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Simulation and Modeling of Solar Pond for Power Generation

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Ranchi University

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **SIMULATION AND MODELING OF SOLAR POND FOR POWER GENERATION** in fulfillment of the requirement for the award of the Degree of Doctor of Philosophy submitted in the **Department of Electrical Engineering** under **Ranchi University** (Faculty of Engineering) is an authentic record of my own work carried out during a period from May 2003 to May 2009 under the supervision of **Dr. S. P. Sharma, Assistant Professor** and **Dr. S. B. L. Seksena, Professor.**

The matter embodied in this work has not been submitted for any other degree.

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ABSTRACT

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.

Solar thermal power generation is an attractive option for cost efficient electricity production and in countries with high solar resources this technology is capable to produce solar electricity on a very large scale from 50 to 200 MW. There are three options for converting solar energy into mechanical/electrical power.

A low temperature system, uses solar pond and working on Rankine Cycle at a temperature about 100^0C, medium temperature cycle using line focusing parabolic collector technology up to 400^0C and parabolic disc trough/central tower receiver for temperature above 400^0C.

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 concentrator 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

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which has low and nearly uniform salt content. Beneath the UCZ is the Non-convective zone 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 Convective Zone (NCZ) or gradient zone of thickness that varies between 1 to 1.5 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 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.

In present work, an analytical model of SGSP 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.

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- 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:

$$T(x) = T_c + \frac{b' A_f}{mCp} \ln(x + \delta) - [\{\frac{b' A_f}{mCp} e^{(x+\delta) A_f} / k\ m\ C_p\} \{ E_4 + \ln(x+\delta)\}] \qquad (1)$$

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

$$E_4 = T_a + \frac{(q-a)}{b'} e^{-(d+\delta)A_f / k\ m\ Cp} + \ln(d+\delta)\{ e^{-A_f (d+\delta) / k\ m\ Cp} - 1\} \qquad (2)$$

And,

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

$$- \{1 - e^{-A_f (d+\delta) / k\ m\ Cp}\} \ln(x+\delta) \qquad (3)$$

For corrugated (wavy)/V-shaped surface, Equ. (1) is further developed considering the area enhancement factor (β) and increased bottom surface area as A_{pf} in place of A_p.

$$T(x) = T_c + \frac{b'\beta A_{pf}}{mCp} \ln(d+\delta) - [\{ \frac{b'\beta A_{pf}}{mCp} e^{(x+\delta)\, \beta\, A_{pf} / k\, m\, Cp})\{ E_4 + \ln(x+\delta)\}] \quad (4)$$

where β is the area enhancement factor, E_4 and T_c are the integration constants and these are expressed as:

$$E_4 = T_a + \frac{(q-a)}{b'} e^{-\beta(d+\delta)A_{pf} / k\, m\, Cp} + \ln(d+\delta)\{ e^{-\beta A_{pf}\, (d+\delta) / k\, m\, Cp} - 1\} \quad (5)$$

And,

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

$$\{- e^{-A_{pf}\, (d+\delta)\, \beta / k\, mCp}\} \ln(x+\delta) \quad (6)$$

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.

The thickness of upper convective zone (UCZ), Non-convective zone (NCZ) and lower convective zone (LCZ) of the solar pond has been taken as 0.2 m, 1m and 0.8 m respectively. The heat extraction rate, heat capacity rate and area enhancement factor (β) have been taken in the range of 0 to 60 W/m^2, 0.75 to 1.5 W/(m^2.K) and 1 to 2, respectively. The average global solar radiation (H) is 215 W/m^2.

It has been found that for β=1 and H=215 W/m^2, the temperature of the solar pond almost remains constant in the UCZ, where as in the NCZ, temperature increases linearly with the increasing depth and again remains constant in LCZ 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 LCZ 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.

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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 to 20.97 percent, 22.51 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. Also, the mathematical expression for collector efficiency, heat removal factor and outlet fluid temperature have been developed for cylindrical parabolic trough collector through which the working fluid flows.

The expressions developed have been expressed here as under:

$$\eta=\frac{Q_u(t)}{q_s(t)A_C} = (\tau\alpha)_e - \frac{1}{q_s(t)A_C}\{\breve{U}\, A_e(\check{T}_e-T_a)-\varepsilon_e\, \sigma\, A_e(\check{T}^4_e-T^4_a)\} \tag{7}$$

In dimensional form or:

$$\eta=\frac{Q_u(t)}{q_s(t)A_C} = (\tau\alpha)_e - \frac{1}{\psi(t)}[b(\theta_e - \theta_a) + a\,(\theta^4_e - \theta^4_a)] \tag{8}$$

In dimensionless form

Where the ratio of absorbing element area to collector aperture area (A_e/A_c). The $q_{s,ref}$ is any convenient reference value of insolation such as the peak-clear day value, and $\check{T}_a$ is the daily average ambient temperature, $\check{T}_e$ is the average absorber surface temperature, and the ambient temperature T_a. The parameters ‘a’ and ‘b’ are related to the magnitude of radiation and thermal losses radiative to a reference insolation value and include the effect of concentration in the ratio of absorbing element area to the collector aperture area, A_e/A_c. The $q_{s,\ ref.}$ is any convenient reference value of insolation such as the peak clear-day value, and $\check{T}_a$ average

Abstract

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collector temperature to the more easily measured fluid inlet temperature and the collector efficiency can now be found in terms of the fluid inlet temperature.

$$\eta = F_R[(\tau\alpha)_e - \frac{1}{q_s(t)A_C}\{\breve{U}\, A_e(\check{T}_{fi}-T_a)-\varepsilon_e\,\sigma\, A_e(\check{T}^4_{fi}-T^4_a)\}]$$

Or. $$F_R = \frac{\eta}{(\tau\alpha)_e - \frac{\{UA_e(T_{fi}-T_a)-\varepsilon\sigma A_e(T^4{}_{fi}-T^4{}_a)\}}{q_s(t)A_c}} \qquad (9)$$

In dimensionless form:

The expression for net enthalpy gain $Q_u(t)$ of the fluid flowing through the collector is given by

$$Q_u(t)=\delta_c\, m_c\, C_p\,(T_{fo}-T_{fi}) \qquad (10)$$

The expression for fluid outlet temperature of the collector has been expressed as

$$T_{fo}=T_{fi}\,(1-\frac{bF_R}{\gamma})+\frac{TF_R}{\gamma}\,[\,\Psi(t)(\tau\,\alpha)_e+b\theta_a]-(\frac{aT_aF_R}{\gamma})(\theta^4_{fi}-\theta^4_a)$$

Where $a = \varepsilon_e\,\sigma\, A_e\check{T}^4_a/q_{s,ref}A_c$; $b = \breve{U}\, A_e\,\check{T}_e/(q_{s,\ ref}A_c)$; $\theta_e = \check{T}_e/\check{T}_a$; $\theta_a = T_a/\check{T}_a$;

$\Psi(t)= q_s(t)/q_{s,\ ref}$ and $\gamma = \delta_c\, m_c\, C_p\,\check{T}_a/q_{s,ref}A_c$

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The parameter γ is a measure of the ratio of the ability of the working fluid to remove energy from the collector to the reference solar energy. The value of γ can ranges from zero to very large values depending on the radiative values of the mass flow rate through the collector, the collector area, and the reference insolation. As γ approaches zero (m_c tends to zero, near stagnation conditions), Eqn. (3.15) predicts [using Eqn. (3.9)] that no flow or stagnation temperature of the collector is given by stagnation temperature of the collector is given by

$$T_{stag} = \check{T}_a + \frac{1}{bq_{s,ref.}}(\tau\ \alpha)_e\ q_s(t)\ \check{T}_a - \frac{1}{b}\ a\ \check{T}_a\ (\theta^4_{stag} - \theta^4_a) \qquad (11)$$

And also,

$$T_{stag} = \check{T}_a + \frac{1}{UA_e}\ (\tau\ \alpha)_e\ q_s(t)\ A_c - \frac{1}{U}\ \varepsilon_e\sigma\ (T^4_{stag} - T^4_a) \qquad (12)$$

The outlet fluid temperature, useful energy collected, collector efficiency and heat removal factor have been simulated for various values of system and operating parameters in order to predict the performance of the cylindrical parabolic trough collector for solar thermal electrical power generation.

The values of the various parameters are taken as, $\check{T}_e$ =600 K, $\check{T}_a$=300 K, T_a=300K, concentration ratio=60, $(\tau\alpha)_e$=0.85, a=0.001165 to 0.00574, b=0.03375 to 0.0562, dimensionless insolation ψ(t) =0.2 to 1, $\check{U}$=3 to 15 W/m^2-K, ξ=1.

The plots of efficiency as a function of dimensionless insolation ψ(t) reveal that the efficiency monotonically increases with increase in ψ(t) for all values of thermal loss parameter ‘b’ and increase in the value of ‘b’, decrease the

efficiencies. The thermal loss parameter, b=0.01125 maintains the highest efficiency value throughout the range of dimensionless insolation investigated. Furthermore, a slight fall is observed in the rate of increase of efficiency as ψ(t). The maximum and minimum efficiency has been found to be 78.63 percent and 53.16 percent, respectively at b=0.01125 and then these maximum and minimum values of efficiencies are decreases as the thermal loss parameter increases as 77.51 percent and 47.54 percent at b=0.0225, 76.38 percent and 41.96 percent at

b=0.03375, 75.26 percent and 36.29 percent at b=0.045, 74.13 percent and 30.68 percent at b=0.056, respectively.

It is also seen that the efficiency increases with increase in dimensionless insolation for all values of radiative loss parameter ‘a’. The radiative loss parameter, a=0.001165, maintains the highest efficiency throughout the range of ψ(t) investigated. The increase in radiative loss parameter ‘a’, decrease the efficiency.

The thermal loss parameter ‘b’ and radiative loss parameter ‘a’ also effects the values of heat removal factor of the cylindrical parabolic trough collector. It has been found that the heat removal factor linearly increases with ψ(t) for all values of thermal loss parameter ‘b’. The value of heat removal factor (F_R) changes from 0.125 to 0.925 for b=0.01125 and a=0.001165 and then these values decrease with increase in the value of thermal loss parameter ‘b’.

The results show that the heat removal factor also increases from 0.139 to 0.943 with increase in ψ(t) for a=0.001165 and b=0.03375. The above values of heat removal factor then decrease with increase in radiative loss parameter ‘a’.

The fluid outlet temperature (T_{fo}) as a function of dimensionless insolation plots show that the outlet fluid temperature increases linearly from 363.54^{0}C to 401.11^{0}C for a=0.00567 and b=0.03375. The values of fluid outlet temperature are 365.74^{0}C and 407.93^{0}C respectively for a=0.00446 and b=0.05625.

It is also seen that the outlet fluid temperature decreases with increase in mass flow rate for all values of ψ(t). The temperature fall for fixed value of ψ(t) is seen to be non-linear, the higher values of mass flow rate showing less steeper fall as compared to lower value of mass flow rate.

The maximum and minimum value of outlet fluid temperatures as mass flow rate increases from 0.2 to 1.0 kg/s is found to be 360.11^{0}C and 341.69^{0}C for ψ(t)=0.2, a=0.00446 and b=0.03375 and then these values increase with respect to increase in mass flow rate at higher values of ψ(t). The maximum and minimum values of temperatures are found to be 370.36^{0}C and 348.57^{0}C at ψ(t)=0.4, 377.15^{0}C and 353.13^{0}C at ψ(t)=0.6, 388.51^{0}C and 360.76^{0}C at ψ(t)=0.8, 399.99^{0}C and 367.15^{0}C at ψ(t)=1, respectively.

It has been found that the temperature rise ΔT increases linearly with increase in dimensionless insolation for all values of thermal loss parameter ‘b’, and fixed value of radiative loss parameter ‘a’. The increase in ‘b’ increases the values of ΔT, the minimum and maximum temperature rise is found to be 371.1^{0}C and 333.5^{0}C respectively for a=0.00342 and b=0.0625 whereas these values are 335.74^{0}C and 377.93^{0}C, respectively for a=0.00567 and b=0.03375.

The coupling between the collector and the thermodynamic cycle is made up of three heat exchangers, yielding the characteristic temperature of the cycle. The conventional Rankine cycle is treated as an endo-reversible Carnot cycle, whereby the mechanical and electrical power is calculated. The efficiency curve of the solar electric generating system whose solar field is composed by LS-2 (area =235 m^2, apertutre =5 m, length = 48 m, receiver diameter =0.07 m, concentration ratio =71.1 m, optical efficiency = 0.764, receiver absorptivity =0.96, mirror reflectivity =0.94, receiver emittance = 0.19, temperature =350^0C, operating temperature =307^0C) parabolic trough collector have been simulated. The second simulation was carried out to estimate the optimum quantity of non-evacuated LS-2 collectors in series in a collector's row, when friction losses along the absorber tubes are considered. The pressure losses of a column of collectors in series have been estimated by using standard formulas for pipe flow in fully turbulent regime. Varying the amount of collectors in series in the solar collector assembly (SCA) and subtracting in each case the electric power supplied to the pumps (P_{el}, loss) from the maximum electric power of the plant (P_{el}. Max.), the difference, referred to as the net electric power (P_{el}, net), is obtained. In the calculation, two values of irradiance were used equal to 400 W/m^2 and 800 W/m^2, and collectors (LS-2) with non-evacuated absorbers.

Also, the performance of a 30 MWe power plant, composed of 50 rows with 16 LS-2 collectors in series (e.i. total 800 collectors) was simulated. Three fields of different collectors were considered, the first field evacuated absorbers, the second with non-evacuated absorbers and the third with bare absorbers.

In this study, it was analyzed that the output power of the plant as a function of the evaporation temperature of the thermodynamic cycle. For this simulation it was choosen a direct irradiation equal to 940 W/m^2. For calculations; the properties of the thermal fluid within the interval of operation has taken between 200^{0}C to 400^{0}C. The enthalpies, for pressure between 5 to 20 MPa were obtained from the thermodynamic tables. The results of simulation for the

efficiency curves of parabolic trough LS-2 collectors, with evacuated absorber vary between 0.73 and 0.65 when ΔT_{ma} varies between 100^{0}C and 350^{0}C. Non-evacuated absorbers show efficiencies equal to 0.70 and 0.58 for the same values of ΔT_{ma}.

The plots of the ratio between net power and maximum net power of the solar plant of capacity 30 MWe with the quantity of non-evacuated collectors in series that optimize the SCA output is 13 with irradiance of 800 W/m^2 and between 24 and 28 with irradiance of 400 W/m^2.

Using the evaporation temperature (T_{ev}) as an optimization parameter, the overall efficiency of the solar plant has been optimized subject to the following restrictions: the temperature (T_4) of the thermal fluid and the temperature pinch points (ΔT_1 and ΔT_2) and condensation temperature (T_0) remains constant while the evaporation temperature (T_{ev}) varies.

It has been found that within certain range of evaporation temperature (250^0C to 330^0C), the conversion efficiency of thermal to electric energy achieves a maximum and does not depend on the type of absorbers. Finally, the overall plant efficiency reaches its maximum at lower temperature, different for each type of collectors.

For irradiance equal to 940 W/m^2, the overall efficiency of the system also presents a maximum which depends on the type of the absorber. The evaporation temperatures and overall efficiency that optimize the electric output are approximately $T_{ev}=320^0$C and $\eta_{ov}=0.262$ with evacuated absorber; $T_{ev}=310^0$C and $\eta_{ov}=0.243$ with non-evacuated absorber and $T_{ev}=300^0$C and $\eta_{ov}=0.219$ with bare absorber (without glass envelop).

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NOMENCLATURE

SGSP	Salt Gradient Solar Pond
UCZ	Upper Convective Zone
NCZ	Non-Convective Zone
LCZ	Lower Convective Zone (Storage Zone)
A_f	Total surface area of the pond with flat bottom surface
A_p	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 LCZ (in m)
L	Depth of Solar Pond (in m)
T(x)	Temperature of the pond at a depth x below the interface between

UCZ	Upper Convective Zone
NCZ	Non Convective Zone
LCZ	Lower 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
δx	Thickness of a layer at a distance x below the UCZ and NCZ interface (in W/m^2)
H	Average global solar radiation incident on the surface of the pond

NOMENCLATURE

K	Thermal conductivity of the fluid in NCZ
q_c	Heat loss due to convection (in W/m^2)
q	Heat loss due to evaporation (in W/m^2)

Nomenclature

q_t	Total heat loss at the pond surface (in W/m^2)
Q_{Load}	Extracted energy 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 (kg/m^3)

τ	Coefficient of transmissivity of air-water interface
a&b	Constants related to absorption of light in water
$Q_u(t)$	useful energy collected by a solar collector
$q_u(t)$	usable energy per unit area per unit time
$q_s(t)$	instantaneous insolation
$(\tau\ \alpha)_e$	fraction of the insolation striking the collector aperture
A_c	aperture area
$\tilde{U}$	overall heat transfer coefficient based on absorber area
A_e	absorber area
ε_e	infrared emissivity

Nomenclature

$\check{T}_e$	average absorber surface temperature
T_a	Daily average ambient temperature
σ	Stefan Boltzmann constant
δ_c	control variable for system model
m_c	mass flow rate of fluid through the collector
C_p	specific heat capacity of the fluid
F_R	heat removal factor
T_{fi}	inlet temperature of the collector fluid
T_{fo}	outlet temperature of the collector fluid
T_{stag}	stagnant temperature of the plate
$T_{f\ o}$	fluid outlet temperature
$T_{f\ i}$	fluid inlet temperature

a	Radiative loss parameter
b	thermal loss parameter
θ	absolute temperature ratio, T/T_a
θ_e	Ratio of average absorber surface temperature and average absolute temperature, $\check{T}_e / \check{T}_a$
$\Psi(t)$	dimensionless insolation,
η	efficiency
α	absorptivity for solar energy

Nomenclature

SUBSCRIPTS

a	ambient
e	effective
f	fluid
I	inlet
o	outlet
stag	stagnation
s	solar
u	usable
~	average value

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