-Convective Zone (NCZ) or (insulation layer), which has salt density increasing with depth. The thickness of NCZ ranges from 0.6 to 1.0m. Hot water in one layer of NCZ cannot rise because of its high relative density (due to its salt content) and water above is lighter (low density). Similarly, water cannot fall because the water below it has a higher salt content and is heavier (high density). Therefore convection motions are hindered and heat transfer from the hot third zone,

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Lower Convective Zone (LCZ) or (storage layer) to the cold UCZ can only happen through conduction. Given the moderately low conductivity of water, the NCZ layer acts as a transparent insulator, permitting solar radiation to be trapped in the hot bottom layer, from which useful heat is withdrawn [1]. Its thickness depends on the temperature and the amount of the thermal energy to be stored. Because of large storage of heat and small diurnal fluctuation in temperature, solar ponds have a variety of applications such as; electrical power generation, water desalination, heating and cooling of buildings and industrial process heating.

Weinberger [2] investigated the thermal energy balance for a large solar pond in 1964. The analytical solution of the partial differential equation for the transient temperature distribution was obtained by superimposing the effects of the radiation absorption at the surface, in the body of the water and at the bottom. Rabl and Nielsen [3] developed the model of Weinberger into a two-zone pond containing a LCZ and NCZ. Analytical solution methods are very useful for simple cases, however, when the model has complex boundary conditions, numerical methods should be utilized.

There have been several efforts for the numerical solution of the partial differential energy equation governing solar pond in the literature. Hull [4], Rubin et al. [5], and Kurt et al. [6] have used a finite difference method, while Jayadev et al. [7] and Panahi et al. [8] have applied a finite element technique.

In this paper, a one dimensional finite difference method for heat and mass transfer are used to solve the governing equations for solar pond located in Baghdad (33.3250° N, 44.4220° E) Iraq. Temperature distribution for one month and for whole year has been found. Salt concentration profile for pond had been considered.
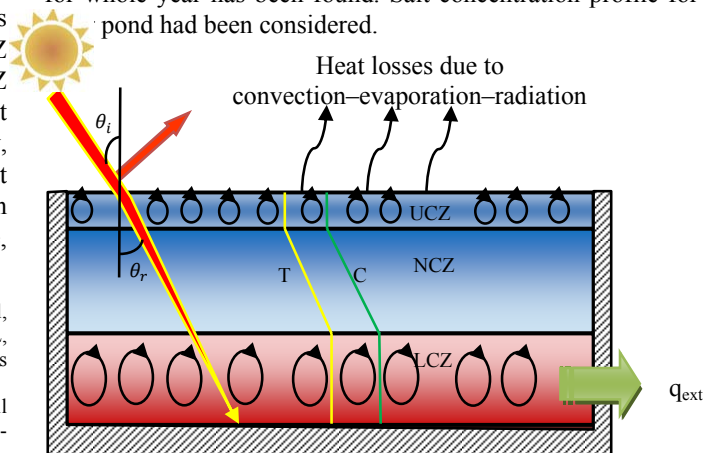

Fig. 1 Schematic view of the salt gradient solar pond

II. MATHEMATICAL FORMULATION

The solution of the heat equation for salt gradient solar pond uses 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 horizontal temperature variations are considered small enough so that they are negligible. Therefore, the temperature and salinity distributions within the pond are one dimension.
3. The temperature and density in upper convective zone and in lower convective zone are uniform and perfectly mixed.
4. The heat losses from the walls are neglected.
5. The bottom surface is blackened in order to maximize the radiation absorption. Therefore, the radiation energy reaching the LCZ is completely absorbed by the solution and the bottom of the pond.

A. Solar Radiation in Solar Pond

The solar radiation, penetrating into the water body, decays exponentially with depth, as fluid layers absorb energy. The rate of decay is a function of the wavelength of the radiation and for the whole spectrum of wavelengths.

This exponential formula was proposed by Bryant and Colbeck, [9] and seems to be in very good agreement with [3] model.

$$\frac{H_x}{H_o} = \left\{ 0.36 - 0.08 \ln\left(\frac{x}{\cos\theta_r}\right) \right\} \tag{1}$$

where H_O is the monthly average insolation incident on horizontal surface in W/m^2 and H_x is the incoming radiation flux at depth x in W/m^2. θ_r = angle of refraction at the pond's surface, which can be calculated from Snell's Law [10].

$$\frac{\sin\theta_i}{\sin\theta_r} = 1.333 \tag{2}$$

where θ_i is the angle of incidence of direct radiation to a horizontal plane with normal (zenith angle).

$$\cos\theta_i = \cos\delta \, \cos\phi \, \cos\omega + \sin\delta \sin\phi \tag{3}$$

where δ is the angle of declination, ϕ the angle of latitude, and ω the hour angle. The declination angle δ is defined in degrees by [10].

$$\delta = 23.45 \sin\left(\frac{360(284+N)}{365.25}\right) \tag{4}$$

N is the day of the year.

The hour angle ω is an angular measure of time considered from noon based on local time h, and is defined as:
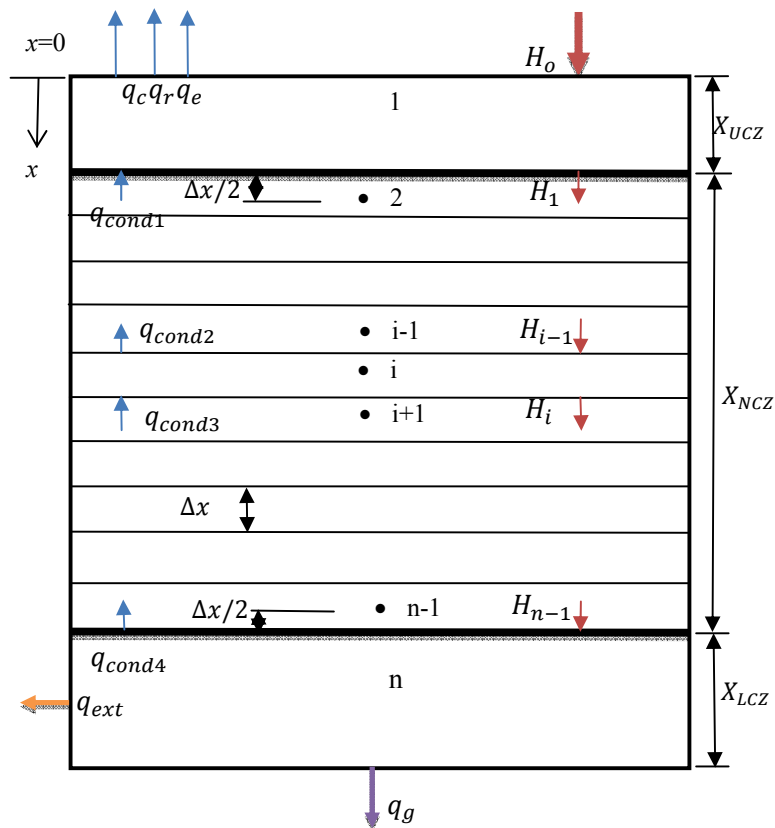
$$\omega = \frac{2\pi(h-12)}{24} \tag{5}$$

Fig. 2 Solar pond's mathematical model

B. Heat Transfer Model

In the vertical system of Cartesian coordinates with (x) measured as a positive downward and $x = 0$ at the surface of the pond as shown in Fig. 2. The mathematical model developed in the present work is based upon an energy balance over a fluid layer. Incoming energy to the layer and radiant energy absorbed by the layer equals the loss of energy from the layer and energy accumulation in the layer with time. Based upon energy conservation, the energy balance for UCZ, NCZ and LCZ are expressed as follows.

1. Energy Balance for UCZ

The energy flows in solar pond's surface can be written as:
Energy in =Energy out +Energy stored

$$[H_o + q_{cond1}] = [H_1 + q_{loss}] + \rho \, C_p \frac{\partial T}{\partial t} X_{UCZ} \tag{6}$$

where q_{loss} is the total heat loss from the pond's surface due to convection, evaporation and radiation.

$$q_{loss} = q_c + q_r + q_e \tag{7}$$

The convection heat transfer from the upper layer to the atmosphere depends mainly on the wind speed and the temperature difference between the atmosphere and the pond's water surface.

$$q_c = h_c(T_1 - T_a) \tag{8}$$

where convection heat transfer coefficient is given by. [11]

$$h_c = 5.7 + 3.8 \, V \tag{9}$$

where V is the average monthly wind speed recorded in Table I from NASA data website [12].

The radiation heat loss equation may be written as the following:

$$q_r = \sigma \, \epsilon_w \{(T_1 + 273)^4 - (T_{sky} + 273)^4\} \tag{10}$$

where ϵ_w is the emissivity of water which is assumed to be 0.83 and σ is the Stefan-Boltzmann's constant.

The sky temperature value may be found by several equations, such as: [13]

$$T_{sky} = T_a - \left(0.55 + 0.061\sqrt{P_1}\right)^{0.25} \tag{11}$$

The heat loss from the surface due to the evaporation phenomenon is given by [11].

$$q_e = \frac{L_v h_c (P_1 - P_a)}{1.6 \, C_s P_{atm}} \tag{12}$$

where

$$P_1 = \exp\left(18.403 - \frac{3885}{T_1 + 230}\right) \tag{13}$$

$$P_a = RH * \exp\left(18.403 - \frac{3885}{T_a + 230}\right) \tag{14}$$

TABLE I
WEATHER DATA FOR BAGHDAD IRAQ BASED ON THE MONTHLY AVERAGE FROM NASA[12]

Months	Insolation kWh/m²/day	T_a °C	V m/s	RH %
January	2.96	9.77	3.67	58.0
February	4.03	11.5	4.00	47.0
March	4.98	16.2	4.20	38.0
April	5.39	23.0	4.26	29.9
May	6.48	29.1	4.53	22.3
June	7.56	33.3	4.88	17.1
July	7.00	36.1	4.76	16.2
August	6.71	35.7	4.65	17.1
September	5.55	32.0	4.34	19.4
October	3.98	26.2	4.13	27.2
November	2.98	17.8	3.76	42.3
December	2.62	11.5	3.71	55.7

The finite difference for upper convective zone heat (6) can be written as:

$$T_1^{j+1} = T_1^j + \frac{\Delta t}{\rho C_p X_{UCZ}} \left[(H_o - H_1) + k\left(\frac{T_2^j - T_1^j}{\frac{\Delta x}{2}}\right) - q_{loss}^j \right] \tag{15}$$

where ρ, C_p and k are density, specific heat and thermal conductivity of sodium chloride brine.

Equation (15) is the first upper boundary condition for solar pond as defined in Fig. 2.

2. Energy Balance for NCZ

The NCZ has been divided into different layers (2 to n-1) which the energy equation is formulated below. The energy balance for any layer in the NCZ can be written as:

$$[H_{i-1} + q_{cond3}] = [H_i + q_{cond2}] + \rho \, C_p \frac{\partial T}{\partial t} \Delta x \tag{16}$$

The temperature for any layer through NCZ in finite difference form can be obtained from (16) as:

$$T_i^{j+1} = T_i^j + \frac{\Delta t}{\rho C_p \Delta x}\left[(H_{i-1} - H_i) + k\left(\frac{T_{i+1}^j - T_i^j}{\Delta x}\right) - k\left(\frac{T_i^j - T_{i-1}^j}{\Delta x}\right)\right] \tag{17}$$

The temperatures of NCZ can be calculated from above equation as internal nodes for the solar pond model.

3. Energy Balance for LCZ

From Fig. 2, the energy conservation equation for LCZ with a thickness of X_{LCZ} can be written as:

$$[H_{n-1}] = [q_{cond4} + q_{ext} + q_g] + \rho \, C_p \frac{\partial T}{\partial t} X_{LCZ} \tag{18}$$

In (18), the left hand side is the radiation energy entering the control volume of LCZ; and in the right hand side, the first term is the heat loss to the non-convective zone at the interface, the second term is the useful heat extracted from the solar pond, the third term is the heat loss to the ground, the forth term is the energy stored within the LCZ layer. The conduction heat loss from LCZ to NCZ at the interface is given as:

$$q_{cond4} = -k \left.\frac{\partial T_n^j}{\partial x}\right|_{x = X_{UCZ} + X_{NCZ}} \tag{19}$$

The ground heat loss can be written as:

$$q_g = -k_g \left.\frac{\partial T_n^j}{\partial x}\right|_{x = X_{UCZ} + X_{NCZ} + X_{LCZ}} \tag{20}$$

Using (19) and (20) in (18) and simplifying, gives the temperature of the LCZ, explicitly at the time of j+1 as:

$$T_n^{j+1} = T_n^j + \frac{\Delta t}{\rho C_p X_{LCZ}}\left[(H_{n-1}) - k\left(\frac{T_n^j - T_{n-1}^j}{\frac{\Delta x}{2}}\right) - q_{ext}^j - U_g(T_n^j - T_g^j)\right] \tag{21}$$

where U_g is the ground overall heat transfer coefficient and it can be obtained from Hull [14].

$$U_g = \frac{k_g}{L_g} + b \, k_g \frac{p}{A} \tag{22}$$

where b is an empirical parameter, equal to 1.37 for vertical wall solar pond [14]; p and A are the pond perimeter and area; k_g is the ground thermal conductivity; L_g can be considered as the distance of water table from the bottom of the pond; T_g can be taken as the ground water temperature.

C. Mass Transfer Model

There are several physical processes occurring in the operation of a solar pond. Convective mass-transfer occurs in the LCZ and UCZ and diffusive mass-transfer in the NCZ. The density gradient could be develop by molecular diffusion. In the proposed model, the total mass of the system in the control volume is constant, and the mass transfer is only the result of molecular diffusion. The mass-transfer processes are assumed to be independent of the thermal processes. Based upon these assumptions, one dimensional mass diffusion in the x-direction for a differential volume-element of thickness, Δx, is given as follows:

$$-\frac{\partial J}{\partial x} = \frac{\partial \rho(x,t)}{\partial t} \qquad (23)$$

The Fick's law of diffusion state that the diffusion flux J is proportional to the density gradient by

$$J = -D\frac{\partial \rho(x,t)}{\partial x} \qquad (24)$$

Substituting from (24) into (23) assuming constant salt diffusivity D in m^2/s, the mass transfer differential equation can be written as:

$$\frac{\partial}{\partial x}\left(D\frac{\partial \rho(x,t)}{\partial x}\right) = \frac{\partial \rho(x,t)}{\partial t} \qquad (25)$$

The salinity can be defined as the ratio of concentration to density of the salt water [1].

$$S(x,t) = \frac{C(x,t)}{\rho(x,t)} \qquad (26)$$

So that the (25) can be written as

$$\frac{\partial}{\partial x}\left(D\frac{\partial C(x,t)}{\partial x}\right) = \frac{\partial C(x,t)}{\partial t} \qquad (27)$$

where S is the salinity % and C is the salt concentration, kg/m^3, the diffusion coefficient of salt water (brine), D is $3*10^{-9}$ m^2/s, according to [15].

The mass transfer partial differential (27) can be discretized to

$$D\frac{C_{(i-1)}^j - 2*C_{(i)}^j + C_{(i+1)}^j}{\Delta x^2} = \frac{C_{(i)}^{j+1} - C_{(i)}^j}{\Delta t} \qquad (28)$$

Then

$$C_{(i)}^{j+1} = \frac{D\Delta t}{\Delta x^2}\left[C_{(i-1)}^j - 2*C_{(i)}^j + C_{(i+1)}^j\right] + C_{(i)}^j \qquad (29)$$

This equation is representing a concentration profile for internal nodes in the NCZ. The initial conditions are assumed to be 10 kg/m^3 at the UCZ and 178 kg/m^3 at the LCZ with linear distribution in the NCZ.

For the mass transfer equation, the two boundary conditions are:

At the top of the pond, the mass balance gives:

$$D\frac{\partial c}{\partial x} = \frac{\partial c}{\partial t} X_{UCZ} \text{(B.C.1)} \qquad (30)$$

At the bottom of the pond

$$-D\frac{\partial c}{\partial x} = \frac{\partial c}{\partial t} X_{LCZ} \text{ (B.C.2)} \qquad (31)$$

III. NUMERICAL SIMULATION

The governing equations (15), (17), (21), (29), (30) and (31) obtained from the heat and mass transfers are solved numerically to determine the temperature and concentration profiles within the pond. The method used in generating solutions to the one dimensional temperature and density finite-difference equations is explicit because unknown nodal variables for a new time are calculated using the known values of the parameters at a previous time. A finite-difference form of the differential equation is derived by integration over the control volume surrounding the typical node (i), as shown in the grid of Fig. 2. MATLAB codes have been written to solve these equations. The NCZ was divided into (n-1) equal size layers, where (n=100) was assumed. A space step of Δx is 0.01 m and a time step Δt of 300 sec were used in the code. The UCZ and LCZ are considered as a single grid points. The numerical stability criterion of explicit formulation is $\tau = \alpha \Delta t /\Delta x^2 \leq 0.5$, where α is thermal diffusivity. The mass transfer equation is of exactly the same form as the one dimension unsteady heat-conduction equation: the same mathematical techniques are applicable for its solution. The results are calculated with constant ambient temperature for each months and the monthly averaged insolation incident on a horizontal surface. The effect of night and day to day variations for solar radiation was neglected due to the monthly average data taken from NASA website. For example, during June is 7.56 KW/m^2/day for 22 years and 33.3ºC for ambient temperature. In the simulation, input data are 2m depth of the pond, $3*10^{-9}$ m^2/s thermal diffusivity, and 0.566 w/m ºC thermal conductivity of salt water. The density of salt water and specific heat at constant pressure at 40ºC and salinity 10% NaCl by mass are 1063.8 kg/m^3, 3758.3 J/kg.ºC respectively. The thermal diffusivity is $1.4156*10^{-7}$ m^2/s at the same temperature and salinity. The thickness of UCZ was taken to 0.3m, the NCZ is 1m and the LCZ is 0.7m.

In ground heat loss $k_g = 2.15$ w/m ºC [16] and $T_g = 23.2$ºC at $L_g = 6$ m depth [17].

The output of the MATLAB codes are the temperature and concentration profiles of the pond. The simulation has been run for a year starting from 1st January until the 30th of January for the next year. The results of temperature for the current month are used as the initial conditions for next month. The computer program has been successfully validated by comparing the calculated temperature distribution with available experimental data for specific period of time and a good agreement was achieved from this comparison.

IV. RESULTS AND DISCUSSION

A. Temperature Distribution inside the Solar Pond

Temperature profiles as a function of the pond's depth for selected city are shown in Fig. 3. The initial pond's temperature is assumed to be 25°C. The average ambient temperature is 33.3°C and the average monthly solar radiation is 7.56 kW/m²/day. It is observed that temperature increases with respect to depth of the gradient zone NCZ of the solar pond, after 30June.Themaximum temperature at the LCZ in the pond is exceed 66°C with included the heat loss to the ground and from the surface. This profile in LCZ temperature is agreed with physical and experimental data of solar pond.

Fig. 3 illustrates the temperature profiles development for the pond. It shows the temperature distribution for different selected days. After fifteen days of simulation the temperature in the LCZ is increased with respect to time and depth exceeding 50°C. If the simulation carries on for next month the temperature will be increased and also the useful heat that extracted from the pond. This heat can be used for any suitable applications such as electrical power generation, and heating and cooling of buildings. The increase in temperature in any day of the simulation is due to accumulated heat absorbed in LCZ from the previous day.
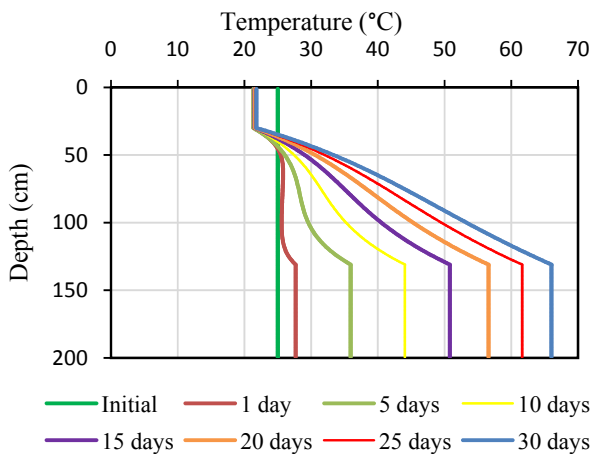

Fig. 3 Temperature profile development for solar pond during June.

B. Concentration Profile inside the Solar Pond

The UCZ has low salt concentration 10 kg/m³ and the LCZ has the high salt concentration 178 kg/m³ and the NCZ is assumed to have linear distribution. Fig. 4 shows the salt concentration profile inside the solar pond. The code was run for one month start from 1st of June until the 30th. It is obvious there is a small change in concentration profile inside the pond, that's means the pond is stable and the salt concentration gradient does not need any maintenance during short period of operation.

The code was also run for one year and two years stating from initial distribution for concentration. It is observed that the salt concentration for UCZ is increased after one year of simulation and increased more after two year, whereas the salt concentration for LCZ is decreased for one and two years.

This is because of the diffusion of salt concentration inside the solar pond and the mass transfer will occur form the high concentration to low concentration varying with the time and it is assumed that the fluid at rest (velocity is zero). If this phenomenon still happens inside the solar pond, the stratification of the NCZ layer will be disturbed. Therefore the stratified regions on the solar pond need maintenance by flushing the UCZ and adding saturated brine in the LCZ.
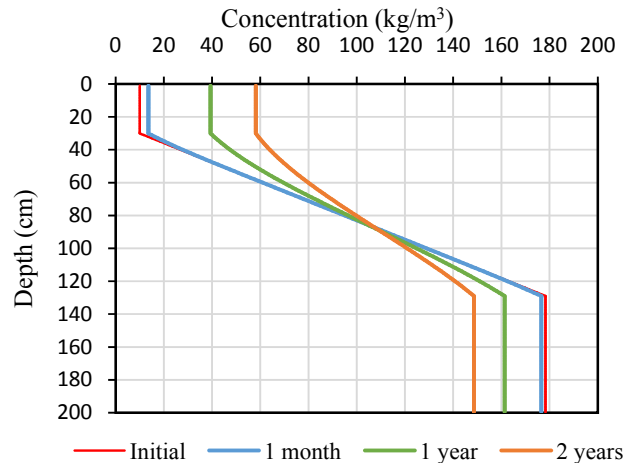

Fig. 4 Salt concentration profile in the solar pond

C. Validation of Temperature Distribution

In order to check the accuracy of the numerical code specifically developed for the solution of the problem considered in the present study, the temperature distribution is validated with experimental temperature data from Pyramid Hill solar pond. It has been constructed at Pyramid Salt's facility at Pyramid Hill in northern Victoria, Australia with a surface area of around 3000 m². Fig. 5 shows temperature distribution inside the solar pond on 3rd February 2006 for present numerical study and experimental data published by [18]. Weather data for specific location is found from Bureau of meteorology [19]. The monthly averaged insolation incident on a horizontal surface is 8.4 kWh/m²/day and the average ambient temperature is 29°C.

The dimensions of pond's layers were UCZ=0.8 m, NCZ=0.7 m and LCZ=0.8 m. The bottom of the solar pond was insulated with 100 mm thick expanded polystyrene (EPS) insulation to reduce the average heat loss by 42% [18]. It can be seen that the temperature profile of present study and experimental data show a good agreement.
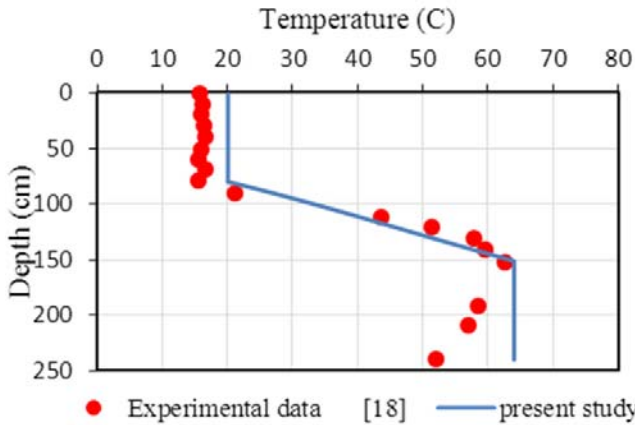
Fig. 5 Validation of temperature distribution with experimental data of [18]

D. Effect of NCZ and LCZ Thicknesses on the Temperature

The NCZ of the solar pond can act as a thermal insulator and the LCZ is the region where the thermal energy is stored. To better understand the effects of the thicknesses of NCZ and LCZ on the thermal behaviour of the solar pond during the storage of solar energy as thermal energy in the bottom of the pond, it has reproduced in Fig. 6 the temperature distribution in a salt-gradient solar pond with different thicknesses of NCZ, (0.7m, 1m and 1.3 m) and LCZ thicknesses are (1m, 0.7 m and 0.4 m) respectively. The thickness of UCZ is fixed to 0.3 m.
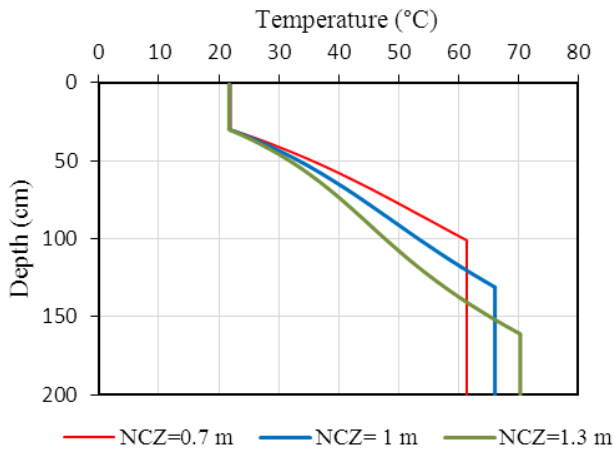

Fig. 6 Effect of the thickness of NCZ and LCZ on the temperature profile at the end of June

Fig. 6 shows that there is a decrease of the temperature of the NCZ due to the increase of its thickness which increases the insulation property and subsequently reduces the upwards heat losses. In addition, the decrease of the thickness of LCZ will increase the storage temperature in this zone.

E. Heat Extracted from the Solar Pond

The code was run from 1st of January until the 30th of January for next year. Heat was extracted from the solar pond after four months (no load) from simulation start point. The heat extracted was different from one case to another

depending on the load applications. From these amounts of heat extracted from the pond and depending on the surface area of solar pond, the heat supplied to different types of applications can be calculated.

Fig. 7 illustrates the annual LCZ temperature profile at the end of each month with the ambient temperature. It can be seen that the LCZ temperature increased to peak in July and then decreased to point higher than its initial value. The LCZ temperature depended on the solar radiation absorbed by the LCZ, ambient and initial temperatures of each months and the amount of heat extracted from the solar pond.
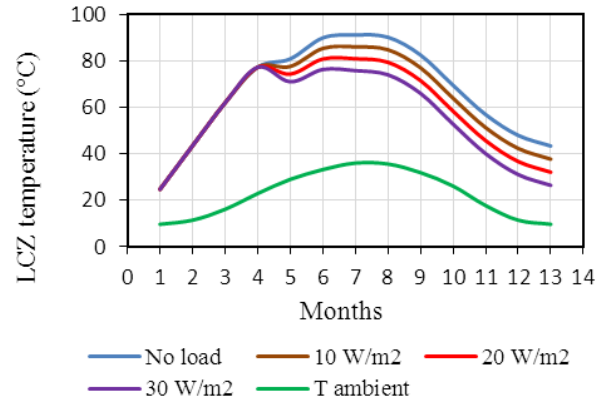

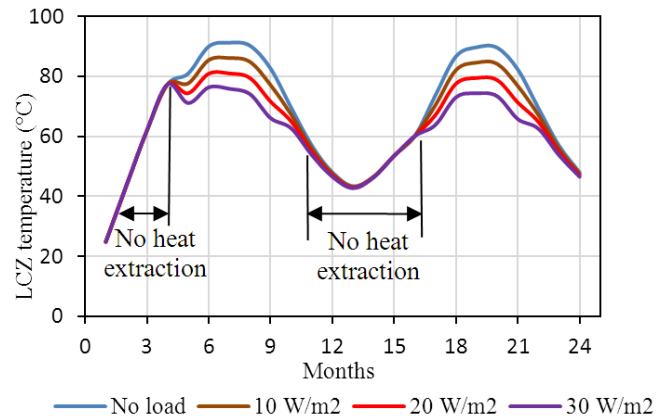Fig. 7 Annual LCZ temperature with heat extracted from the solar pond

Fig. 8 LCZ temperature for two years with heat extraction

In Fig. 8, the simulation for solar pond was run for two years started from 1st of January until the 30th December for the next year. No heat extracted during the first four months and also from October to April for next year. Different heat extracted applied for solar pond depending on the load demand for different applications. The minimum LCZ temperature is 42 °C in December first year and the maximum LCZ temperature is 91°C in June first year.

V. CONCLUSIONS

This paper has presented heat and mass transfer mathematical model for salt gradient solar ponds.

Temperatures distribution and concentration profile are calculated. Temperature distribution has been compared and validated with experimental data. The results have showed a good approximation and agreement. The following conclusions seem to be pertinent:

- Solar ponds are reliable solar collector-storage systems which can provide thermal energy during summer. So that it could be used to supply energy for different applications.
- The solar pond cannot work without a stable concentration profile. This means, the concentration should be increase downwards to prevent any gravitational overturn. In contrast, a weak salt gradient cause's instability in solar pond and this leads to effect on solar pond's insulation so that energy will be lost through the surface of the pond.
- The maximum LCZ temperature is 91°C in July without heat extraction from the pond whereas the maximum LCZ temperature is 76° C in June with 30 W/m^{2}heat extraction. Total power output from a typical pond's area (100*100) m^{2}is 300 KW.
- LCZ temperature is decreased when NCZ thickness decrease and it is increased when LCZ thickness decrease.

NOMENCLATURE

Symbol	Quantity	Units
A	Pond's area	m^2
b	Empirical parameter (22)	
C	Salt concentration	kg/m^3
C_p	Specific heat capacity of salt water	J/kg °C
C_s	Humid heat capacity of air	J/kg °C
D	Coefficient of salt diffusion	m^2/s
h	Local time	hours
h_c	Convective heat transfer coefficient	W/m^2°C
H_O	Monthly average insolation incident on horizontal surface	W/m^2
H_x	Incoming radiation flux at depth x	W/m^2
J	diffusion flux	kg/m^2 s
k	thermal conductivity of NaCl brine	W/m °C
k_g	Ground thermal conductivity	W/m °C
L_v	Latent heat of evaporation of water	J/kg
L_g	distance of water table from the bottom of the pond	m
N	Day of the year	
p	Perimeter of the pond	m
P_1	Vapor pressure of water at the surface temperature	Pa
P_a	Partial pressure of water vapor in the ambient air	Pa
P_{atm}	Atmospheric pressure	Pa
q_c	Convection heat transfer	W/m^2
q_{cond}	Conduction heat transfer	W/m^2
q_e	Evaporation heat transfer	W/m^2
q_{ext}	Heat extracted from the pond	W/m^2
q_g	Heat loss to the ground	W/m^2
q_{loss}	Total heat loss from the pond's surface	W/m^2
q_r	Radiation heat transfer	W/m^2
RH	Relative humidity	%
S	Salinity	kg/m^3
T	Temperature	°C
T_a	Ambient temperature	°C
T_g	Ground water temperature	°C
t	Time	s

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