Parametric design study of 500m^2 Salt Gradient Solar Pond

G. S. Gunasegarane

Abstract—Solar pond output is characterized by the magnitude and temperature of the thermal energy stored which in turn depends on the pond depth and the surface area as well as the local climatic conditions. Hence, the design of a solar pond involves determining the zone depths matching to a given load. This paper deals with the development of a numerical model to optimize the design parameters of a 500 m^2 salt gradient solar pond. The design optimization gives the optimum depth of each zone namely upper convective zone (UCZ), non-convective zone (NCZ) and lower convective zone (LCZ) based on the local weather conditions. Results from the numerical model shows that the thickness of the insulating zone (NCZ) depends on the monthly average hourly solar radiation as well as on the temperature of the LCZ. The thickness of the NCZ is determined as 1.2m for UCZ=0.2m thick.

Index Terms— Solar pond, gradient, optimization, solar radiation, zone thickness, efficiency.

1 INTRODUCTION

Solar pond provides thermal energy at low temperatures on continuous basis and hence is usually designed as an energy system with 100% solar traction. The pond's output depends on the quantity and quality of the energy stored which in turn depends on the depth of the storage zone (LCZ) and the collecting surface area apart from the local metreological factors and pond's operating characteristics. Earlier studies (1), (2), (3), (4), (5), (6), (7) and (8) have pointed out that there is no single exact method available for the design of the pond matching the given load. However, the estimation of rate of energy collected per unit pond area based on the R N model from which the estimation of collector area matching the demand load was given by (9). The sizing of the gradient or non-convective zone (NCZ) plays an important role in the performace of the solar pond. The increase in NCZ thickness provides higher quality energy in terms of temperature stored in LCZ by reducing the top heat loss.
However, increase in NCZ thickness reduces the fraction of radiation reaching LCZ thereby decreasing the quantity of energy stored. At Optimum NCZ thickness, the reduction in radiation input matches the reduced heat loss when the pond collection efficiency will be maximum. The present study deals with the determination of optimum thickness of NCZ by matching with the fraction of insolation reaching the LCZ. many theorectical investigations (10), (11), (12), (13), and (14) have shown that decrease in NCZ thickness results in increased heat loss, lower temperature and lower collection efficiency. These studies have also shown that increase in NCZ thickness from the optimum value results in lower efficiency. So it is imepartive that the optimum thckness of NCZ needs to be determined formaximizing the pond collection efficiency.

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Apart from these, studies have shown that the optimum thickness of NCZ also depends on local available solar insolation, temperature of operation and pond clarity.
Results from earlier studies both theorectical (15), (2), (16), (9) and (17) and model simulation (18) have shown that the optimum thickness of NCZ ranges from 1.0 to 1.5*m*. In the presentwork an attempt is made to fix the optimumthickness of NCZ using the one dimensional three zone pond model.
The performance of a solar pond is also influenced by the daily seasonal and intermittent effects of temperature gradient, salinity gradient, ambient temperature fluctuation, solar insolation, evaporation rate, surface wind and rainfall both at the free surface as well as at its interface with the gradient zone. A thin top convective layer (UCZ) will result in unstable UCZ-NCZ boundary and a thicker UCZ will result in reduced fraction of radiation reaching the storage zone. Hence the optimum thickness of UCZ needs to be fixed based on the pond operating temperature, ambient conditions and the intensity of solar insolation available locally.
Tabor (15) has showed that even without flushing of surface, the density gradient at the top surface was lost at the rate of 1cm/week resulting in top convecting zone. Theorectical studies have shown that the UCZ thickness ranges from 0.1 to 0.3*m* whereas experimental studies have shown that the thickness of UCZ varies from 0.3 to 0.9*m* for maximizing the collection efficiency. The lower region is the heat storage zone (LCZ) from which heat is extracted for various applications. In the simplest operating mode, the LCZ is maintained convective and isothermal by the fraction of solar radiation absorbed. The temperature variation that results due to the diurnal variation of solar input is mainly influenced by the LCZ thickness. For thinner LCZ as small as 0.5*m*, a large temperature gradient develops at the zone boundary contributing to boundary erosion.
Further to conduct the pond performace analysis under steady state condition, the diurnal temperature variation should not

exceed 1^oC (19). Similar to UCZ, NCZ thickness, studies have shown that the thickness of LCZ ranges from 1.0 to 1.8*m* based on different applications keeping in mind the pond stability as well as the rate of heat extration at the required temperature.

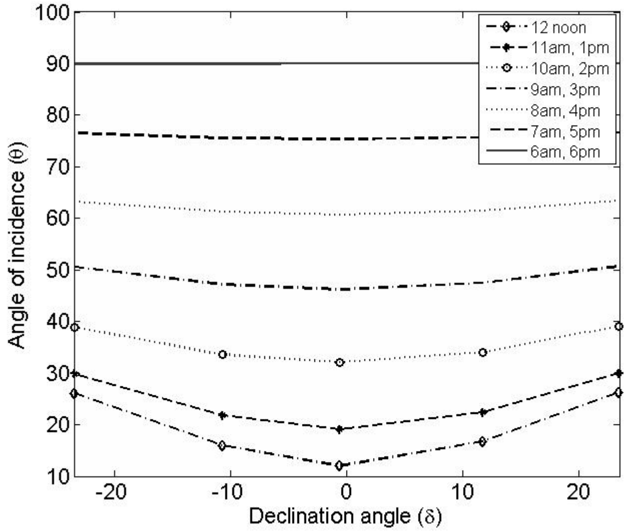

Fig. 1. Variation of incident angle θ with the declination angle δ for different hours of a day based on the location latitude of 12^oN.

In the present study, a simple three zone model was considered to optimize the zones thickness so as to maximize the pond collection efficiency operating at steady state condition.

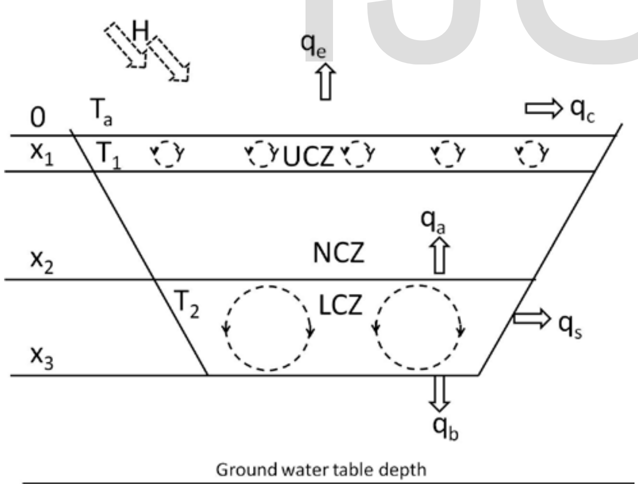

Fig. 2. Schematic of three zone solar pond model

The monthly average hourly radiation estimated to vary from 180 to 270Wm^{-2} for the given location of latitude 12^oN is taken as the input to determine the temperature distribution and the energy flux reaching each zone and to arrive at an equation for the efficiency of the Hottel-Whillier-Bliss form given by (10).

2 MODEL AND SIZING OF SOLAR POND

The model chosen for the analysis consists of three zones as shown in figure 2. The upper convective zone (UCZ) thickness having uniform temperature close to the ambient air temperature is given as x_1 *m*. UCZ is followed by the non-convecting zone of thickness ($x_2 - x_1$) in which salt concentration increases with depth and acts as a thermal insulating layer. The heat collection and storage zone is given as ($x_3 - x_2$). For the present analysis, the following assumptions were made

1. The zone boundaries are stable and can be adjusted to any height.
2. The thermal conductivity and optical properties of water are assumed to be independent of salt content and temperature.
3. During heat extraction the boundary between NCZ and LCZ is kept stable at x_2.

Using the one dimensional steady state heat conduction equation,

$$kw\frac{d^2T(x)}{dx^2} = H\frac{dh(x)}{dx} \tag{1}$$

the temperature distribution $T(x)$ is obtained as

$$T(x) = \frac{H}{kw}\int_{x_1}^{x} h(x)dx + [A - H\int_{x_1}^{x_2} h(x)dx]B \tag{2}$$

where

$$A = [kw(T(x_2) - T(x_1))] \tag{3}$$

and

$$B = \frac{(x - x_1)}{kw(x_2 - x_1)} + T(x_1) \tag{4}$$

Figure 1 shows the variation of angle of incidence q of solar radiation with the angle of declination d for different time of the day determined for the location with latitude $\phi = 12^oN$. From the estimated angle of incidence, the monthly average hourly radiation *H* falling on the pond was determined to be in the range of 180–270Wm^{-2}.

The temperature distributions as a function of NCZ thickness for *H* ranging from 180–270Wm^{-2} are shown in figures 3, 4, 5 and 6. Figures also show that the temperature of NCZ is dependent on the thickness of UCZ and the average hourly insolation falling on the pond. For a given insolation *H*, figures 3 and 4 show that the temperature of NCZ increases with decrease in thickness of UCZ. This is due to the fact that more fraction of radiation penetrates UCZ and is absorbed in the NCZ.

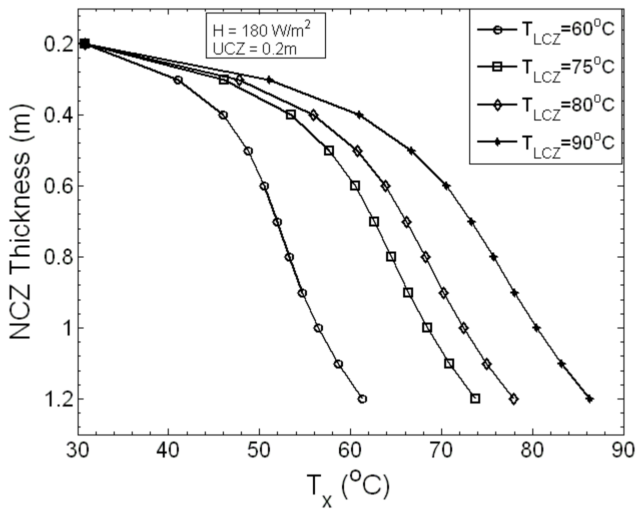

Fig.3. Variation of temperature with change in thickness of NCZ for H = 180Wm^{-2}, x_1 = 0.2m and different storage zone temperatures.

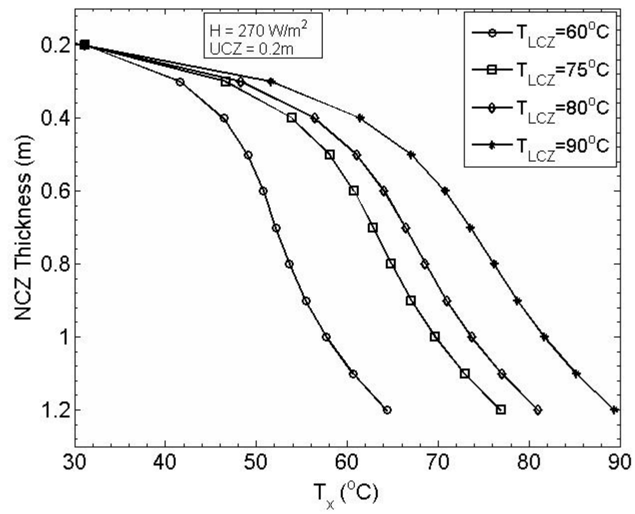

Fig.5. Variation of temperature with change in thickness of NCZ for H = 270Wm^{-2}, x_1 = 0.2m and different storage zone temperatures.

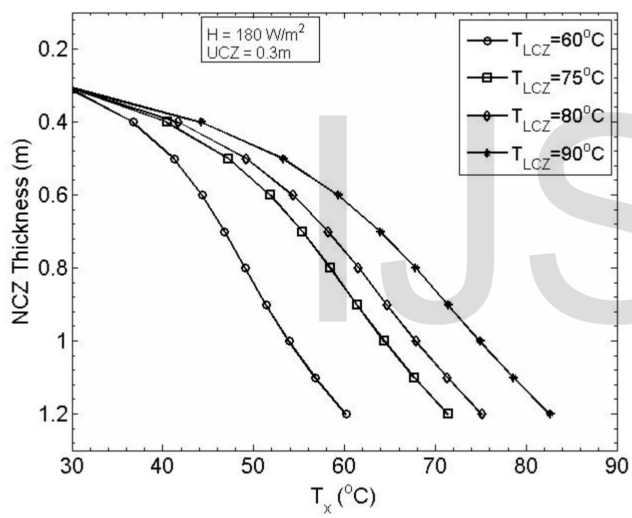

Fig.4. Variation of temperature with change in thickness of NCZ for H = 180Wm^{-2}, x_1 = 0.3m and different storage zone temperatures.

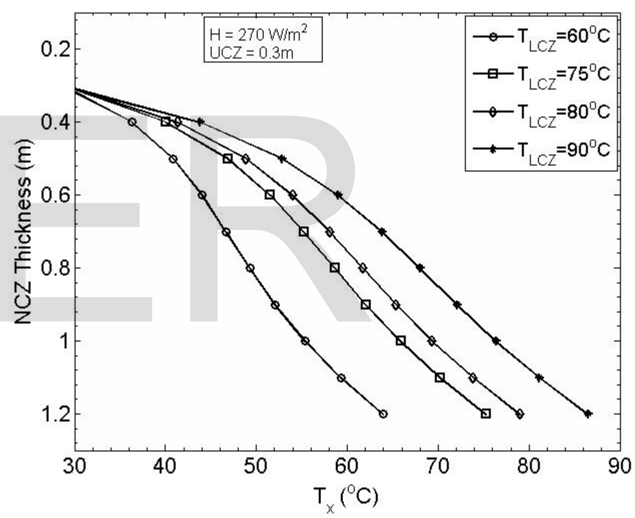

Fig.6. Variation of temperature with change in thickness of NCZ for H = 270Wm^{-2}, x_1 = 0.3m and different storage zone temperatures.

Since a solar pond is strongly influenced both at its free surface and at its interface with the gradient zone by the daily seasonal solar insolation, ambient temperature fluctuations, evaporation rate, surface wind and rainfall, a thin UCZ will get affected and hence disturb the NCZ-UCZ boundary. However, taking the undue reduction in insolation and the stability of NCZ-UCZ interface, the UCZ thickness is fixed as 0.2–0.3m based on the avreage insolation received at the pond site and the required LCZ temperature. Figures (3, 5) and (4, 6) show that for a given UCZ thickness, the temperature of NCZ increases with increase in the average hourly solar insolation H received. The gradient zone thickness is an important parameter which affects the storage zone temperature.

An increase in NCZ thickness reduces the heat loss from NCZ and at the same time reduces the inetnsity of radiation reaching the LCZ. However at optimum NCZ thickness the effect of reduction in radiation flux input becomes equal in magnitude to the reduction in heat loss when the pond will have the maximum solar collection efficiency. Many theorectical studies have shown that the optimum thickness of NCZ for the pond to have maximum collection efficiency is in the range of 1.2 to 1.5m. Figures (7, 8, 9 and 10) show the variation of pond collection efficiency and the fraction of radiation reaching the LCZ with NCZ thickness.

It is seen from figures (7) and (9), that the optimum thickness of NCZ (where $h(x)$ intersects the η_P curves) decreases with

ISSN 2229-5518

increase in H as the fraction of insolation reaching LCZ increases.

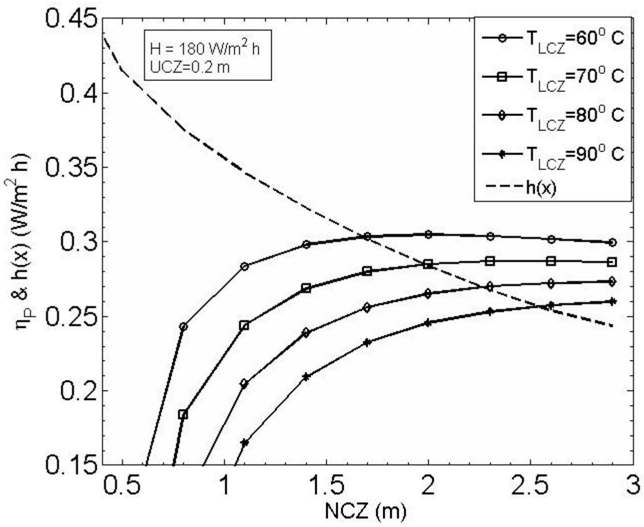

Fig.7. Variation of pond efficiency and h(x) with change in thickness of NCZ for H = 180Wm^{-2}, x_1 = 0.2m and different storage zonetemperatures.

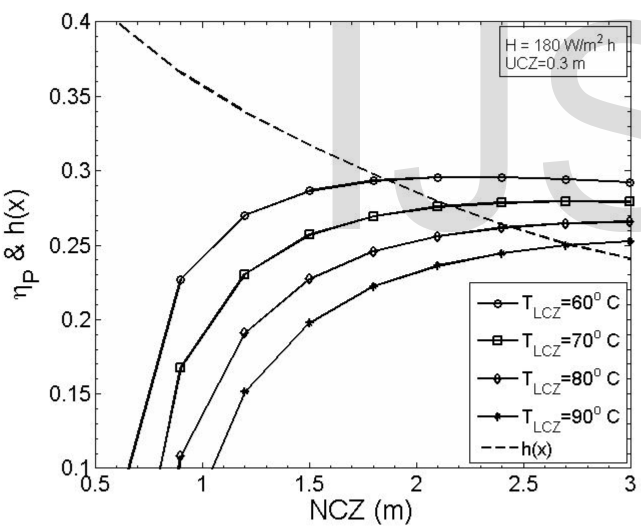

Fig.8. Variation of pond efficiency and h(x) with change in thickness of NCZ for H = 180Wm^{-2}, x_1 = 0.3m and different storage zonetemperatures.

Similarly figures (8) and (10) shows the optimum thickness of NCZ for the UCZ thickness of 0.3m for different storage zone temperatures.

2.1 Heat losses in solar pond.

The various forms of heat losses taking place in solar pond are:

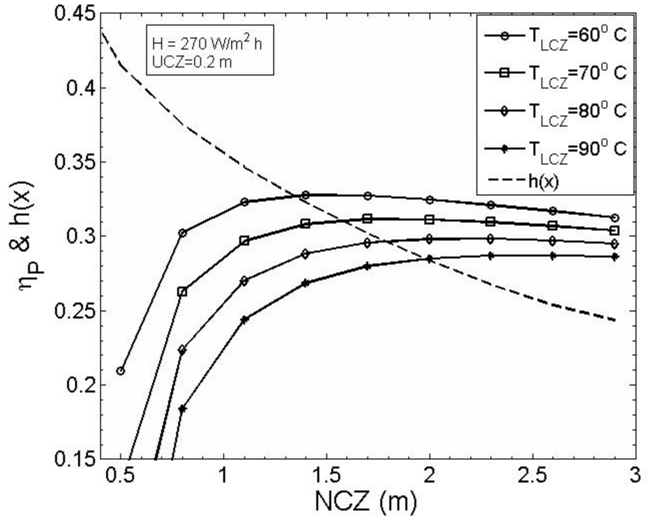

Fig.9. Variation of pond efficiency and h(x) with change in thickness of NCZ for H = 270Wm^{-2}, x_1 = 0.2m and different storage zonetemperatures.

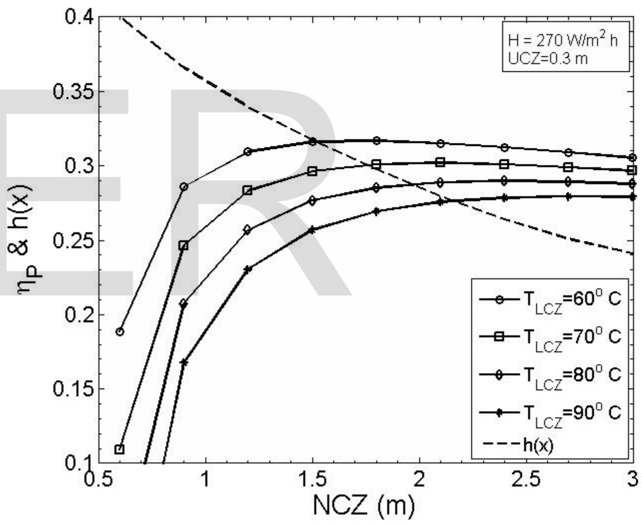

Fig.10. Variation of pond efficiency and h(x) with change in thickness of NCZ for H = 270Wm^{-2}, x_1 = 0.3m and different storage zonetemperatures.

1. Evaporative heat loss from the free surface.
2. Conductive heat loss from LCZ to NCZ.
3. Convective heat loss from UCZ.
4. Bottom and side wall heat loss.

The evaporative heat loss from the pond surface is

$$q_e = \Phi \rho_a V^3 \left(\frac{P_{sv} - P_a}{\rho_a V^2}\right)^{1.245} (RH)^{-0.56} \quad (5)$$

where ϕ = 8.73×10^{-3} V wind velocity and RH is the relative humidity. The bottom heat loss through cuddappa, cement

$$q_b = \frac{T_w' - T_w''}{\sum l_i/k_i} \quad (6)$$

and insulation is

where i varies from 1 to 9, T_w' is LCZ temperature and T_w'' is ground temperature. Similarly, the heat loss through the side walls q_s are calculated using the above equation. The heat loss from the top surface of UCZ through convection is determined from the expression

$$q_c = h_c(T_s - T_a) \quad (7)$$

Where hc = 5.7+3.8V is the convective heat transfer coefficient, Ts is the surface temperature. Using the heat balance of the storage zone, the heat extraction rate U in Wm^{-2} is given as

$$U = \tau H\lambda(a-b) + h_2(T_b - T_2) + (1-\alpha)\tau H\lambda * b - B \quad (8)$$

where $a = exp(-\mu * x_2)$, $b = exp(-\mu * x_3)$,
$h_2 = 0.14(GrPr)^{1/3} * k_w/L$,
$GrPr = \frac{g\beta\Delta T L^3}{\nu\alpha}$ and $T_b = (q_c/h_2) + T_2$

$$B = \frac{-P}{A} * k_s(T_2 - T_g) * ln(\frac{x_3 - x_1}{x_2 - x_1}) - \frac{k_w}{\delta}(T_2 - T_\delta) \quad (9)$$

Considering the heat losses and heat extraction, the efficiency of the pond is given as

$$\eta_p = F_r(\alpha\tau - U_l * \frac{\Delta T}{H} - \frac{q_{loss}}{H} - \frac{U}{H}) \quad (10)$$

where $qloss = qe+qc+qb+qs$.

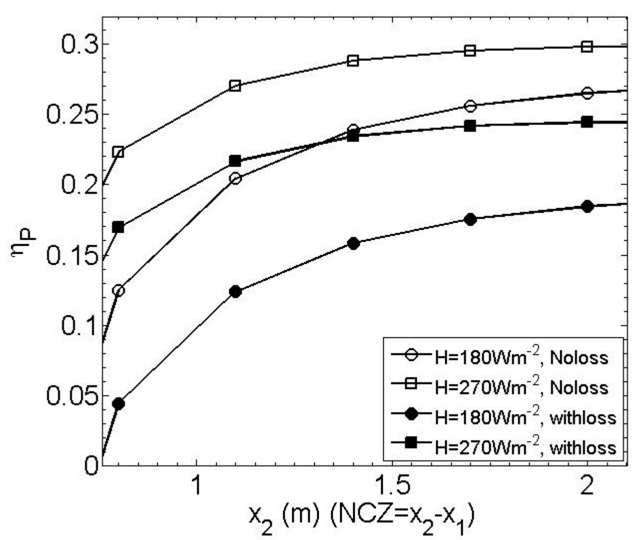

Fig. 11. Variation of pond efficiency with change in thickness of NCZfor H = 180,270Wm^{-2} x_1 = 0.2m with and without heat loss

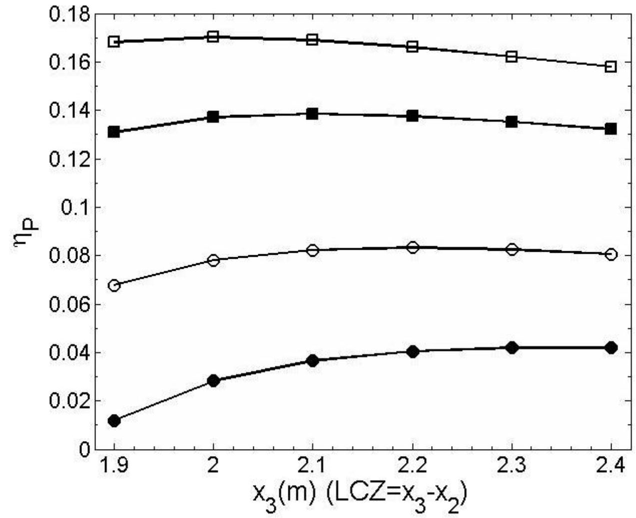

Fig. 12. Variation of pond efficiency with pond depth for H = 180,270Wm^{-2} x_1 = 0.2m with and without heat extraction.

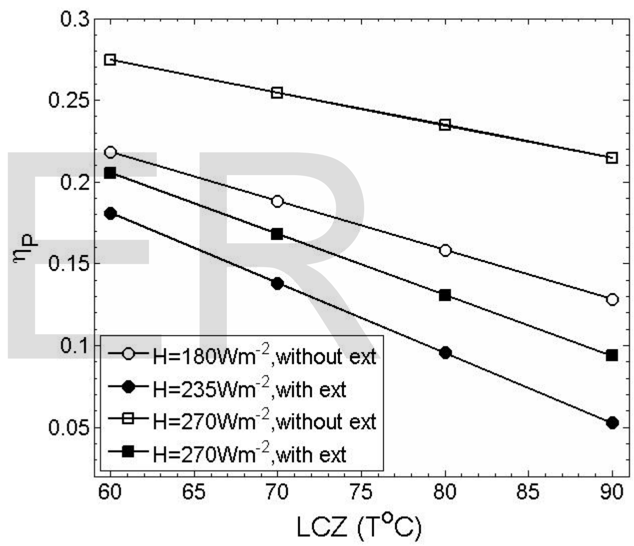

Fig. 13. Variation of pond efficiency with storage zone temperature for H = 180,270$Wm-2$ $x1$ = 0.2m with and without heat extraction.

Figure (11) shows the variation of pond efficiency with the gradient zone thickness considering the heat losses from the pond. The open symbols shows the variation of pond efficiency without heat losses and the filled symbols shows the variation with heat losses. It is seen from the figure that the pond efficiency increases initially with increase in NCZ = x_2-x_1 and after an optimum thickness of NCZ =1.3m, the pond efficiency becomes almost constant for all values of H with and without heat losses. The effect of variation of storage zone thickness with the pond efficiency is shown in figure (12). Though the pond efficiency increases with increase in LCZ=x_3-x_2, an optimumthickness of LCZ =0.9m gives the maximum collection efficiency of the solar pond with and without heat extarction. The open symbols show the variation of pond efficiency with-

ISSN 2229-5518

out heat extraction whereas the filled symbols shows the variation with heat extraction. The variation of pond collection efficiencywith storage zone temperature is shown in figure (13).

For all operating conditions of the solar pond, the pond efficiency decreases with increase in storage zone temperature. This is due to the reason that *qloss* increases with increase in LCZ temperature. The maximum efficiency is obtained when the pond is operated at $60^{o}C$ both with and without heat extraction.

3. CONCLUSIONS

For the monthly average hourly solar radiation $H = 180 - 270 Wm^{-2}$ available, the optimum thickness of the three zones were determined from the present study and are given as$UCZ = 0.2m$, $NCZ = 1.3m$ and $LCZ = 0.9m$. These optimum values were determined for the maximum collection efficiency of the solar pond whose values are in the range of 0.22 to 0.17 when the pond is operated with and without heat extraction.

References

[1] Tabor, H., 1981. "Review article: Solar ponds". *Solar Energy*, **27**(3), pp. 191–194.

[2] Weinberger, H., 1964. "The physics of solar pond". *Solar Energy*, **8**(2), pp. 45–56.

[3] Hull, J., 1985. "Solar pond ground heat on to a moving water table". *Solar Energy*, **35**, p. 221.

[4] Hull, J., 1982. "Calculation of solar pond thermal efficiency with a diffusively reflecting bottom". *Solar Energy*, **27**, pp. 195–198.

[5] Zangrando, F., and Bryant, H., 1976. Solar ponds fro residential heating. Tech. rep., NewMexico Energy Resources Board. Grant ERB-161.

[6] Wang, Y., and Akbarzadeh, A., 1983. "A parametric study on solar ponds". *Solar Energy*, **30**, pp. 555–562.

[7] Anderson, C., 1958. "Limnology of shallow salline-meromistic lake". *Limnology and Oceanography*, **3**, pp. 259–269.

[8] Dake, J., 1973. "The solar pond: analytical and laboratory studies". In Intl. Cong-Sun in the service of mankind, UNESCO.

[9] Gupta, C., Isaac, R., and Patel, S., 1980. "Design procedure for a solar pond". *J. of Energy, Heat and Mass Transfer*, **2**(3), pp. 193–203.

[10] Kooi, C., 1981. "Salt gradient solar pond with reflective bottom". *Solar Energy*, **27**, pp. 181–190.

[11] Bansal, P., and Kaushik, N., 1981. "Salt-gradient stabilized solar pond collector". *Energy Conversion and Management*, **21**, pp. 81–85.

[12] Rabl, A., and Nielson, C., 1975. "Solar pond for space heating". *Solar Energy*, **17**(1), pp. 1–12.

[13] Mehta, A., Pathak, N., Shah, B., and Gomkale, S., 1988. "Performance analysis of a bittern based solar pond". *Solar Energy*, **40**, pp. 469–475.

[14] Al-Marafie, A., Al-Homoud, A., Al-Kandari, A., and Abou-Seido, E., 1991. "Performance of 1700 m2 solar pond operation in arid zone". *Intl. J. Energy Research*, **15**, pp. 535–548.

[15] Tabor, H., and Matz, R., 1965. "Solar pond: Status report". *Solar Energy*, **9**(4), pp. 177–182.

[16] Akbarzadeh, A., Donald, R. M., and Wang, Y., 1983. "Reduction of surface mixing in solar pond by floating rings". *Solar Energy*, **31**, pp. 377–380.

[17] Srinivasan, J., 1990. Dynamics of solar pond. Tech. rep., Karnataka state council for science and technology, IISc, Sept'90.

[18] Nielsen, C., 1975. "Salt gradient solar ponds for solar energy untilization". *Environ. Conser.,*, **2**, pp. 289–292.

[19] Tabor, H., and Doron, B., 1990. "The beith haarava 5 mwe solar pond power plant (sppp)-progress report". *Solar Energy*, **45**, pp. 247–253.