Salt Gradient Solar Pond Heat Transfer Model for Lahore

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***Abstract*—**A solar pond with salt gradient is a system used to collect, convert and store heat energy absorbed from solar energy. Basic salt gradient operation in a solar pond is presented in this study. A numerical model is developed and simulated for mass and heat transfer behavior of a solar pond. Pond's water temperatures and salt concentration distributions are observed. The results are obtained for the climatic conditions of Lahore and established that system is viable to operate in this climatic condition.

***Keywords*—**Solar Pond, Solar Thermal Energy Lahore, Solar Pond Heat and Mass Transfer.

I. INTRODUCTION

Solar energy is widely available renewable and clean energy resource with its direct use as solar radiation and indirect use as wind, biomass, hydro, and ocean and wave energy [i]. The global annual energy consumption in 2013 was approximately 0.154 Million TWh, which is very less than the solar energy availability on earth. [ii] Pakistan lies in a region with sufficient potential for solar thermal application. The annual average solar insolation is 5-6 kWh/m^2.day with 8-10 sunshine hours a day [iii].

Solar pond is a water reservoir which is used for solar energy collection and storage. For a normal water body, hot water rises to the surface when sunlight heats up the water, and exchanges its heat with surface air. The salt gradient solar pond technology controls this process of hot water heat loss with depth by the salt concentration, makes a density gradient at the middle layer. The difference of salt concentration acts as membrane to avoid mixing. The pond is 1 to 3 meter deep with the black color lined bottom surface to increase solar energy absorption. The solar pound has three salt gradient layers as shown in Fig. 1. Upper Convective Zone (UCZ) is the top layer, which is cold and in contact with ambient conditions, having lowest salt concentration. The thickness of UCZ layer is normally from 10cm to 40cm. The Non Convective Zone (NCZ) is the second layer, it works as insulator. The thickness of this layer is from 60 - 100m. The bottom layer is Lower Convection Zone (LCZ) with highest salt density and works as heat storage layer. The salt density in NCZ is more than UCZ and less than LCZ, this creates a non-convection layers system which inhabits heat transfer between layers by thermal convection. The conductivity of water is lower and solar radiation passes NCZ to LCZ and get absorbed. The temperature of bottom layer is almost constant and in can be up to 100°C [iv]. Solar pond area varies with the heat energy requirement and application. Solar pond is used for multiple applications such as water desalination, refrigeration, cooling and heating in buildings and low temperature heat application in industry.

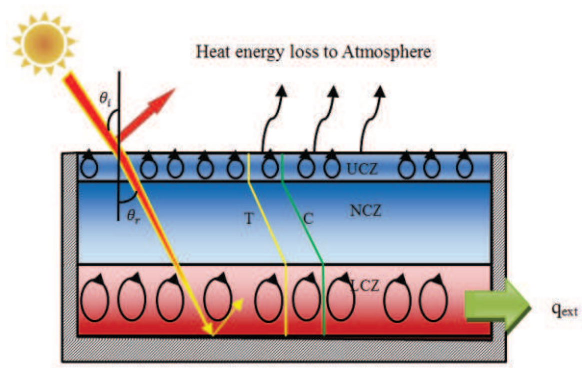

Fig. 1. Construction of simple salt gradient solar pond

Many studied have been carried out about salt diffusion and heat transfer with in solar pond to predict its performance. Researchers of [v] was the first who presented the mathematical model to study behavior of salt gradient solar pond. He analyzed processes like absorption of solar radiation, heat energy loss to atmosphere and ground surface. He used partial differential equation and obtained the analytical solution for the transient temperature distribution of the solar pond. Reference [vi] designed a salt gradient solar pond for experimental plant. The pond was used to investigate the behavior and use of solar pond for collection and seasonal storage of solar energy. Authors of [vii] has predicted the time-dependent behavior of the interface between the convecting and the non-convecting zones of the solar pond by developing a numerical model. Reference [viii] modified the

Weinberger model for two-zone simple pond with Lower and Non Convective Zones only.

For solar pond models with complex boundary conditions, numerical methods are suitable. The authors of [ix-xii] used finite difference method for solar pond. Reference [xiii] used a finite element method to develop and simulate a one-dimensional model and studied the dynamic performance of a salt-gradient solar pond. Researcher [xiv] also used finite element method.

In this paper, simple mathematical equation (one dimension) model for mass and heat transfer is used to simulate solar pond located in Lahore (31.5497° N, 74.3436° E) Pakistan. The temperature profile for the pond layers is analyzed for the month of May and salt concentration behavior is observed for 2 year period. The 22 years monthly average solar insolation and weather data for Lahore is shown in Table I.

TABLE I
MONTHLY AVERAGE WEATHER DATA FOR LAHORE [XV]

Month	Insolation kWh/m² day	Ta °C	V m/s	RH %
January	3.31	10.6	3.77	53.9
February	4.3	13.5	3.89	49.2
March	5.41	19.6	3.94	40
April	6.53	26.2	4.08	30.2
May	7.34	30.6	4.42	30
June	7.26	32.5	4.53	39.4
July	6.14	30.1	3.68	63.5
August	5.69	28.4	3.34	71
September	5.58	26.8	3.59	61.8
October	5.04	22.9	3.67	42.3
November	4.01	17.7	3.82	38.2
December	3.24	12.5	3.85	45.9

II. MATHEMATICAL FORMULATION

The mathematical heat equation of salt gradient solar pond is solved in Matlab.

A. Solar Radiation and Heat Transfer in Pond

The solar radiation penetration in the water body is not linear. Reference [xvi] proposed an exponential formula for solar energy penetration in the pond.

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

where

H_o =Mean monthly solar insolation on horizontal (W/m²)

Hx =Incident solar radiation flux at depth 'x' (W/m²)

θ_r =Angle of refraction for Pond's surface

The angle of refraction can be calculated from Snell's law and zenith angle, declination angle and hour angles from basic solar energy equations. [xvii]

The heat transfer system model for solar pond is shown in Fig. 2 The value of depth 'x' is zero at surface and increases towards bottom of the solar pond. For this work mathematical model is developed for energy balance in each layer of the pond.

Each layer energy input is equal to energy absorbed/stored and energy loss by that layer.

For UCZ energy balance is described the following equations;

$$[H_o + q_{cond1}] = [H_1 + q_{loss}] + \rho C_p \frac{\partial T}{\partial t} X_{UCZ} \qquad (2)$$

where

q_{loss} = pond surface total heat loss including evaporation (q_e), convection (q_c) and radiation (q_r).[xviii, xix]

ρ = Density of sodium chloride brine (kg/m³)

Cp=NaCl brine specific heat (kJ/Kg.°C)

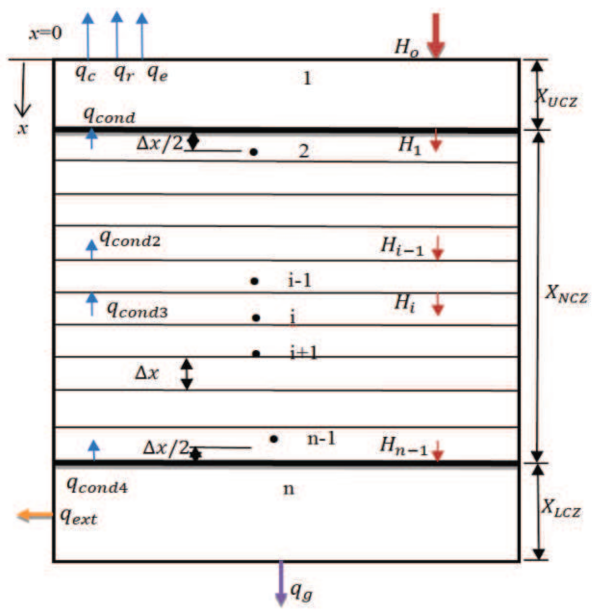

Fig. 2. Representation of solar pond's mathematical model.

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

The finite difference equation for UCZ heat balance for temperatures can be written as;

$$T_1^{j+1} = T_1^j + \frac{\Delta t}{\rho C_p X_{UCZ}}\left[(H_o - H_1) + k\left(\frac{T_2^j - T_1^j}{\frac{\Delta x}{2}}\right) - q_{loss}{}^j\right] \qquad (3)$$

where;

k = NaCl brine thermal conductivity (W/m °C)

X_{UCZ} =Thickness of UCZ

The boundary for NCZ ranges from 2 to n-1 and energy balance for this layer is written as;

$$[H_{i-1} + q_{cond3}] = [H_i + q_{cond2}] + \rho C_p \frac{\partial T}{\partial t} \Delta x \quad (4)$$

The finite difference equation for NCZ heat balance for temperatures can be written as;

$$T_i^{j+1} = T_i^j + \frac{\Delta t}{\rho C_p \Delta x}\left[(H_{i-1} - H_i) + k\left(\frac{T_{i+1}^j - T_i^j}{\Delta x}\right) - k\left(\frac{T_i^j - T_{i-1}^j}{\Delta x}\right)\right] \quad (5)$$

The thickness of LCZ is X_{LCZ}, the heat balance equation can be written as;

$$[H_{n-1}] = [q_{cond4} + q_{ext} + q_g] + \rho C_p \frac{\partial T}{\partial t} X_{LCZ} \quad (6)$$

The finite difference equation for LCZ heat balance for temperatures can be written as;

$$T_n^{j+1} = T_n^j + \frac{\Delta t}{\rho C_p X_{LCZ}}\left[(H_{n-1}) - k\left(\frac{T_n^j - T_{n-1}^j}{\frac{\Delta x}{2}}\right) - q_{ext}{}^j - U_g(T_n^j - T_g^j)\right] \quad (7)$$

where, U_g= Ground over all heat transfer coefficient [xx]

B. Mass Transfer Model for Solar Pond

During operation of solar pond different mass transfers processes occur due to temperature, heat and density gradient. In the NCZ diffusive mass-transfer occurs, whereas in UCZ and LCZ convective mass-transfer occurs. For this model, total mass of pond is constant with in fix volume, and only molecular diffusion creates mass transfer. Thermal gradient based mass transfer is neglected. The one dimensional mass transfer in x direction with thickness of Δx in NCZ is written as:

$$\frac{\partial}{\partial x}\left(D\frac{\partial C(x,t)}{\partial x}\right) = \frac{\partial C(x,t)}{\partial t} \quad (8)$$

This equation can be transformed for salt concentration as;

$$C_{(i)}^{j+1} = \frac{D\Delta t}{\Delta x^2}\left[C_{(i-1)}^j - 2 * C_{(i)}^j + C_{(i+1)}^j\right] + C_{(i)}^j \quad (9)$$

where;

C = Salt concentration (kg/m^3)

D = Diffusion co-efficient of saline water (3×10^{-9} m^2/s) [xxi]

The mass transfer equation for UCZ is as:

$$D\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} X_{UCZ} \quad (10)$$

The mass transfer equation for LCZ is as:

$$-D\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} X_{LCZ} \quad (11)$$

The above equation the initial conditions of salt concentrations are assumed for UCZ and LCZ as 10kg/m^3 and 178 Kg/m^3 respectively with linear distribution in NCZ.

III. Methodology

The heat and mass transfer equations (3), (5), (7), (9), (10) and (11) have been solved by MATLAB codes to obtain the temperature profile and salt concentration of the solar pond. The boundary conditions are shown in the Fig.2. The NCZ is divided into equally sized layers (n-1). Where it is assumed that n=100, Δx = 0.01m and Δt =300 sec.

The upper and lower convective zones are supposed as one grid point. The explicit formulation of numerical stability criterion is

$\tau = \alpha \Delta t / \Delta x^2 \leq 0.5$, where α is thermal diffusivity.

The results are obtained from simulation with monthly average solar insolation on a horizontal surface and monthly average ambient temperature and. From Lahore weather data, 22 years monthly average insolation is 7.34 kWh/m^2.day and ambient temperature is 30.6ºC for the month of MAY is used. In the simulation the input data used as; pond depth of 2m, thermal diffusivity and thermal conductivity of saline water are 3×10^{-9} m^2/s, and 0.566 W/m ºC respectively. The specific heat, density and thermal diffusivity of saline water at constant pressure and temperature of 40ºC with salinity of 10% NaCl by mass are 3758.3 J/kg. ºC, 1063.8 kg/m^3 and 1.4156×10^{-7} m^2/s respectively. The thicknesses of upper, non-convective and lower zones are 0.30m, 1.0 m and 0.70m respectively. The other parameters used are ground heat loss kg = 2.15 W/m ºC [xxii] and Tg = 23.2 ºC at Lg = 6m depth [xxiii].

This simulation outputs are pond three zones temperatures and salt concentration profile inside zones. The start time of simulation is 1st January and ends on 31 December for one year and the output of one month used input to next month. The initial temperature of pond is considered at 25°C.

VI. Results and Discussion

A. Solar Pond Temperature Distribution Profile

The temperature of solar pond depends on pond's depth and is shown in Fig.3. The selected month is May as the maximum average solar energy available in this month. The result shows that pond's temperature increases with increase in depth. The maximum temperature is at LCZ in the end of month is about 67°C including heat loss to surface and ground. After two weeks of time; temperature in LCZ rose with respect to depth and is about 50°C. The next month simulation starts with this temperature and heat availability thus produce high temperature and more heat energy. The available heat energy can be extracted and used for any application for heating, cooling or thermal process.

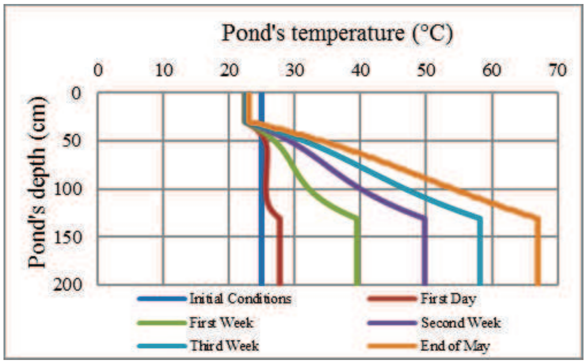

Fig. 3. Temperature profiles in solar pond in the month of May

B. Solar Pond Salt Concentration Profile

For the selected duration of simulation (1st to 31 MAY), the salt concentration for solar pond is shown in Fig. 4. The UCZ has lowest (10kg/m^{3}) and LCZ has highest (178kg/m^{3}) salt concentration, the concentration of NCZ is supposed as linear. During simulation time the concentration in zones changes but its effect is negligible as system is stable.

The simulation was also run for one and two year time period to observe the effect on salt concentration inside pond with long time operation. The results showed that for UCZ the salt concentration is increasingly continuously both for 1st year and second year as shown in Fig. 4.

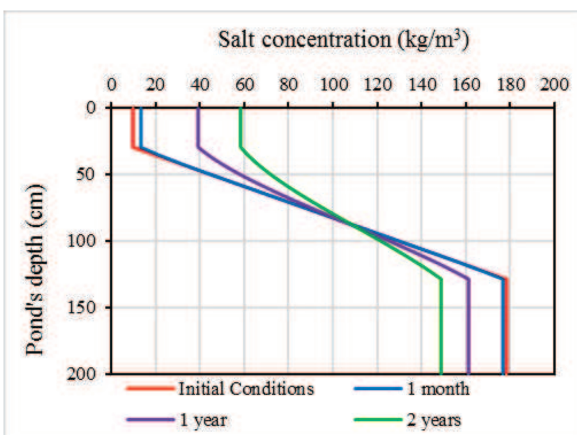

Fig. 4. Solar pond salt concentration profile

For LCZ the salt concentration has decreased continuously in both of the years. This is due to mass transfer and salt concentration diffusion over the long time period. It is assumed that fluid inside the pond is static. The change of concentration will disturb the NCZ layer and can be avoided by replacing the brine in the LCZ after few months.

C. Heat Extraction from Solar Pond

The simulation runs from 1st of January to 31st December for a complete year. The heat is extracted in summer season from April to October. Different loads are applied to extract heat from pond and the respective pond temperature with NCZ thickness is shown in Fig. 5.

The heat extracted from the pond for 24 hours each day. It is clear that more the load less will the pond LCZ average temperature. The maximum temperature is in month of July and the LCZ temperature depends upon heat extracted, ambient and initial temperature, solar radiation and relative humidity. Comparing the weather conditions of June, July and August, the pound temperature and heat energy is availability is more than other months of the year.

The more the heat is extracted the lower the LCZ temperature and vice versa with the given heat extraction the temperature more than 60°C which can be used for heating, cooling and other thermal energy application. The pond temperature in winter season is lower but it's enough to use as domestic hot water for washing and bath.

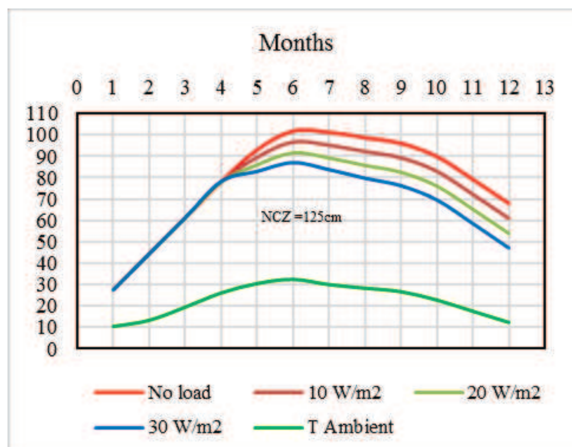

Fig. 5. LCZ monthly maximum temperature with heat extraction

D. Simulation Validation

Researcher [xii], carried out similar simulation for salt gradient solar pond for Iraq. The simulation results were in good agreement with the experimental work.

V. CONCLUSIONS

This paper work was to simulate both mass and heat transfer model of salinity gradient based solar pond and investigate the potential of using solar pond in Lahore climatic conditions. The temperature distribution and salt concentration of the different layers were studied. The following conclusions are established;

- Solar ponds work as collector and storage systems and can provide handsome amount of thermal energy during summer. The hot water can be used for multiple thermal energy applications.
- The efficiency of solar ponds is in range of 15-20 % similar to Photovoltaic system and can be easily used in rural or remote areas for multiple application i.e. fruit drying and water desalination.
- With1.25m NCZ thickness, the maximum temperature of LCZ is 101°C without load extraction and 87°C with 30W/m^2 load extraction in month of July. The total power output for a typical (100 ×100) m^2 pond is 300kW. This model can also have same output during summer with temperature 70-80 °C.

NOMENCLATURE

Symbol	Quantity	Units
C	Salt concentration	kg/m^3
C_p	Specific heat capacity of salt water	J/kg °C
D	Salt diffusion coefficient	m^2/s
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
k	Thermal conductivity of NaCl brine	W/m °C
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}	Pond's surface heat loss	W/m^2
q_r	Radiation heat transfer	W/m^2
RH	Relative humidity	%
T	Temperature	°C
T_a	Ambient temperature	°C
T_g	Ground water temperature	°C
t	Time	s

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