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Rational design of non-convective zone of salt gradient solar pond considering turbidity and biological growth in water.

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Abstract

The optimum size of non-convective zone of a Salt Gradient Solar Pond is determined from the heat balance considerations of the storage zone. The equation governing heat flow in storage zone are simplified considering a linear heat flow through the storage zone to the upper convective zone.The radiation absorption in pond liquid is estimated considering the effect of various Environmental parameters in pond like turbidity and biological growth in it. This has made the analysis more confirming to the real work situation for a pond. The ambient parameter like temperature and radiation are accounted to vary hourly. One significant observation is that the influence of turbidity on pond's performance is so drastic that at turbidity value higher than 0.8\ NTU, the optimum Non-Convective Zone (NCZ) size is not obtained analytically.

Keywords: *Non Convective Zone, optimum size, salt gradient solar pond, stability, thermal performance, turbidity*

Introduction

Salt gradient solar ponds are known as reliable and economical source for long-term heat collection and storage since over hundred years (Weinberger, 1964). With the dawn of new millennium as the energy and environmental crises have got exaggerated, ponds have appeared as environmental friendly and reliable energy alternative. Israel is working with an ambitious plan of fulfilling its entire energy demand by solar pond in near future (Amnon Einav, 2004). Substantial research work has been done on thermal as well as stability aspects of solar ponds. (Zangrando, 1991), (Singh *et al*, 1994), (Punyasena *et al*, 2003), (Angeli and Leonardi, 2004), (Jaefarzadeh, 2004), (Angeli and Leonardi, 2005) have done pioneer work on the stability aspect. For the maintenance of experimental solar ponds with variety of salts and different operating conditions, (Ouni *et al*, 2003), (Huseyin, 2006) have contributed their research experiences. (Huanmin *et al*, 2004) has given a glossary of major works in the maintenance of pond. The first analytical solution of pond was obtained by (Weinberger, 1964). (Tybout, 1966) proposed use of iterative methods for analyzing the pond. Estimation of radiation flux is a very important aspect of pond thermal behavior analysis. Many researchers have explored this aspect (Hull, 1982; Husain *et al*, 2004 and Kooi, 1981). Few investigators observed the effect of turbidity on performance of pond (Husain *et al*, 2004; Sugandhi *et al*, 2006; Wang J and S Yagoobi, 1994,1995).

Kooi, 1979 has proposed an analytical approach for determining optimum size of non-convective zone (NCZ) of the pond. With this optimum size (x_M), the pond retrieves maximum heat at steady state. How ever there is a limitation in the approach of Kooi. The pond takes a very long span of time for its warm up. Kooi's optimum size does not give efficient performance of the pond during warm up phase. Husain *et al*, 2003 have proposed an approach for optimum size of NCZ for rapid warm up of pond. All these researchers considered the pond liquid to be clear water. However in reality, pond is exposed to ambient and receives dust load continuously (Wang and Yagoobi, 1994). Also some biological growth in the pond is unavoidable. These parameters create turbidity in water which affects the radiation transmission so drastically that no realistic analysis of the pond can be done ignoring turbidity (Wang and Yagoobi, 1995; Husain *et al*, 2004).

In the present work, an expression is developed to estimate optimum size of NCZ for rapid warm up (x_m), considering the turbidity in water. Thermal performance of the pond is analyzed with this Optimum (x_m) size of NCZ. Further, it is proposed that in the beginning (during maturation phase) the NCZ size may be kept as x_m and may be later change to x_M.

Theory

Heat balance in the storage zone of SGSP is given as (Sukhatme, 1994**;** Duffie *et al*,1981)

$$r\, C_p\, l_3\, dT/dt = -KdT/dx - Q_{LOSS} - Q_{LOAD} + I_{STZ} \qquad (1)$$

Where r is density of pond liquid, C_p is specific heat, K is Conductivity, T is Temperature, t is time, l_3 is size of STZ, x is thickness of NCZ, Q_{Loss} is losses towards ground, Q_{LOAD} is heat extraction, I_{STZ} is radiation absorbed in STZ. Since pond is not loaded in the warm up phase, $Q_{LOAD} = 0$. Bottom and sides are considered as insulated. Hence $Q_{LOSS} = 0$. Equation (1) is rewritten as

$$r\, Cpl_3\, (T_{STZ} - T_{amb})/Dt = -K[(T_{STZ} + T_{amb})/2 - T_{amb}]/(l_1 + x_n) + I_{STZ} \quad (2)$$

I_{STZ} is calculated by considering turbidity in water. x_n is the thickness of NCZ.

Equation (2) is differentiated with respect to x_n to obtain its optimum value. This equation deals the over all heat balance for the period Dt. In which initial temperature of STZ is increase from T_{amb} to T_{STZ}. Where T_{amb} is ambient temperature, x_n is thickness of NCZ. The term $K[(T_{STZ} + T_{amb})/2 - T_{amb}]/(l_1 + x_n)$ account for the conductive heat losses from STZ to surface, through NCZ assuming a linear temperature profile. Rewriting equation (2) as

$$(T_{STZ} - T_{amb})/Dt = (-KDT_m/(l_1 + x_n) + I_{STZ})/rCpl_3 \qquad (3)$$

Where $DT_m = (T_{STZ} + T_{amb}/2) - T_{amb}$

In equation (3), x_n is variable. Equation (3) is differentiated with respect to x_n and equated to zero to find its maxima. Maxima is denoted by x_m.

$$d/dx_n(-K\,(DT_m/(l_1 + x_n) + I_{STZ})/rCpl_3 = 0. \qquad (4)$$

Say $f(x) = 0$

Solving which, the optimum NCZ thickness x_m is obtained. The analysis is given in appendix-I. Using this value of x_m, the warm up time is calculated. Optimum size of NCZ is also calculated by Kooi's method for comparison. Analysis is presented in appendix II.

Input Data

Hourly varying ambient temperature and solar radiation is considered for city of Jalgaon (21^0 N, 75^0W) (Mani and Rangrajan, 1982). UCZ temperature of pond is estimated by Weinberger's, 1964 approach. Bottom and sides are considered to be insulated. Bottom is considered to be black. Turbidity of water is varied between 0.3 NTU to 1.0 NTU. Pond depth is taken as 1.75 m and UCZ size is taken as 0.2m. The target (desirable) temperature of STZ is varied in the range of 70 ^{0}C to 85 ^{0}C.

Result and Discussion

1. Fig. 1 shows the influence of NCZ size on warm up time of pond. It is seen that, with an increase in NCZ size, the warm up time is getting reduce continuously. While in case of no turbidity the warm up time comes out to be minimum wit h about **0.8x¢**$_{m,}$ where **x¢**$_{m}$ is the optimum size of NCZ as proposed by (Husain *et al,* 2003).
2. At calculated x_m value and values of NCZ lower than this, the target temperature is not achieved. At NCZ values higher than x_m, the target STZ temperature achieved as shown in fig. 1-7.
3. In over all, the use of value close to x_m is advantageous because, too large size of NCZ will be practically difficult and infeasible to be maintained from stability considerations also.
4. Because the over all depth of pond is constant, an increase in NCZ size results in the decrease of STZ size. Lower STZ size means, in over all reduction in storage of quantum of heat. This further justifies the use of x_m as close to the optimum size of NCZ, which gives a lower warm up time, still results into a higher storage of heat in STZ.
5. Similar observation can be obtained from fig. 1 to 7, in which other parameters are varied like turbidity, target temperature of STZ etc.
6. The optimum size of NCZ, x_M according to the Kooi's approach (Kooi 1979), is always constant for fig. 1 to 7, irrespective of target temperature of STZ.
7. The optimum size of NCZ obtained by Kooi's approach does not result into target STZ temperature within reasonable time duration. This is a significant observation with variable ambient parameters while considering constant parameter optimum NCZ size has always obtained target temperature.
8. At lower turbidity range, the optimum size of NCZ (x_m) according to present approach is coming out to be always close to the size (x_M) proposed by (Kooi, 1979). It is different to the findings of (Husain *et al,* 2003) for turbidity free water in which x¢$_m$ is always less than x_M.
9. For higher STZ temperature and higher turbidity values, optimum value of x_m does not exist. While considering constant ambient conditions, optimum value of x_m is always obtained. [Sugandhi *et al*, 2006 communicated]. This is a typical observation with variable parameters.
10. For higher turbidity values like 0.8 and 1.0 NTU, The x_m, values are not found to be in practical range. The values obtained are too small like 10 cm or so. This strongly suggests that the pond turbidity must be maintained below 0.8 NTU. This is an important guideline for pond's operation and maintenance.

Conclusion

Turbidity is an unwanted reality of SGSP. The forgoing analyses explicitly maintain that the turbidity has a very profound influence on optimum NCZ size. In the present case, 0.3 to 1.0 NTU turbidity is considered. The analysis indicates that turbidity greater than 0.8 NTU becomes too high for the pond and the optimum size of NCZ is not obtained. Any real pond exposed to ambient and maintained regularly by coagulant, will always have turbidity; but it must be maintained below 0.8 NTU. For a realistic analysis of SGSP, turbidity must be accounted. The present paper provides an analytical rational approach of determining optimum size of NCZ for faster warm up and over all optimum performance of the pond, considering the turbidity aspect, with hourly varying ambient data. This makes the analysis more realistic as compared to considering constant ambient parameters.

Nomenclature

C_p	*Heat capacity of liquid in pond (kJ/kg/^{0}C)*
h	*Transmission function defined by Wang and Yagoobi*
I	*Symbol for radiation flux*
Io	*Radiation flux incident at surface (W/m^2)*
I_{STZ}	*Radiation energy absorbed in STZ (W/m^2)*
I_{xin}	*Radiation flux incident at depth x (W/m^2)*
K	*Thermal conductivity of liquid in pond (W/m/^{0}C)*
l_1	*Thickness of UCZ (m)*
l_2	*Depth from surface to the interface of NCZ-STZ (m)*
l_3	*Thickness of STZ (m)*
L	Depth of pond (m)
NCZ	*Non-convective zone*
STZ	*Storage zone*
UCZ	*Upper convective zone*
Q_{LOAD}	*Heat extraction rate (W/m^2)*
Q_{LOSS}	*Loss of heat through bottom and sides of the pond (W/m^2)*
t	*Symbol used for denoting time*
T	Symbol used for denoting temperature
T_{amb}	*Ambient temperature (^{0}C)*
T_{STZ}	*STZ temperature (^{0}C)*
x_n	*Thickness of NCZ*
x_m	*Optimum Thickness of NCZ for rapid warm up while considering the turbidity*
$x¢_m$	*Optimum Thickness of NCZ proposed by Husain et al.*

x_M *Optimum Thickness of NCZ according to the Kooi's approach*

f *Turbidity of water in NTU*

r *Density of liquid in pond (kg/m³)*

Appendix - I

The equation (1) is solved here. In requires estimation of I_{STZ}. *Which is done by (Wang and Yagoobi, 1995) method considering turbidity. Wang and Yagoobi proposed following correlation based upon their experimental investigation to estimate radiation flux.*

$$I_{xin}(f, x) = I_0 h(, x)$$

Where I_0, *f and* x *are the radiation flux incident at the surface, turbidity of water in Nephelo-metric turbidity units (NTU), and depth in meter, respectively. The non-dimensional transmission function* h *is defined as*

$$h(f, x) = h(0.3, x)\ r(f, x)$$

Where $h(0.3, x) = 0.58 - 0.076 \ln(100x)$ and

$$r(f, x) = 1.0 - 0.1975x(f - 0.3) + 0.0144x(f - 0.3)^2$$

$r(f, x)$ accounts for turbidity greater than 0.3 NTU.

Solution of equation (4) is done as

$$f(x) = Dx_n[-KDT_m/(l_1 + x_n) + I_{STZ}]/rCpl_3 = 0$$

$$f(x) = d/dx(-KDT_m)/(l_1 + x_n) + d/dx\ I_{STZ} = 0$$

Because $rCpl_3$ is a constant.

$$f(x) = KDT_m/(l_1 + x_n)^2 + d/dx\ Io[(a - b\log_e(100(l_1 + x_n))$$
$$(1 - 0.1975(l_1 + x_n)(f - 0.3) + 0.0144(l_1 + x_n)(f - 0.3)^2]$$

$$f(x) = K\ DT_m/(l_1 + x_n)^2 + Io[(a - b\log_e(100(l_1 + x_n))(0 - 0.1975(f - 0.3) + 0.0144(f - 0.3)^2) + (1 - 0.1975(l_1 + x_n)(f - 0.3) + (0.0144(l_1 + x_n)(f - 0.3)^2)\ (0 - b\ d/dx(\log_e 100(l_1 + x_n))]$$

$$f'(x) = d/dx\ f(x)$$

$$f'(x) = -2KDT_m/(l_1 + x_n)^3 + Io[b/(l_1 + x_n)[0.1975(f - 0.3) - 0.0144(f - 0.3)^2] + b/(l_1 + x_n)^2$$

The solution is obtained numerically with the help of computer program

Appendix- II

Kooi's expression for steady state optimum thickness of NCZ x_M given as

$$? \ (I_T)dx - x_M I_{(l1+xM)} = KDT/I_0 \qquad (5)$$

Say $y(x) = 0$

For determination of $x_{M,}$ equation (5) is solved using Wang and Yagoobi correlation.

$I_{xin}(f, x) = Io\ h\ (f, x)$ as given in appendix (1)

$y(x) = \ ? \ (I_T)dx - x_M I_{(l1+xM)} - KDT/I_0 = 0$

$y(x) = Io \ ? \ (a\text{-}b\ log_e 100x)(1 - 0.1975x(f - 0.3) + 0.0144x(f - 0.3)^2$

$- Io\ x_M [a - b\ log_e 100\ (l_1 + x_M)][1 - 0.1975(l_1 + x_M)\ (f - 0.3)$

$+ 0.0144(l_1 + x_M)\ (f - 0.3)^{2]} - KDT/Io = 0$

$y(x) \quad = Io[a\text{-}blog_e 100[x_M - (x_M{}^2 + 2l_1 x_M)/2\ (0.1975(f - 0.3)$

$- 0.0144\ (f - 0.3)^2)] - b[\ (l_1 + x_M)\ log_e\ (l_1 + x_M) - l_1 log_e l_1 - x_M]$

$+ b\ (0.1975\ (f - 0.3) - 0.0144(f - 0.3)^2)$

$[(l_1 + x_M)^2/2\ (log_e(l_1 + x_M) - 1/2) - l_1{}^2/2\ (log_e l_1 - 1/2)]]$

$- Io\ x_M [a\text{-}blog_{e100}(l_1 + x_M)]\ [1 - 0.1975(l_1 + x_M)\ (f - 0.3)$

$+ 0.0144(l_1 + x_M)\ (f - 0.3)^{2]} - KDT/Io = 0$

$y'(x) = d/dx\ y(x)$

$d/dx\ y(x) = Io\ [\ (a\text{-}blog_e 100)d/dx\ x_M - [(a\text{-}blog_e 100)(0.1975(f - 0.3) -$

$0.0144f - 0.3)^2)]\ d/dx(x_M{}^2 + 2l_1 x_M)/2 - \ b\ (d/dx\ (l_1 + x_M)$

$loge(l_1 + x_M) - d/dx\ l_1 log_e l_1 - d/dx\ x_M) + b\ (0.1975\ (f - 0.3) -$

$0.0144(f - 0.3)^2)d/dx(l_1 + x_M)^2/2\ (log_e(l_1 + x_M) - 1/2) - d/dx$

$l_1{}^2/2(log_e l_1 - 1/2)] - Io\ d/dx(x_M [a\text{-}blog_{e100}(l_1 + x_M)]\ [1 -$

$0.1975(l_1 + x_M)\ (f - 0.3) + 0.0144(l_1 + x_M)\ (f - 0.3)^2])] - d/dx\ KDT/Io$

$y'(x) \quad = Io\ [a - b\ log_e 100\ [1 - (0.1975(f - 0.3) - 0.0144(f - 0.3)^2)\ (l_1 + x_M)]$

$- b[log_e(l_1 + x_M)] + b[0.1975(f - 0.3) - 0.0144(f - 0.3)^2][\ (l_1 + x_M)$

$$(\log_e(l_1 + x_M) - 1/2) + (l_1 + x_M)/2]\,]$$

$$- Io\,[[a - b\log_e 100\,(l_1 + x_M)[1 - 0.1975(l_1 + x_M)(f - 0.3)$$

$$+0.0144(l_1 + x_M)(f - 0.3)^2]$$

$$- x_M\,[b(0.1975(f - 0.3) - 0.0144(f - 0.3)^2)][1 + \log_e(100(l_1 + x_M)\,]$$

$$- a\,x_M\,(-0.1975(f - 0.3) + 0.0144(f - 0.3)^2) + b\,x_M/(l_1 + x_M)\,]$$

The solution is obtained numerically with the help of computer program

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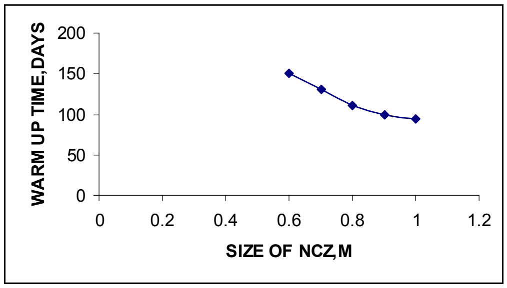

Fig.1: Variation of warm up time with NCZ size considering varying ambient parameters. $T_{STZ} = 70\,^0$C, l_1= 0.2 m, L = 1.75 m. Turbidity = 0.3 NTU. Bottom is Insulated and black. x_m = 0.5 m, x_M = 0.5 m.

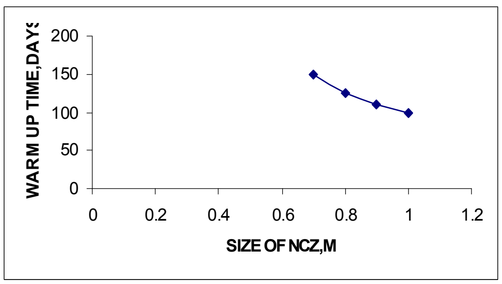

Fig. 2: Variation of warm up time with NCZ size considering varying ambient parameters. $T_{STZ} = 75^0$C, l_1= 0.2 m, L = 1.75 m. Turbidity = 0.3 NTU. Bottom is Insulated and black. x_m = 0.6 m, x_M = 0.5 m

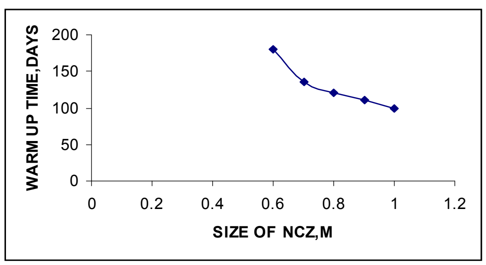

Fig.3: Variation of warm up time with NCZ size considering varying ambient parameters. $T_{STZ} = 70\,^0$C, l_1= 0.2 m, L = 1.75 m. Turbidity = 0.5 NTU. Bottom is Insulated and black. x_m = 0.45 m, x_M = 0.5 m.

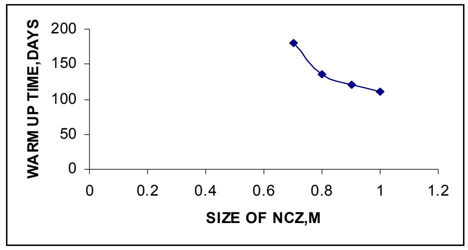

Fig.4: Variation of warm up time with NCZ size considering varying ambient parameters. T_{STZ} = 75 ^{0}C, l_1=0.2 m, L=1.75 m. Turbidity=0.5 NTU. Bottom is Insulated and black. x_m =0.5 m, x_M =0.5 m.

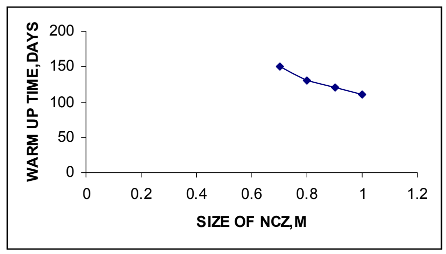

Fig.5: Variation of warm up time with NCZ size considering varying ambient parameters. T_{STZ} = 70 ^{0}C, l_1=0.2 m, L=1.75 m. Turbidity=0.8 NTU. Bottom is Insulated and black. x_m =0.21 m, x_M =0.5 m.

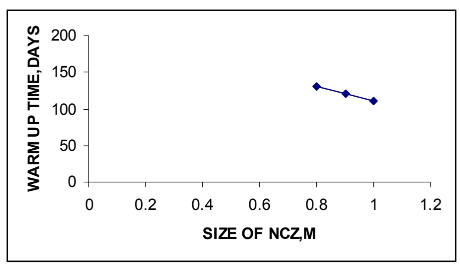

Fig.6: Variation of warm up time with NCZ size considering varying ambient parameters. T_{STZ} = 75 ^{0}C, l_1=0.2 m, L=1.75 m. Turbidity=0.8 NTU. Bottom is Insulated and black. x_m =0.25 m, x_M =0.5 m.

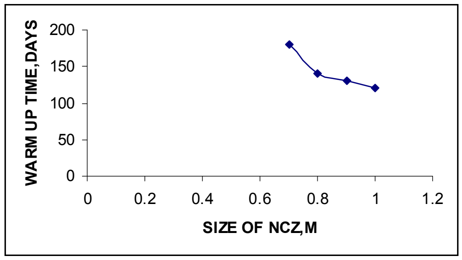

Fig.7: Variation of warm up time with NCZ size considering varying ambient parameters.T_{STZ} = 70 ^{0}C, l_1= 0.2 m, L = 1.75 m. Turbidity = 1.0 NTU. Bottom is Insulated and black. x_m = 0.1 m, x_M = 0.5 m.

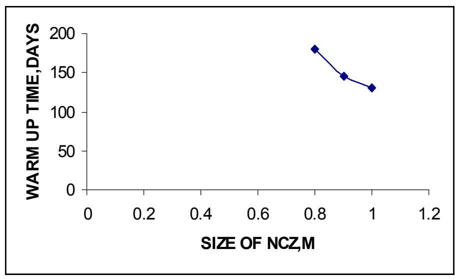

Fig.8: Variation of warm up time with NCZ size considering varying ambient parameters.T_{STZ} = 75 ^{0}C, l_1= 0.2 m, L = 1.75 m. Turbidity = 1.0 NTU. Bottom is Insulated and black. x_m = 0.1 m, x_M = 0.5 m.