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Effects of system and operating parameters on performance of salt gradient solar pond (SGSP)

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ABSTRACT

The effects of system and operating parameters are investigated. The investigation of the effects of system and operating parameters on the performance of salt gradient solar pond based on the analysis of governing equation of salt gradient solar pond, considering the boundary conditions at the surfaces between the zones. The results obtained by simulation using the computer program C++. The effects of system and operating parameters of the SGSP like depth of different zones, temperature distribution, heat extraction rate, heat capacity rate and efficiency have been developed. It has been found that the temperature distribution in the GSPP.

1.0 Introduction

Salinity gradient solar ponds are artificially constructed large body of water between 2 to5m deep which can collect solar radiation and store it in the form of heat [1] [2]. Solar ponds are characterized by their ability to collect large amount of solar radiations and, at the same time, provided long term energy storage. Solar ponds may be used as a heat source for many applications, one of which is the generation of electricity. Some of the attractive merits for solar pond power generation plants such as no fossil fuel necessary, low running cost, use of local resources, and no environment pollution.

Mathematical modeling of solar ponds have been reported by many investigators to predict the temperature, salinity profile, prediction of the stability of the solar ponds as well as the effects of the variation of different zone thickness on pond performance. About 25 % of the solar radiation incident at the surface penetrates to the bottom of the pond and is absorbed there, causing the adjacent brine to heat up. The pond consists of three distinct regions at the top (upper convective zone, UCZ) and the bottom (lower convective zone, LCZ), separated by a quiescent region (non-convective zone, NCZ), characterized by strong temperature and salinity gradients, which prevent the occurrence of convection currents. Salt diffusion caused by both molecular diffusion and thermo-diffusion (also known as Soret Effect, [3]) tends to homogenize the system. Angeli [4] and Leonardi [5]. It used a model based on a finite difference scheme to describe the salt diffusion within a solar pond. In the present work, the analysis of the behavior of the pond is extended by considering other effects besides the salt diffusion.

2.0 Mathematical formulation

In a solar pond, saline is stored in three different zones, increasing in salinity. The surface convective zone is homogeneous and convective, where the density saline is close to fresh water. In the middle zone or non-convective zone (NCZ) or gradient zone, saline density increases with depth, thereby, natural convection is stopped.

In this zone, mass or thermal energy is transported only by molecular diffusion which is a very slow process.

The bottom layer or lower convective zone (LCZ) or storage zone, is dense and convective, and has relatively uniform density close to saline saturation. The part of solar radiation transmitted to this zone increases its temperature. The heat stored there can only be transferred through the non-convective zone by conduction. Therefore, the non\-convective zone acts as an insulator. The thermal energy collected in the storage zone may be utilized later.

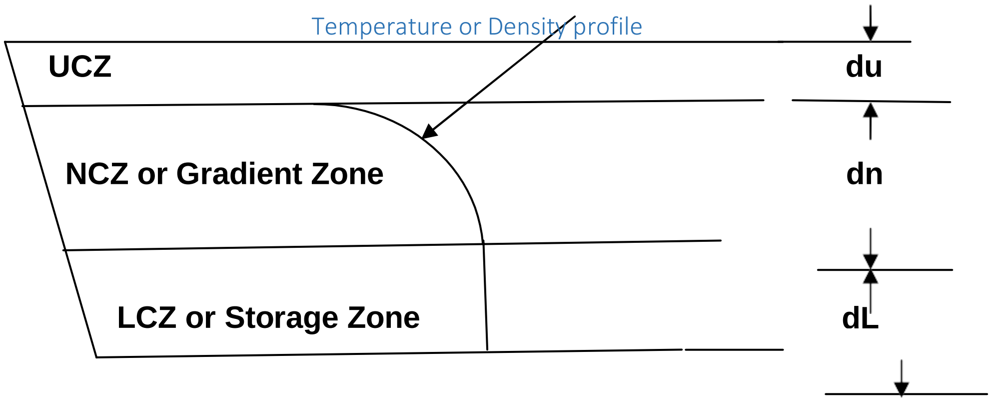

Fig. 1 Solar pond with three convective zones including temperature density profile

Fig. 1 shows a vertical system of co-ordinates, with z measured as positive downward, and z=0 at the surface of the pond, the transient equation of heat conduction in one dimension for the non- convective zone is written as [6]

$\rho\, C_P\, \partial T/\partial t=\partial/\partial z(k\partial T/\partial z)+H(z,t)$ for $du \leq z \leq du+dz$ (1)

where ρ is the fluid density in kg/m^3, C_p is the specific heat of the fluid in J/kg ^{0}C, T is the temperature in degree Celsius, t is the time, Ꝁ is the co-efficient of heat conduction in W/m ^{0}C, H(z, t) is the energy absorbed in the body of the solar pond, du is the thickness of the UCZ, `dn is the thickness of the gradient zone.

The thermo-physical properties for a saline solar pond in terms of temperature T, and salt concentration 'C' in kg/m^3 are given as [7]

Ꝁ$=0.5553 - 0.0000813\,C + 0.0008(T-20)$ (2)

$\rho=998+0.65C - 0.4(T-20)$ (3)

$C_p=4180+4396C+0.0048C^2$ (4)

The solar incident radiation absorbed in the body of the solar pond, H(z,t) is given by

$H= -d\, I_R\, (z, t) / dz$ (5)

Where I_R is the direct radiation flux in W/sq-m that reaches to a depth of z at any time 't', the wall . Shading effect may be neglected for large solar pond. There are two boundary conditions at the interfaces: one at the interface between UCZ and NCZ i.e. at z=du, and the other at the interface between NCZ and LCZ i.e. at z=du+dn. For the upper boundary, it is assumed that the temperature of UCZ is constant and equal to the ambient temperature, i.e.

$T=T_{ambient}$ (6)

This assumption has been applied by a number of researchers in most of the similar models.

For lower boundary condition, it is assumed that the temperature T_L of the LCZ is constant, and can be calculated from the energy conservation equation for the storage zone, giving

$Ro\, C_p\, d_L(\delta T_L)/(\delta t)=I_R+k_g\,(\delta T/\delta z)_{z=du+dn} + k_G(\delta t/\delta z)_{z=du+dn+dL}-Q_L/A$ (7)

In Eq. (7), the left hand side is the time variation of thermal energy in the unit area of the storage zone, and in the right hand side, the first term is the radiation energy flux entering into the storage zone, the second term is the energy loss flux to the non-convective zone at the interface, the third term is the energy loss flux to ground, and the last term Is the extracted energy, Q_L, from the storage zone, per unit area (A, m^2) of the pond in a loading period, d_L is thickness of the LCZ, and k_G is the co-efficient of heat conduction from the bottom of the pond. It is assumed that the pond is large and the heat losses through the side walls may be neglected. The initial condition is obtained by assuming a uniform temperature profile at the start of the pond operation.

3. ESTIMATION OF SOLAR RADIATION

The direct beam radiation in a region of altitude h kilometer above the mean sea level is given by [8]

$$I_R=I_0[(1-0.14\ h)\exp\{-0.357(\sec\theta_z)^{0.678}\}+0.14\ h] \quad (8)$$

In which I_0=1353 W/sq-m is the solar constant, θ_z is the zenith angle. This angle changes throughout the day, all year around and is given by

$$\cos\theta_z=\sin phi\ \sin delta+\cos phi\ \cos delta\ \cos w \quad (9)$$

in which delta is the angle of declination, phi is the angle of latitude and w is the hour angle. The declination angle delta is defined in degree by [9] as below

$$\delta=23.45\sin(360(284+n)/365) \quad (10)$$

where n is the day of the year. Its accuracy of prediction is adequate for engineering purposes.

4. (a) ATTENUATION OF SOLAR RADIATION IN THE DEPTH OF SOLAR POND

It is assumed that all the incident solar radiation that encounters the surface of the pond, the beam radiation with the incidence angle fixed at 2 PM on the corresponding date. Assumptions will not introduce errors more than 5% into the solar pond. The radiation that reaches to a certain depth is obtained as

$$IR=(I-R)\ \theta\text{ح}\ IG \quad (11)$$

Where,

R is the co-efficient of reflection and is calculated from the equation

$$R=[(\sin^2(\theta_i-\theta_r)/2\sin^2(\theta_i+\theta_r))+(\tan^2(\theta_i-\theta_r)/2\tan^2(\theta_i+\theta_r))] \quad (12)$$

θ_i is the angle of incidence and θ_r is the angle of refraction, and for water is obtained from $\sin\theta_i=1.33\sin\theta_r$ (13)

In Equ. (11), ح is the attenuation function given by

$$\text{ح}=0.36-0.08\,Ln(z/\cos\theta r) \quad (14)$$

And the value of theta depends on many parameters such as the salt concentration, propagation of solar radiation in different zones of solar pond, bottom reflection and water turbidity etc. Here we assume theta =0.85, which has been assumed by other researchers [10].

4(b) SALT DIFFUSION IN A SOLAR POND

Salt diffusion with a solar pond is made up of two factors: molecular diffusion and thermo- diffusion which is the separation of the components of a liquid mixture introduced by temperature gradient.

The thermo-diffusion coefficient varies significantly according to the nature of the components of the mixture and their concentration. Until now there has not been a hydro-dynamical explanation and/or a macro scopical model of the phenomenon, and therefore there is not a way to determine a priori the direction of the thermo-diffusion flux. In fact it appears to be sensitive to detail of the molecular interaction potentials and cannot easily be measured experimentally and predicted theoretically [11] and [12].

5. HEAT EXTRACTION FROM THE SOLR POND

A critical aspect of Solar Pond technology is the heat extraction from the solar pond [13] by using a submerged heat exchanger on the lower surface of either the gradient layer or storage zone or by pumping the hot brine from either the gradient zone or from the storage zone to an external heat exchanger and then returning to it to the solar pond after application. A schematic diagram for heat extraction shown in Fig. 2 below which has avoids temperature discontinuities.

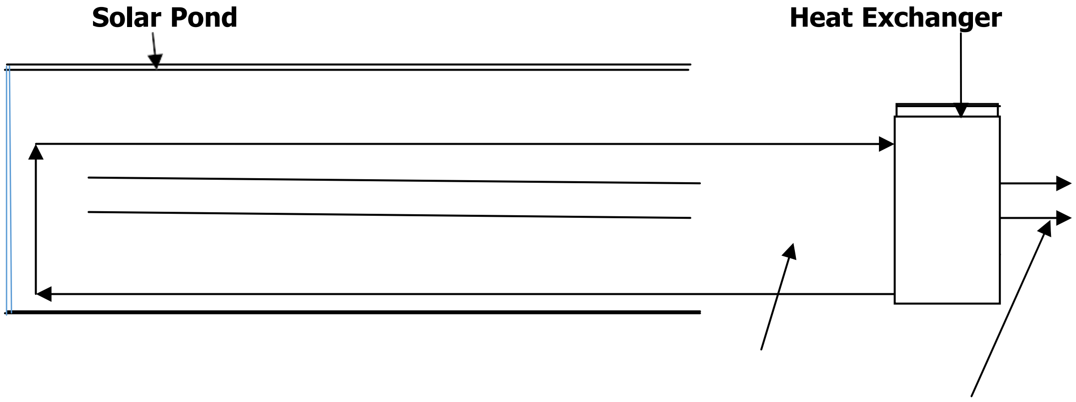

Fig. 2: Schematic diagram for heat extraction from the solar pond

In Fig.2, the solar pond is U-shaped with a heat exchanger located between the inlet and outlet sides of the solar pond, thus reducing the length of the pipe lines and the energy cost incurred by the need to pump the brine along the close circuit. In order to apply this scheme, the translational motion of the brine in the zone from which hot brine extracted must not affect the stability of the salinity gradient layer, therefore the translational velocity of the brine must be lower than the brine velocity due to the natural convection.

6. SALT DIFFUSION

Salt diffusion within a solar pond is conducted considering the two factors: molecular diffusion and thermo-diffusion, which is the separation of the components of a liquid mixture induced by temperature gradients.

The thermo-diffusion coefficient varies significantly according to the nature of the components of the mixture and their concentration. Until now there has not been a hydro-dynamical explanation and/or micro-scopical model of the phenomenon, and therefore there is not a way to determine a priori the direction of the thermo-diffusion flux. In fact it appears to be sensitive to details of the molecular interaction potentials and cannot easily be measured experimentally and predicts theoretically [12, 13].

7. RESULTS AND DISCUSSIONS

In this work, a mathematical model has been developed for the study of various effects on the thermal performance and salinity gradient of the solar pond.

The results show that the solar pond performance is affected strongly by the temperature of the storage zone and the temperature profile with the pond depth. To increase the efficiency for the storage zone of the pond, heat losses from the upper surface, bottom and side walls should be decreased. Also, to increase the pond performance, zone thickness should be modified to achieve higher efficiency and salinity of the pond.

Several parameters for upper convective zone (UCZ) and non-convective zone have influence on the thermal performance and discussed. It is also shown that the introduction of the other two zones (UCZ & NCZ) provides many conveniences in calculating the storage efficiency in the heat storage zone, and in determining the relations with heat loads and a best operating state. Therefore, the energy efficiency of the inner zones of a solar pond is an important parameter in practical applications.

7.1 EFFECT OF THICKNESS OF NON-CONVECTIVE ZONE

Once the thickness of the UCZ has been fixed, the thickness of the NCZ is most because the se of the tradeoff between an increase in the thermal insulation with a concurrent decrease in the solar radiation penetrating into the storage zone as an insulating layer is thin, the upward heat loss by conduction becomes the dominant, causing the storage zone to be low. And on the other hand, an increase of the thickness of NCZ would increase the amount of solar radiation absorbed in its path through the pond, therefore, reducing the radiation reaching the storage zone, and the storage zone temperature will again low.

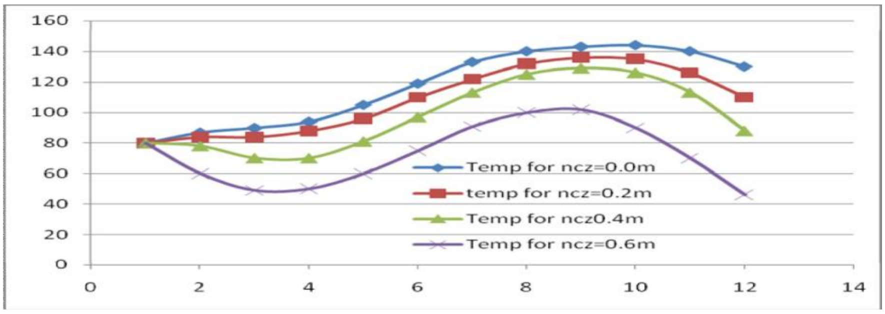

Fig. 7.1 Temperature distribution within the solar pond for various values of NCZ

Fig. 7.1 shows that the optimum thickness of the NCZ is 1.0 m on the basis of the requirement of highest mean annual storage temperature 71.5^0 C for 1.5 m of storage zone.

7.2 EFFECT OF THICKNESS OF LCZ

The thermal performance of the solar pond is analyzed to investigate the effect of increasing the thickness of LCZ. The storage zone temperature for different values of the NCZ has been plotted and shown in Fig. 7.2(a) and temperature distribution within the storage zone for various thickness of LCZ shown in Fig. 7.2(b).

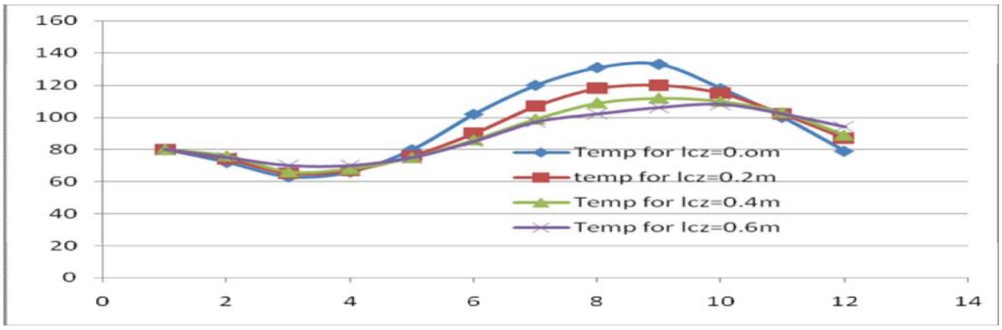

Fig. 7.2 Temperature distribution within the solar pond for various values of CZ

- However, the maximum temperature of the LCZ varies inversely with its depth. The low maximum temperature in the deep LCZ, results simply because the absorbed energy heats a large volume of brine per unit surface area more than the heat capacity of a zone of larger depth. The higher minimum LCZ, which in turn, results in lower rate of cooling

7.3 EFFECT OF THICKNESS OF UCZ

The irregular growth of the UCZ thickness is one of the most common problems in the solar ponds. The most important causes are ascribed to the following factors:

- A large amount of the irradiance flux absorbed in a few centimeters near the surface of the pond produces a high temperature gradient ($\partial T/\partial Z \approx 500^0$C/m). Weinberger's stability criterion at the surface requires

$$\partial C/\partial Z \geq 0.44\ \partial T/\partial Z \tag{15}$$

By substituting for the temperature gradient in Eq. (15), we obtain $\partial C/\partial Z \geq 220$kg/m^4 for the concentration gradient. In cases where this condition is not satisfied. The surface instability results in an upper convective zone. However, it can be shown that for a 0.2m UCZ, the temperature gradient is reduced by 50%, and we will obtain $\partial C/\partial Z \geq 110$kg/m^4. This requirement can easily be satisfied in a solar pond.

- The surface mixing caused by the wind driven currents erodes the NCZ and produces an upper zone of uniform density. The thickness of this zone depends on the intensity of the kinetic energy of the turbulent eddies, and may even reach to 1m in service conditions.
- The salt diffusion from the LCZ as well as the evaporation, will increase the surface salinity that results in the generation of an upper convective layer. The lower boundary of this layer moves down to the level where the salinity in the gradient zone matches the increased salinity in the surface zone, so as to maintain the continuity of salinity across the boundary.

In order to investigate the effect of the surface layer growth on pond performance, four different thicknesses of 0.0, 0.2, 0.4, and 0.6m were assumed for the UCZ. In Fig. 7.3, it is seen that when there is no UCZ, the temperature of the LCZ rises to 130^{0}C. However, by increasing the thickness of the UCZ to 0.6m, the maximum temperature of the LCZ drops to 112^{0}C. Therefore, in order to maximize the storage zone temperature, the thickness of the UCZ should be kept as thin as possible. The application of floating rings and continuous surface flushing are highly recommended for the effective control and maintenance of a relatively thin UCZ. In practice, however, a thickness of0.2m of UCZ is inevitable.

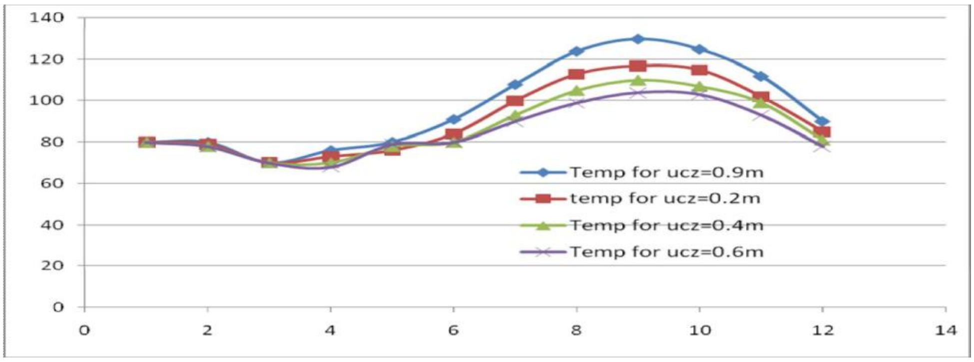

Fig. 7.3 The effect of the thickness of the UCZ on the performance of the pond

7.4 EFFECT OF COEFFICIENT OF HEAT CONDUCTIVITY OF THE GROUND

There are three cases of fully insulated ground (k_g=0 W/m^{0}C), ground with a high coefficient of conductivity (k_g=2.5 W/m^{0}C), and ground with very high coefficient of conductivity (k_g=2.5 W/m^{0}C), were compared with the ordinary reference case (k_g=0.96 W/m^{0}C). In Fig. 7.4, the temperature of the LCZ is plotted for various cases. It is seen that the ground heat loss, even in large solar ponds where the wall heat loss is normally ignored, has a major role in pond performance. Therefore, the bottom insulation, especially in cases where the phreatic surface is high and acts as a heat sink, is necessary, and will improve the pond temperature, considerably. This has been the subject of several investigations.

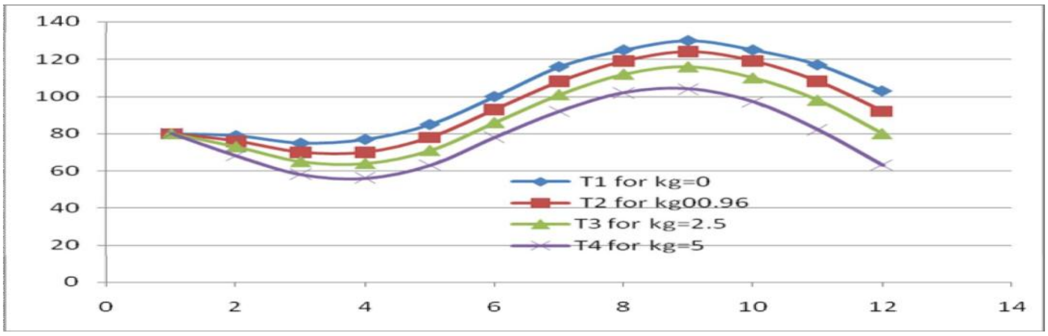

Fig. 7.4 The effect of coefficient of heat conductivity of the ground

7.5 EFFECT OF LOADING ON THE PERFORMANCE OF SOLAR POND

The strategy of loading of solar pond is completely based on the mainly three factors:

- temperature of storage zone
- the total amount of energy consumption and
- distribution of the amount of energy during a complete year.

The performance of solar pond has been studied on the basis of several loading patterns. Fig.7.5 shows that the variation of the storage zone temperature of the solar pond is plotted for a 15% loading for yearly average irradiation, and 15% loading for daily average irradiation. The first loading pattern remains constant throughout the year while the latter is variable if the total energy extraction will be same for both the above cases in a year. In the variable loading, much more energy is extracted in summer than in winter. Consequently, the fluctuation in the temperature of the LCZ will be reduced. This option is recommended when there is a need for a relatively uniform operating storage zone temperature. In Fig. 7.5, the ambient temperature, plus temperature of LCZ for no loading, 25% loading of the daily average, and yearly average irradiation are drawn. It has been found that the 25% of the constant loading will not be possible for four months approximately, when the temperature of the LCZ decreases lower than the ambient temperature. It has also been investigated that for the variable loading pattern, heat can be extracted throughout the whole year without any losses.

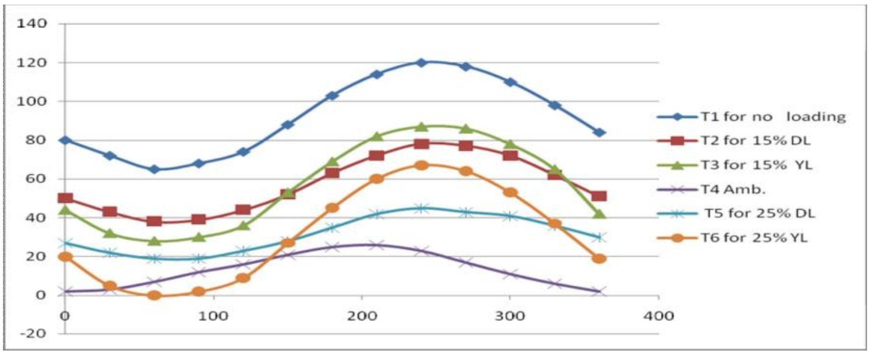

Fig. 7.5 The effect of loading on the performance of solar pond

8.0 CONCLUSIONS

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

- A mathematical model has been developed for thermal performance of a solar pond.
- The storage zone temperature is obtained for the various thicknesses of the UCZ or SCZ, NCZ and LCZ respectively.

- It is seen that the temperature LCZ rises up to 1300 C for zero thickness of UCZ and decreases if the thickness of UCZ increases.
- The thickness of NCZ may not be less than 1 m because it acts as an insulating zone. It should not be more than 2 m due to risk of instability and reduction in irradiation that reaches LCZ.
- The thickness of LCZ may be designed based on the needs and applications of the thermal energy.
- The solar radiation has an important effect on the internal temperature field and also the pond stability characteristics.
- It has been found that there exist two critical zones, one located beneath the water free surface and the other one observed near the bottom surface.
- Regarding the time evolution of the pond characteristics, results have clearly shown that the above critical zones appear to become more vulnerable to instabilities with the increase of time of operation of the solar pond.
- It has been observed that within the critical zones, the solar heating effect as well as heat losses from the free surface have an important influence on the solar pond stability characteristics in time, even during a very short period of time, say several hours of operation.

To summarize, it can be stated that the thermal performance of solar pond can be considerably enhanced by modifying the configurations of the solar pond. Furthermore, the parametric dependence of thermal performance bring out clearly, the need for a judicious choice of the system and operating parameters to obtain the maximum benefit from the solar pond.

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