Comparison of Thermal Behavior of Solar Ponds with Flat and Corrugated Bottom

U. K. Sinha[1], Monika[2], S. P. Sharma[3], S. B. L. Seksena[4],Swapnil Saurav[5],

[1, 3]Electrical Engineering Department, National Institute of Technology Jamshedpur
[2]National University of Singapore, Singapore

[4]Mechanical Engineering Department, National Institute of Technology Jamshedpur
[5]Loyola School, Jamshedpur

Abstract: **The heat extraction from the lower convective zone or storage zone of salinity gradient solar pond with corrugated bottom is investigated with the aim of increasing the overall efficiency of collecting solar radiation, storing heat and delivering this heat to different applications. The energy balance equations for each zone have been used to develop the expression of temperature distribution in the solar pond. Then this equation has been used to develop the equation for efficiency of the solar pond. The analysis is based on the boundary conditions at the interface between the zones and the matching conditions. In this method, heat is extracted from the storage zone of the solar pond. A theoretical analysis is conducted to obtain expression for the variation of temperature with depth of solar pond. The dependence of the energy efficiency of the solar pond on the thickness of storage zone, temperature of delivered heat, variation combinations of the pond and storage zone heat extraction only explored. The theoretical analysis suggests that heat extraction from the storage zone has the potential to increase the overall efficiency of a solar pond delivering heat at a relatively high temperature by up to 50 %, compared with the conventional solar pond method of heat extraction solely from the storage zone. The potential gain in efficiency using storage zone heat extraction is attributed to the storage zone that can be achieved with this method. The results are then obtained by computer simulation. The effects of system and operating parameters of the solar pond like area enhancement factor (β), heat extraction rate, heat capacity rate and depth of the pond on the temperature distribution and efficiency have been developed. It has been found that the temperature distribution in the solar pond is a strong function of system and operating parameters.**

I. INTRODUCTION

Electrical or Mechanical power may be generated by direct conversion of solar energy either by photo-voltaic cells or via thermo-electric power system. Among the above mentioned ways of converting solar energy, at present the thermo-electric system is most promising, as the technology and economics for the other ways are still far away from the acceptable limits.

A basic solar energy conversion system has been shown in Fig. 1. Solar thermal power generation system comprises solar pond/solar collector/solar concentrator, turbine, condenser, storage system, cooling tower, alternator, control unit etc. The most important among those being the solar pond/solar

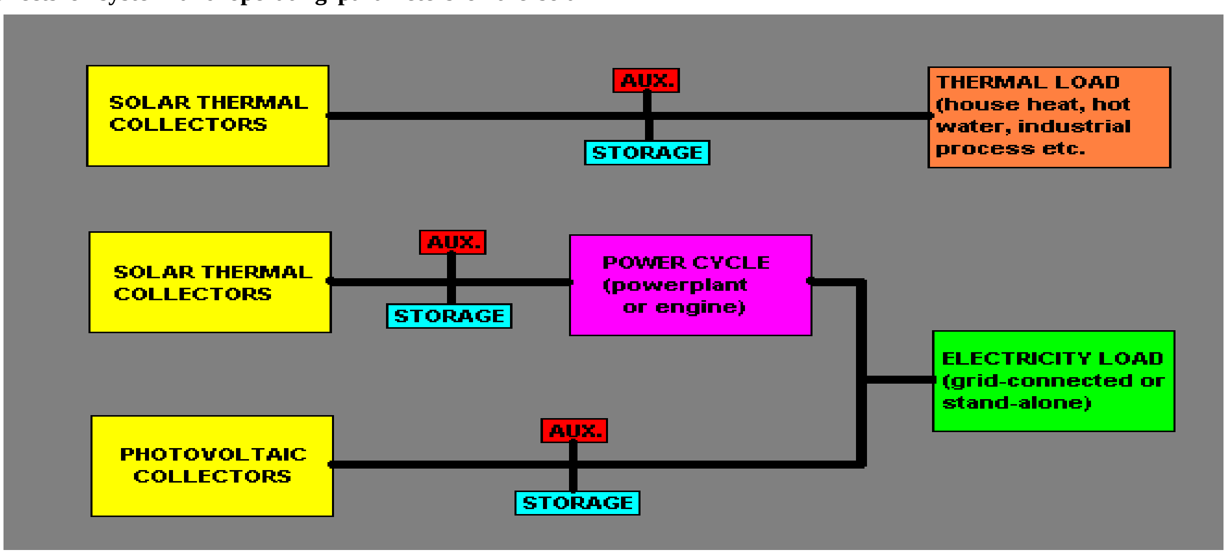
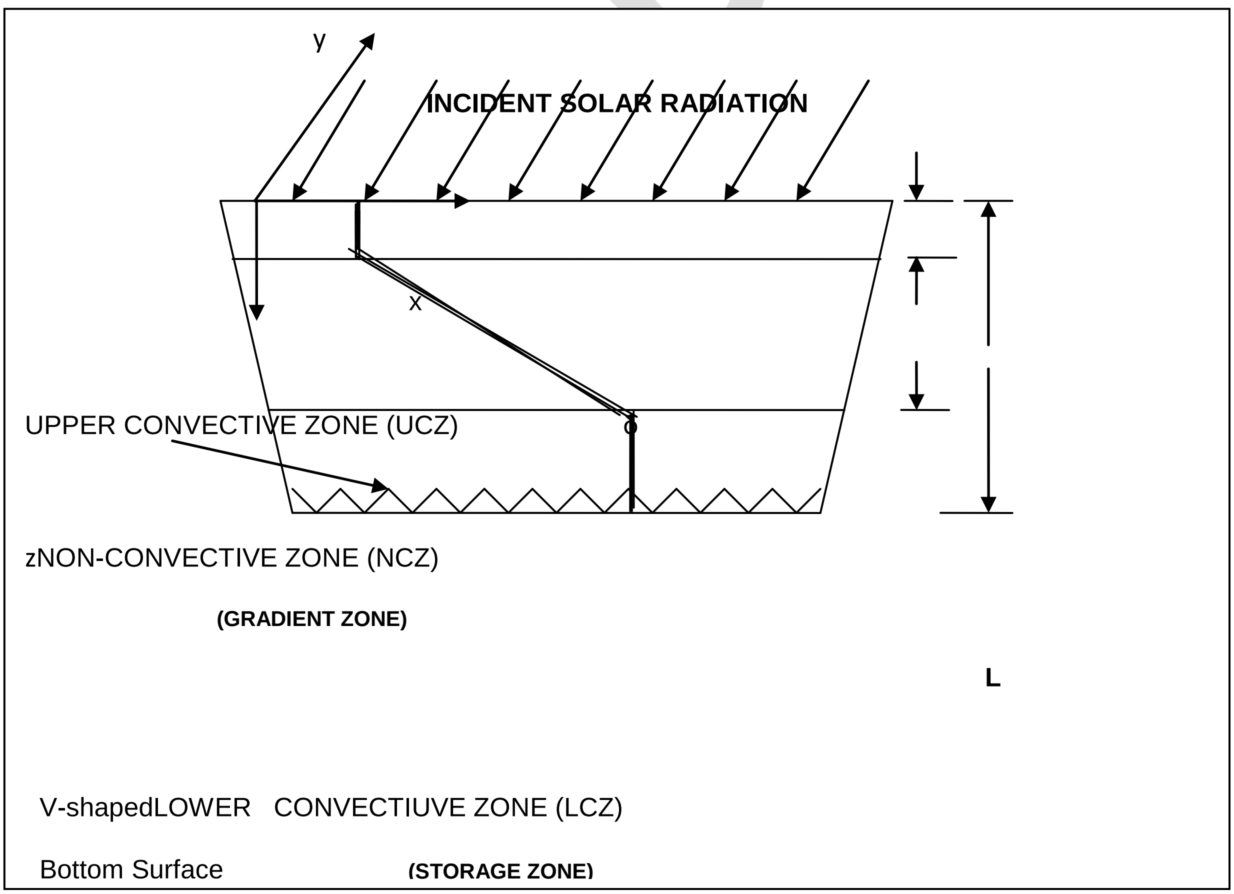


Figure 1.1: Block Diagram of Basic Solar Energy Conversion Systems

concenterator that accounts for the cost of the major portion of the system. Due to this, the solar pond and solar concentrator both have been the areas of research and development work.

A Salt Gradient Solar Pond (SGSP) consists of three distinct zones. The Upper convective zone (UCZ) whose thickness varying between 0.15 to 0.3 m which has low and nearly uniform salt content. Beneath the UCZ is the Non-Convective Zone (NCZ) or gradient zone of thickness that varies between 1 to 1.5 m whose salt content increases with increasing depth and is therefore a zone of variable salinity properties. The bottom layer is the lower convective zone (LCZ) or storage zone, which has a thickness 1.0 to 2.0 m and has a nearly uniform high salt concentration just like saturated saline water. Salinity of the UCZ increases due to convective mixing with the NCZ and salt diffusion from bottom surface to upper surface. Several methods for enhancement of thermal performance of SGSP have been proposed and investigated by [1] a number of investigators. One of the most promising means of improving the thermal performance of conventional SGSP is to increase the bottom surface area by making the surface corrugated (wavy)/V-shaped, which increases the heat transfer capability to the fluid (water) and consequently increases the performance of the solar pond. The important role of upper surface layer dynamics has been discussed by Atkinson and Harleman [2] and Schladow [3] while Tabor [4] and Nielsen [5] provide good general reviews of Solar Pond Technology. Rubin et al. [6-9] performed several numerical and experimental simulation of the solar pond mechanism; they eventually demonstrated that one of the most significant design modifications for increasing the solar pond thermal efficiency was the increased stability of the surface layer. The effect of the various parameters on the thermal behavior with a consideration of the stability criteria in a SGSP are studied results of the steady state indicates that the thickness of the NCZ has a significant effect on the performance of the SGSP.



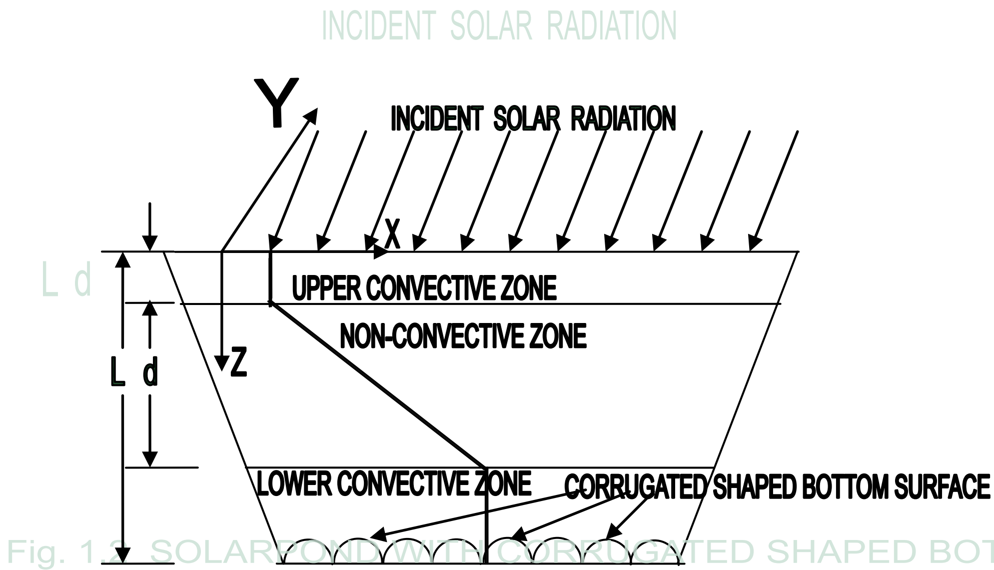


Fig. 1.2 SOLARPOND WITH CORRUGATED SHAPED BOTTOM SURFACE

Moreover, the optimum value of this thickness is found to vary with the rate of the heat to be extracted from the system [10]. A novel scheme of heat extraction from the solar pond has been presented along with preliminary two dimensional computational fluid dynamics (CFD) simulations [11] In present work, an analytical model of SGSP with corrugated bottom surface has been developed in order to analyze the effect of various parameters like depth of solar pond, heat capacity rate, heat extraction rate, mass flow rate on temperature distribution and efficiency.

The analysis is based on the boundary conditions at the surfaces between the zones and on the following assumptions:

- The UCZ and NCZ are assumed to be perfectly mixed layers at a uniform temperature which changes only with time.
- The lateral dimensions of the solar pond are large as compared to its depth so that the temperature variation is only in the vertical direction.
- The properties are constant and assisted with these above assumptions.

Based on the energy balance equation, an expression for temperature distribution in the gradient zone of conventional solar pond has been developed as:

A schematic diagram of a salt gradient solar pond (SGSP) with corrugated bottom surface is shown in Fig.1.2. Typically, it is about 1 to 2 m deep with a thick durable plastic liner laid at the bottom. Materials used for the liner include low density polyethylene (LDPE), high density polyethylene (HDPE), woven polymer yarn (XB-5), and hypalon reinforced with nylon mesh. Salts like Magnesium chloride ($MgCl_2$), Sodium Chloride (NaCl) or Sodium Nitrate ($NaNO_3$) are dissolved in the water, the concentration varying from 20 to 30 percent at the bottom to almost zero at the top surface. Salt concentration gradient will disappear over a period of time due to upward diffusion of the salt. At the same time, concentrated brine is added at the bottom of the solar pond. The amount of the salt required for this purpose is about 50 gm/m^2/day, which is a large quantity when considered on an annual basis. For this reason the normal practice is to recycle the salt by evaporating the saline water run off from the surface in an adjacent evaporation pond.

2.0 MATHEMATICAL ANALYSIS

The energy flow diagram shown in Fig. 1.3 for different zone for corrugated bottom of the solar pond for showing depth of the different zones.

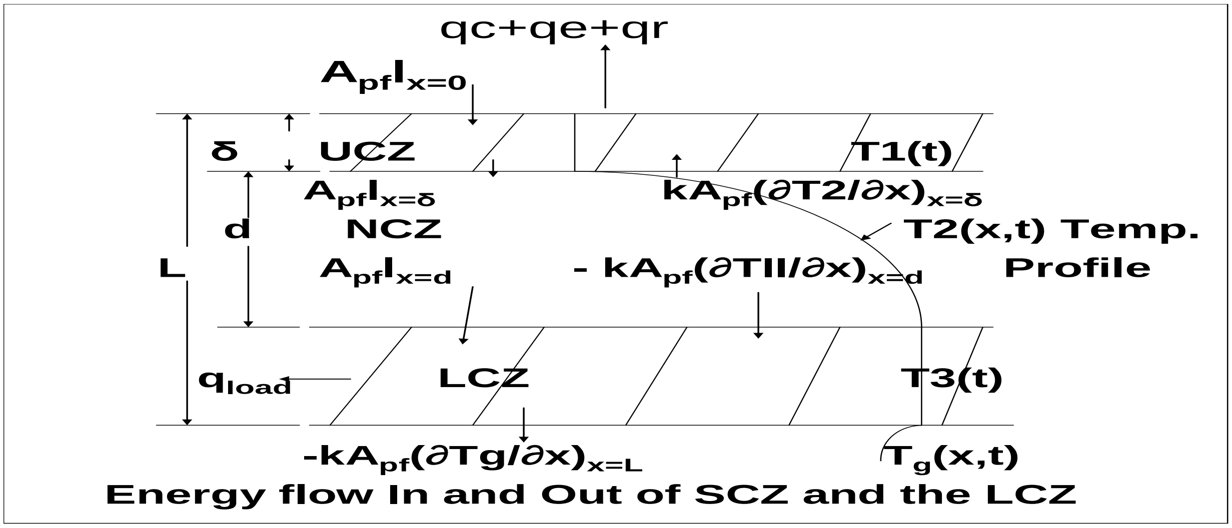


Fig. 1.3 Energy flow In and Out of the Surface Convective Zone and Lower Convective Zone

2.1 Upper Convective Zone

The differential equation is to be satisfied for the UCZ of the pond is obtained by taking energy balance equation as follows-

(Rate of change of energy contained in the UCZ of thickness, δ) = (Rate at which heat is conducted in from the NCZ) + (Solar radiation absorbed in the thickness, δ)–(Rate at which heat is lost from te top surface by convection, evaporation and radiation).Thus,

$$\rho\, \delta\, C_p\left[\frac{\partial T_1}{\partial t}\right]_{x=0} = k\left[\frac{\partial T_2}{\partial x}\right]_{x=\delta} + [(I)_{x=0} - (I)_{x=\delta}] - \frac{q_c + q_e + q_r}{\beta A_f} \tag{2.1}$$

where β is the area enhancement factor which is the ratio of the area of corrugated or V-shaped surface, A_{pf} and the corresponding surface area of conventional solar pond, A_f.

2. 2 non-convective zone

The differential equation for the NCZ zone is the heat conduction equation of the form

$$\frac{\rho C_p \partial T_2}{\partial t} = k\,\frac{\partial^2 T_2}{\partial x^2} - \frac{dI}{dx} \tag{2.2}$$

where $I = I_b \tau_{rb} \tau_{ab} + I_d \tau_{rd} \tau_{ad}$ (2.3)

2. 3 Lower Convective Zone

Taking energy balance equation as above for the LCZ of the pond as below:

[Rate of change of energy contained in the LCZ of thickness {L-(d+δ)}] = [(Rate at which heat is conducted in from the NCZ) + {Solar radiation absorbed in the thickness (d+δ)} – (Rate at which heat is conducted out to the ground underneath) – (Rate of useful heat extraction)]. Thus,

$$\rho[L-(d+\delta)]C_p\left(\frac{\partial T_3}{\partial t}\right)_{x=d+\delta} = -k\left(\frac{\partial T_2}{\partial x}\right)]_{x=d+\delta} + (I)_{x=d+\delta} + [\,k_g\left(\frac{\partial T_g}{\partial x}\right)_{x=L}] - \frac{q_{load}}{A_{pf}} \quad (2.4)$$

Now, solution to the sets of equations (2.1), (2.2) and (2.3) have been obtained and expressed for distribution of temperature in the gradient zone for conventional solar pond as

$$T(x) = T_c + \frac{b' A_f}{mCp}\ln(x+\delta) - [\{\frac{b' A_f}{mCp} e^{(x+\delta) A_f / k\, m\, C_p}\}\{E_4 + \ln(x+\delta)\}] \quad (2.5)$$

where E_4 and T_c are the integration constants and these are expressed as:

$$E_4 = T_a + \frac{(q-a)}{b'} e^{-(d+\delta)A_f / k\, m\, Cp} + \ln(d+\delta)\{e^{-A_f (d+\delta) / k\, m\, Cp} - 1\} \quad (2.6)$$

And,

$$T_c = T_a + \frac{(q-a')A_f}{mCp} e^{dA_f / k\, m\, Cp} + \frac{b' A_f}{mCp}(1 - e^{-\delta A_f / k\, m\, Cp})\ln\delta\} - \{1 - e^{-A_f (d+\delta) / k\, m\, Cp}\}\ln(x+\delta) \quad (2.7)$$

For corrugated bottom surface of the solar pond,

The Equ.(2.5) is further developed as

$$T(x) = T_c + \frac{b' \beta A_{pf}}{mCp}\ln(d+\delta) - [\{\frac{b' \beta A_{pf}}{mCp} e^{(x+\delta)\beta A_{pf} / k\, m\, Cp}\}\{E_4 + \ln(x+\delta)\}] \quad (2.8)$$

where β is the area enhancement factor, E_4 and T_c are the integration constants

and these are expressed as:

$$E_4 = T_a + \frac{(q-a)}{b'} e^{-\beta(d+\delta)A_{pf} / k\, m\, Cp} + \ln(d+\delta)\{e^{-\beta A_{pf} (d+\delta) / k\, m\, Cp} - 1\} \quad (2.9)$$

And

$$T_c = T_a + \frac{(q-a)\beta A_{pf}}{mCp} e^{\beta d A_f / k\, m\, Cp} + \frac{b' \beta A_{pf}}{mCp}(1 - e^{-\delta \beta A_{pf} / k\, m\, Cp})\ln\delta\} -$$

$$\{- e^{-A_{pf} (d+\delta)\beta / k\, mCp}\}\ln(x+\delta) \quad (2.10)$$

Where,

$b' = \tau * H * b$ (2.11)

T_c and E_4 are the integration constants and $C = mc_p$, the heat capacity rate per unit area of the solar pond for the working fluid in the heat exchanger of the gradient zone.

The first boundary condition to be applied is that when x=0, $T(0)=T_a$. The second boundary condition arises from the energy balance at the interface between gradient layer and lower convective zone.

3.0 EFFICIENCY CALCULATION FOR VARYING PARAMETERS

The thermal efficiency of the solar pond is defined as

$$\eta = \frac{C\{T(d) - T_a\} + q}{H} \tag{3.1}$$

where H is the average flux of solar radiation incident on the surface of the solar pond. The numerator on the right side of this equation is composed of two terms: one is the rate of heat transfer from the gradient layer per unit area of the pond, [C{T(d)-T_a }]/H, and the second term is the rate of heat withdrawal from the lower convective zone per unit area of the pond, q/H. T(d) is the temperature at the bottom of the gradient layer can be found by putting x=d in equation (2.25) as well as in equation (2.28) and T_a is the ambient temperature.

4.0 RESULTS AND DISCUSSIONS

4.1 Effect of heat extraction rate on temperature distribution of solar pond

The results showthat there is a significant influence of area enhancement factor on thermal performance of salt gradient solar pond with corrugated (way)/V-shaped bottom.

Fig. 4.1 shows the effect of heat extraction rate on temperature distribution of solar pond for area enhancement factor of 1.5 and heat capacity rate of 0.75 W/m^2-K. It has been found that the temperature of the solar pond almost remains constant in upper convective zone, whereas in the non-convective zone the temperature of the solar pond linearly increases with increasing depth and again remains constant in lower convective zone or storage zone for a particular value of heat extraction rate. The value of temperature in NCZ and LCZ decreases with increasing the value of heat extraction rate.

The maximum temperature attains in the LCZ is 91.72^0 C for zero heat extraction rate (i.e., q=0 W/m^2) at β=1.5 and then these value decreases as 69.77^0 C, 60.25^0 C and 50.74^0 C for q=10 W/m^2, q=20 W/m^2, q=30 W/m^2 and a fixed value of heat capacity rate of 0.75 W/m-K^2. It is also seen that the temperature in storage zone is higher than the temperature in storage zone of conventional solar pond.

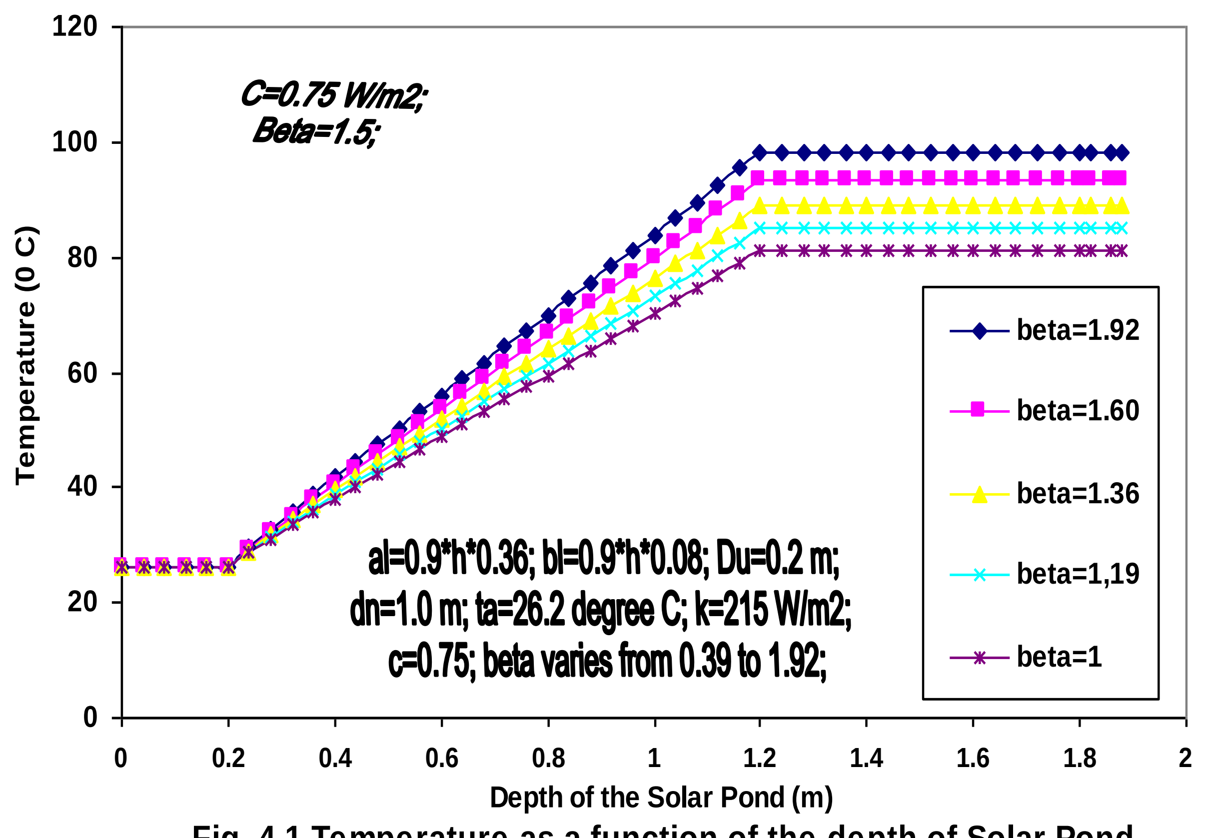


Fig. 4.1 Temperature as a function of the depth of Solar Pond

4.2 Effect of heat capacity rate on temperature distribution of solar pond

Fig. 4.2 shows the effect of heat capacity rate on temperature distribution of solar pondwith respect to depth of the pond for heat extraction rate of 20 W/m^2 and area enhancement factor β=1.5 .It has been found that the temperature of the solar pond almost remains constant in the UCZ, whereas in the NCZ, temperature increases linearly with increasing depth and again remains constant in LCZ for a particular value of heat capacity rate. These values of temperatures decrease with increase in heat capacity rate.

The maximum temperatures attains in the storage zone is found to be 69.1^0 C at q=20 W/m^2 and C=0.75 W/K-m^2 and then these values decreases as 65.31^0 C at C=0.95 W/K-m^2 and 61.86^0 C at C=1.15 W/K-m^2, 58.72^{0}C at C=1.35 W/K-m^2 and 55.85^0 C at C=1.55 W/K-m^2, respectively.

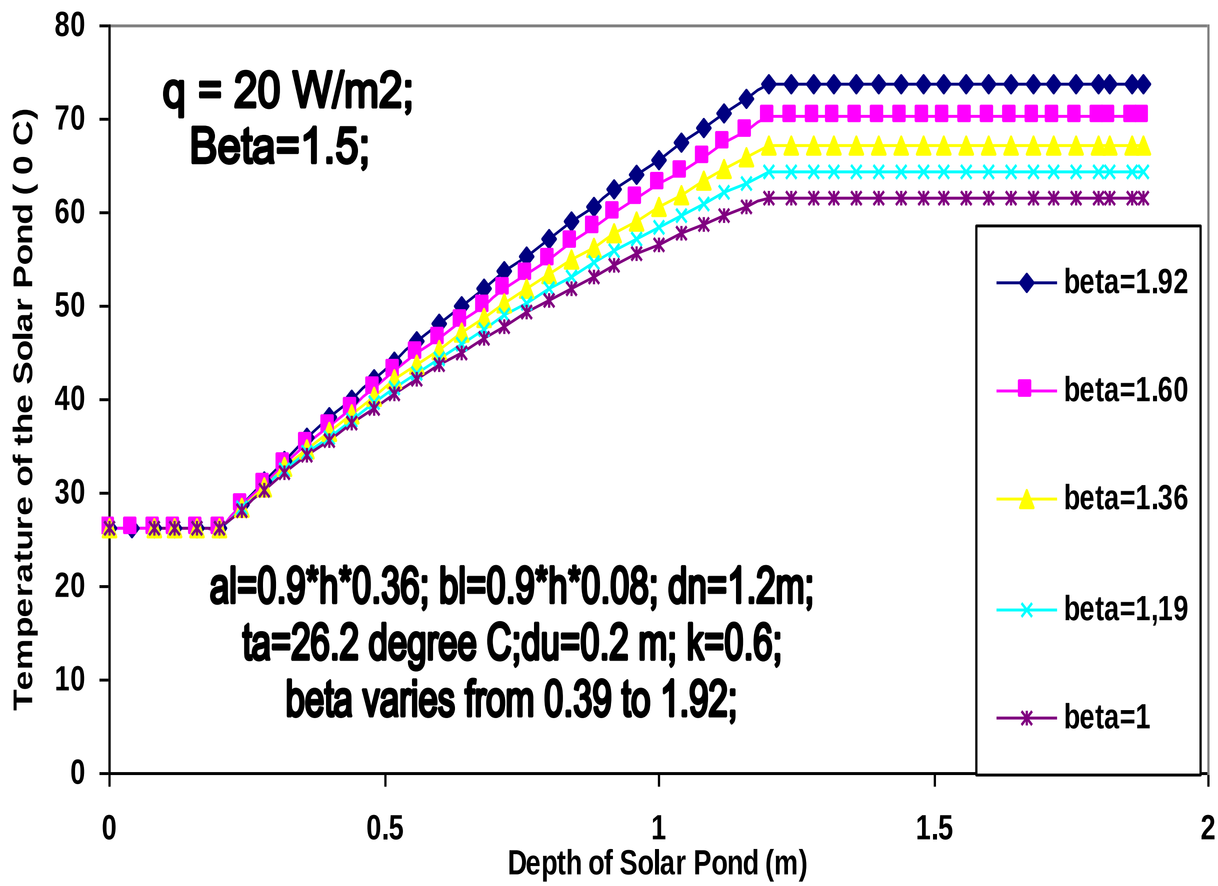


Fig. 4.2 Temperature as a function of the depth of Solar Pond

4.3 Effect of area enhancement factor (β) on temperature of solar pond

Fig. 4.3 shows the effect of area enhancement factor (β) on temperature distribution of the solar pond with respect to depth of the pond for q=0 W/m^2 and C=0.75 W/K-m^2. The system and operating parameters are same as in previous plot shown in Fig. 4.10. It has been found that the temperature in the UCZ remains constant, whereas temperature linearly increases in the non- convective zone or gradient zone with increasing depth and again remains constant in the storage zone for a particular value of heat extraction rate.

The maximum temperature attains in the storage zone is 91.72^0 C for zero heat extraction rate and then these values decreases as 87.98^0 C, 83.87^0 C, 80.13^0 C and 76.73^0 C for β =1.6, 1.36, 1.19 and 1, respectively.

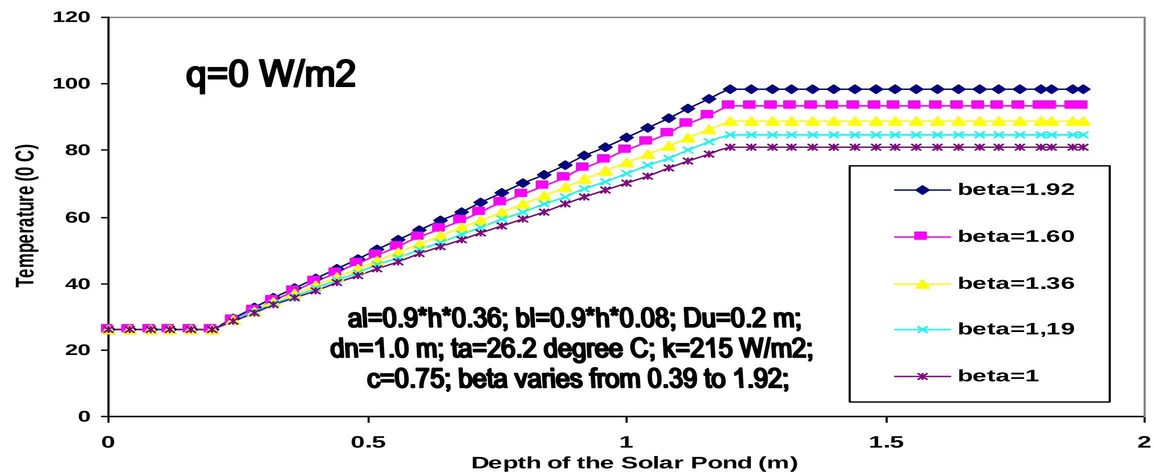


Fig. 4.3 Temperature as a function of the depth of Solar Pond

4.4 Effect of heat extraction rate on temperature of storage zone

Plot shown in Fig. 4.4 shows the effect of heat extraction rate on temperature of storage zone of solar pond. The temperature of storage zone of the solar pond decrease+ from 91.72^0 C to 71.25^0 C at zero heat extraction rate and area enhancement factor of 1.5, and then these values of maximum and minimum temperature decreases at various values of heat extraction rate as 82.45^0 C to 62.73^0 C, 70.52^0 C to 53.15^0 C and 59.42^0 C to 47.25^0 C respectively for heat extraction rate of 10, 20 and 30 W/m^2.

It has also been observed that the rate of fall of temperature is higher for lower value of heat extraction rate and is lower for higher value of heat extraction rate.

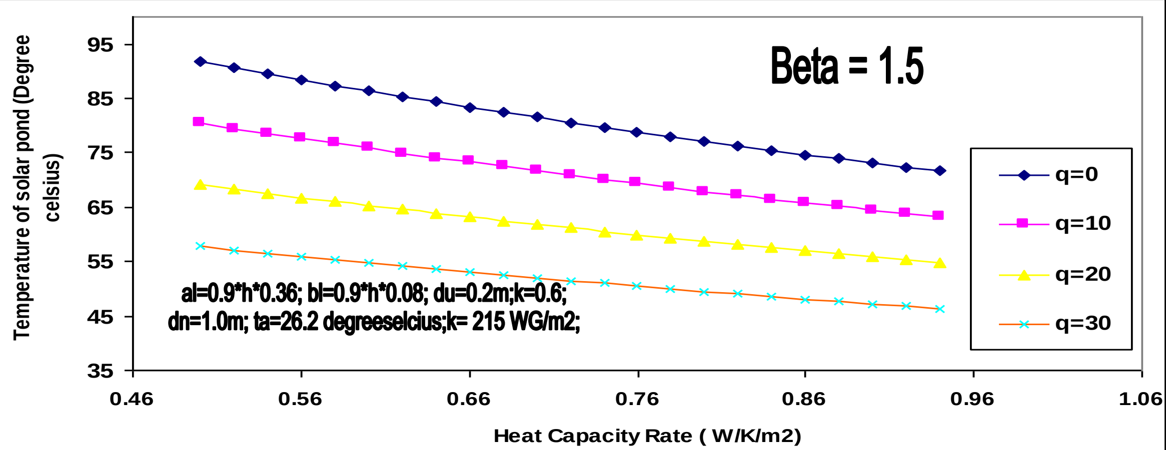


Fig. 4.4 Effect of heat extraction rate on the temperature of solar pond as a function of heat capacity rate

4.5 Effect of heat extraction rate on efficiency of storage zone

Fig. 4.5 shows the effect of heat extraction rate on efficiency of storage zone. It has been observed that the efficiency of storage zone is decreasing with increasing value of heat capacity rate for all values of heat extraction rate.

The minimum and maximum value of efficiencies are 17.91 percent and 19.95 percent, 19.29 percent and 20.88 percent, 20.79 percent and 21.82 percent and 22.29 percent and 22.76 percent respectively for heat extraction rate of 0 W/m^2, 10 W/m^2, 20 W/m^2 and 30 W/m^2.

It has also been observed that the increase and decrease of efficiency is mainly depends upon the heat extraction rate. Efficiency increases if heat extraction rate increases and decreases as heat extraction rate decreases.

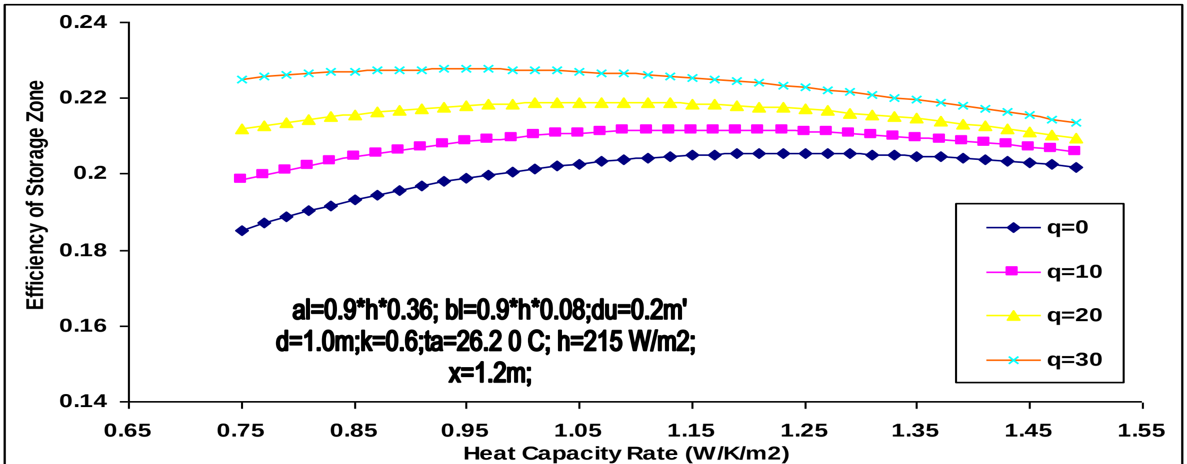


Fig. 4.5 Efficiency of Storage Zone as a function of Heat Capacity Rate

4.6 Effect of heat capacity rate on temperature of storage zone

Fig. 4.6 shows the effect of heat capacity rate on temperature of storage zone for area enhancement factor of 1.5 and heat capacity rate from 0.75 to 1.5 W/m^2-K. It has been observed that the fall in temperature of storage zone of solar pond. It is also observed that fall in temperature is higher at low values of heat extraction rate at all values heat capacity rate.

The maximum and minimum values of temperature of storage zone have been found to be 91.72^0 C and 28.55^0 C, 88.98^0 C and 27.85^0 C, 83.87^0 C and 27.12^0 C, 77.25^0 C and 27^0 C, and 74.56^0 C and 21.65^0 C at heat capacity rate of 0.75, 0.95, 1.05, 1.20 and 1.5 W/K-m^2, respectively.

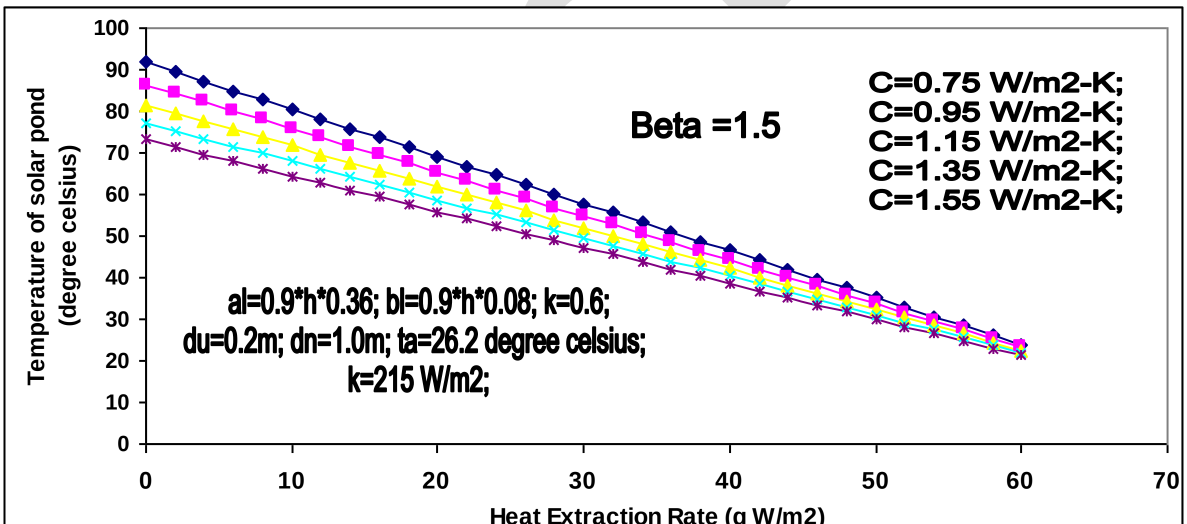


Fig. 4.6 Effect of heat capacity rate on the temperature of solar ponf as a function of heat extraction rate

4.7 Effect of area enhancement factor on efficiency of storage zone of Solar Pond

Fig. 4.7 shows the effect of area enhancement factor on efficiency of storage zone of solar pond. The efficiency of storage zone of solar pond for area enhancement factor of 1.5 and heat capacity rate of 0.75 W/m^2-K linearly increases with heat extraction rate for all values of area enhancement factor.

The minimum value of efficiencies has been found to be 12.5 percent, 15.48 percent, 16.25 percent, 17.20 percent and 18.15 percent at area enhancement factor of 1, 1.25, 1.15, 1.75 and 2 for a fixed value of heat capacity rate of 0.75 W/m^2-K.

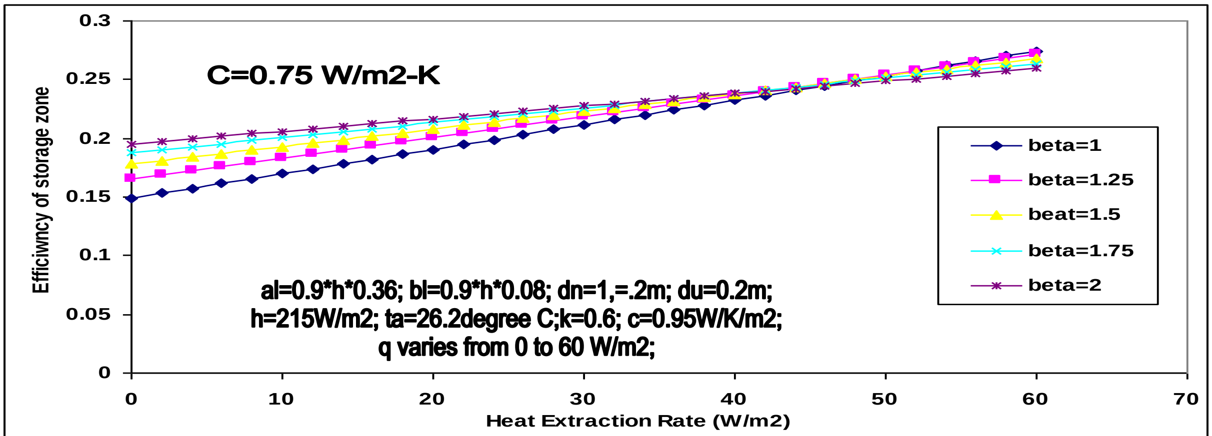


Fig. 4.7 Effect of area enhancement factor on the efficiency of storage zone

5.0 CONCLUSIONS

On the basis of analytical investigations carried out in this paper in connection with the simulation and modeling of solar pond, the following conclusions are drawn:

- An analytical model of salt gradient solar pond has been developed in order to analyze the effect of various parameters like depth of solar pond, heat capacity rate, heat extraction rate, mass flow rate on temperature distribution and efficiency.

- The results are then obtained by computer simulation using C^{++} program for temperature distribution along the increasing depth of the solar pond for various value of the system and operating parameters in order to prophesy the performance of the solar pond for electrical power generation.

- It has been found that for area enhancement factor equal to 1, the temperature of the solar pond almost remains constant in the upper convective zone or surface convective zone, where as in the non convective zone, temperature increases linearly with the increasing depth and again remains constant in non convective zone for a particular value of heat extraction rate (q) whereas these values decreases with increasing values of heat extraction rate. The maximum temperature attains in the lower convective zone is 79.28^0C for q=0 W/m^2 and then these values decreases as 69.77^0C, 60.25^0C and 50.74^0C for q=10 W/m^2, q=20 W/m^2 and q=30 W/m^2, respectively.

- It has been found that the temperature of the storage zone decreases with an increase in the heat capacity rate(C=mC_p), at all values of heat extraction rate. For no heat extraction, the maximum temperature is found to be 79.28^0 C for C=0.75 W/(m^2.K) and Minimum value of temperature is 55.81^0C at C=1.49 W/(m^2.K). These maximum and minimum values of temperature decrease with increasing values of heat extraction rate.

- It has been observed that the efficiency of solar pond is strong function of heat capacity rate and heat extraction rate. The efficiency of solar pond increases exponentially from 18.51 percent to 20.19 percent with an increase in heat capacity rate, for q=0 W/m^2 while 19.84 percent to 20.58 percent for q= 10W/m^2. For q=20, 30 and 40 W/m^2, the efficiency slowly decreases with increase in heat capacity rate. The above efficiencies values have been found to be 21.18 percent to 20.97 percent, 22.51 percent to 21.35 percent and 23.84 to 21.74 percent, respectively.

- The results show that the efficiency of the storage zone of the solar pond increases linearly with increase in heat extraction rate for various values of heat capacity rate. The minimum and maximum values of efficiencies are found to be 18.51 to 25.98 percent in the range of parameters investigated.

- The results show that there is a significant influence of area enhancement factor on thermal performance of corrugated/V-shaped solar pond. At constant value of heat capacity rate (0.75 W/m^2.K) and heat extraction rate (q=0 W/m^2), the percentage enhancement in temperature efficiency have been found to be 21.16 percent and 22.42 percent, respectively. These results are due to the fact that the increase in heat transfer surface area increases the heat transfer capability to the working fluid (water) and consequently increase the temperature and efficiency of the solar pond.

NOMENCLATURE

SGSP Salt Gradient Solar Pond

UCZ Upper Convective Zone

NCZ Non-Convective Zone

LCZ Lower Convective Zone (Storage Zone)

β Area Enhancement Factor

A_f Total surface area of the pond with flat bottom surface

A_{pf} Total surface area of the pond with corrugated bottom surface

c Concentration of the salt (kg/m^2)

C_P Specific heat f the salt (J/kg-0C)

d Thickness of the non convective zone (in m)

T(x) Temperature of the pond at a depth x below the interface between UCZ Upper Convective Zone

Φ(x) Solar radiation reaching a depth x below the NCZ and LCZ interface (W/m^2)

δ Thickness of the upper convective zone (in m)

[L-(d+ δ)] Thickness of the lower convective zone (in m)

H Average global solar radiation incident on the surface of the pond

k Thermal conductivity of the fluid in NCZ

q_c Heat loss due to convection (in W/m^2)

q_e Heat loss due to evaporation (in W/m^2)

q_r Heat loss due to radiation (in W/m^2)

q_t Total heat loss at the pond surface (in W/m^2)

Q_{Load} Extracted enegy from the solar pond In W)

T_a Ambient temperature (in ^{0}C)

T_c Integrtation constant

E_4 Integration constant

C Heat capacity rate (=mC_p) per unit area of the pond for the working fluid in the gradient layer heat

exchanger

ρ density of the fluid used in the pond (in kg/m^3)

τ Coefficient of transmissivity of air-water interface

a&b Constants related to absorption of light in water

REFERENCES

[1] Jaefarzadeh, M. R., “Thermal Behavior of Large Salinity Gradient Solar Pond in the City of Mashhad.” Iranian Journal of Science and Technology, Transaction B, Engineering, Vol. 29, No. B2, Printed in The Islamic Journal of Iran, 2005.

[2] Atkinson, J. R. and Harleman, D. r., “A wind-mixed layer mode for Solar Ponds.” Solar Energy, 31, 243-259, 1983.

[3] Schladow, S. G., “The upper mixed zone of a Salt Gradient Solar Pond: Its dynamics and Control.”Solar Energy, 33, 417-426, 1984.

[4] Tabor, H., “Solar Ponds: Reviewed.” Solar Energy, 27, 181-191, 1981.

[5] Nielsen, C. E., “Non-convective Salt Gradient Solar Ponds.” In: W. C. Dikinson and P. N. Chereminoff (eds.), Solar Energy Technology Handbook, Part A, pp. 345-376, Marcel Dekker, New York, 1980.

[6] Rubin, H. and Bemporad, G. A., “The Advanced Solar Pond (ASP): Basic theoretical aspects.” Solar Energy, 43, 33-34, 1989.

[7] Rubin, H. and Bemporad, G. A., “Analysis of turbulent flow in thermal layers of a advanced solar pond (ASP).” Solar Energy, 43, 25-33, 1989.

[8] Keren, Y., Bemporad, G. A. and Rubin, H., “Basic experiments related to the advanced solar pond performance.” Transaction of ASME, J. Fluids Engineering, 113, 116-123, 1991.

[9] Rubin, H., Keren, Y. and Bemporad, G. A., “Feasibility of the advanced solar pond (ASP) according to Osdor method: Feasibility experiments.” Coastal and Marine Engineering Research Institute(CAMERI) Report, June, 1990.

[10] Mohammed, A. D., “Computer Simulation Yearly or Seasonally Optimum Salt –gradient of Solar Pond in Jordan ‘Dead Sea’.” Australian journal of Basic and Applied Sciences, 2(4), pp. 1172-1185, 2008.

[11] Angeli, C., Leonardi, E. and Maciocco, L., “A Computational Study of Salt Diffusion and Heat extraction in Solar Pond Plants.” Solar Energy, 80, 1498-1508, 2006.