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Efficiency and Thermal Analysis of a Salinity Gradient Solar Pond

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ABSTRACT

In the view of current requirements of power generation and the increased interest on renewable energy sources, many options are available for generation of clean power. Solar power generation would be one of the best options in this context. The solar pond uses the principle of conversion of solar energy into heat energy, and also has the capability of storing this energy for certain period of time. The solar ponds could be best option for the regions with high solar radiation throughout the day, and also has free land availability. The paper depicts the significance of solar pond for conversion of solar energy into heat energy with a sight towards the parameters like thermal efficiency, working conditions and cost of construction. The simulation of solar pond system has been carried out for understanding the trends of the thermal efficiencies with respect to time.

Keywords : Energy Sources, Solar Energy, Heat Energy, Upper Convective Zone, Thermal Analysis, UCZ, NCZ LCZ, SLEACH, RCD, RMCM, CKM, KDD

I. INTRODUCTION

The ecological problems and energy crisis in the world have induced the researchers to develop sustainable energy utilization systems, in which solar energy is an attractive one. The solar energy comes to earth as an amount equal to several thousand times that of present fossil fuel usage and it drives all the natural ecosystem services of the planet. The fossil fuels presently meet the all global energy needs to some extent. The fossil Fuels need replacement by renewable energy sources in the view of their depletion rates and emission legislation. The usage of renewable energy sources can cut the pollutant emissions into the atmosphere. Exploration of solar energy plays a vital role in developed and developing countries [1-9]. Solar ponds are one of the simplest and less expensive technologies for converting and storing solar energy. The solar pond is unique in its ability to act both a collection and storage system [10]. Solar ponds can be operated at virtually all latitudes and can provide energy for space heating and cooling, industrial process heating, pre-heating, and power generation via an organic Rankine cycle engine [11]. Solar pond contains, layers of salt solutions with increasing concentration (and therefore density) to a certain depth, below which the solution has a uniform high salt concentration. When solar radiation (sunlight) is absorbed, the density gradient prevents heat in the lower layers from moving upwards by convection and leaving the pond. This means that the temperature at the bottom of the pond will rise to over 90 °C, while the temperature at the top of the pond is usually around 30^0C [12]. They can be located anywhere that is suitable for building a pond, regardless of the distance to the nearest power outlet, since there is gaining access to direct sunlight near the pond site.

There are four basic types of solar ponds viz. (I) salt gradient solar ponds (ii) shallow solar pond (iii) salt-less convecting ponds and (iv) gel and viscosity stabilized pond. Fresh water forms a thin insulating surface layer at the top, and beneath to that is salted water. A salt gradient pond is the most common type of non-convecting solar pond [13-14]. The initiative of creating artificial solar ponds was proposed many researchers and many developments are in progress in this subject [1].

II. METHODS AND MATERIAL

1. Efficiencies of Solar Pond

Literature reviews suggests that the solar pond is a low cost system having less efficiency compared with conventional direct solar heating system. The efficiency of a solar pond for heating is about 10%- 20%, and the efficiency for electricity production drops to 1% - 2% (insolation to electrical output). Despite these low efficiencies, solar ponds can be economical in many areas because of their low cost [16].The Solar Pond Thermal efficiency can be defined as useful energy collected (heat removal plus change in the energy stored in the storage zone) over a given period of time divided by the total insolation for the area over that same period [17]. The relationship could be expressed as follow.

$$\eta_{th} = \frac{E_{uc}}{I_t}$$

Where, E_{uc} = Useful energy collected (J)
I_t= Integrated Insulation over the time period (J)

In addition parasitic losses occur at an average of 5% for heating applications and an average of 20% for power generation on the total energy production. Thermal efficiency for each zone of a solar pond can be determined for thermodynamic analysis. The thermal (energy) efficiency for the upper convective zone (UCZ) can be expressed as

$$\eta = \frac{Q_{net}}{Q_{in}} \quad (1)$$

$$Q_{net} = Q_{in} - Q_{out} = (Q_{solar} + Q_{down}) - (Q_{wa} + Q_{side}) \quad (2)$$

Where Q_{net} is the net heat stored in the UCZ, Q_{solar} is the quantity of net incident solar radiation absorbed by the UCZ, Q_{down} is the total heat transmitted to the zone from the zone beneath it, Q_{side} is the total heat loss to the side walls of the pond and Q_{wa} is the total heat loss to the surroundings from the upper layer. Therefore, energy efficiency can be written as

$$\eta_{UCZ} = 1 - (Q_{wa} + Q_{side}) / (Q_{solar} + Q_{down}) \quad (3)$$

where Q_{wa}, Q_{side}, Q_{solar}, Q_{down} in Eq. (3) can be written as

$$Q_{wa} = U_{wa} A_{UCZ} (T_{UCZ} - T_{amb}) \quad (4)$$

$$Q_{side} = U_{side} A_{side} (T_{UCZ} - T_{side}), \quad (5)$$

$$Q_{solar} = \beta E A_{UCZ} h_1 \quad (6)$$

Here h_1 is the ratio of the solar energy reaching layer I to the total solar radiation incident onto the surface of the pond, A is the pond area and β is the incident beam rate entering the water.

$$Q_{down} = \frac{K}{X_1} A_{UCZ} (T_{down} - T_{UCZ}), \quad (7)$$

Where k is the thermal conductivity, x_1 is the thickness of the first layer, β and h_1 in Eq. (6) are given as

$$\beta = 1 - 0.6 \left[\frac{\sin(\theta_g - \theta_k)}{\sin(\theta_g + \theta_k)}\right] - 0.4 \left[\frac{\tan(\theta_g - \theta_k)}{\tan(\theta_g + \theta_k)}\right] \quad (8)$$

$$h_1 = 0.727 - 0.056 \ln(X_1 - \delta)(100\,\%) \quad (9)$$

The thermal (energy) efficiency for the non convective zone (NCZ) can be expressed as

$$Q_{net} = Q_{in} - Q_{out} = (Q_{NCZ,solar} + Q_{down}) - (Q_{up} + Q_{side}) \quad (10)$$

Following Eq. (1), the thermal (energy) efficiency for the non-convective zone (NCZ) can be expressed as

$$\eta_{NCZ} = 1 - (Q_{up} + Q_{side}) / (Q_{NCZ,solar} + Q_{down}) \quad (11)$$

Where Q_{up} is the heat loss from the NCZ to the zone above it, $Q_{NCZ,solar}$ is the amount of solar radiation entering the NCZ, which is transmitted from the upper convective zone after attenuation of incident solar radiation in the upper convective zone. $Q_{up}, Q_{side}, Q_{NCZ,solar}, Q_{down}$ in Eq. (11) can be written as

$$Q_{up} = \frac{KA}{\Delta X} (T_{UCZ} - T_{NCZ}) \quad (12)$$

$$Q_{side} = U_{side} A_{side} (T_{NCZ} - T_{side}) \quad (13)$$

$$Q_{NCZ,solar} = \beta E A_{NCZ} h_1 \quad (14)$$

$$Q_{down} = \frac{KA}{\Delta X} (T_{down} - T_{NCZ}) \quad (15)$$

The energy balance for the LCZ can be written as

$$Q_{net} = Q_{in} - Q_{out} = (Q_{NCZ,solar} + Q_{up}) - (Q_{side} + Q_{bottom}) \quad (16)$$

Following Eq. (1), the thermal (energy) efficiency for the lower convective zone (LCZ) can be expressed as

$$\eta_{LCZ} = 1 - (Q_{up} + Q_{side} + Q_{bottom}) / (Q_{LCZ,solar}) \quad (17)$$

Where Q_{bottom} is the total heat loss to the bottom wall from the heat storage zone. $Q_{up}, Q_{side}, Q_{bottom}, Q_{NCZ,solar}$ in Eq. (11) can be respectively written as

$$Q_{up} = \frac{KA}{\Delta X_{LCZ}} (T_{LCZ} - T_{up}) \quad (18)$$

$$Q_{side} = U_{side} A_{side} (T_{LCZ} - T_{side}) \quad (19)$$

$$Q_{bottom} = U_{bottom} A_{bottom} (T_{LCZ} - T_{bottom}) \quad (20)$$

$$Q_{NCZ,solar} = \beta E A_{LCZ} h_1 \quad (21)$$

2. Developments In Solar Pond System

The modifications to the salt gradient solar ponds carried out both theoretically and experimentally by many researchers [18-31]. Kayali et al. [32] developed a novel theoretical model capable of giving the temperature variation at any point inside or outside a non-isolated rectangular solar pond at any time. Subhaker and Murthy have used a model to predict the long-term performance of a saturated solar pond for various heat extraction temperatures and rates [33]. Jaefarzadeh investigated the time history of the development of temperature, salinity and elevation of lower and upper layers at various climatologically situations [34]. Tahat et al. [40 -41] carried out dimensional analysis to show the effect of the mini solar pond's size on its thermal behavior.

Mehta et al. [35] analyzed the performance of a bittern-based solar pond with an area of 1600m^2 located in Bhavnagar, India. Bezir [36] investigated a salt gradient solar pond with a surface area of 3.5×3.5m^2 and a depth of 2 m, built for supplying hot water to a leather workshop on the campus area of Vocational College of Isparta /Yalvaç. Bezir and his co-worker [37] studied a cover system for the surface of the pond used to reduce the thermal losses from the top to air during nighttime and to increase the thermal efficiency of the pond during daytime, and thermal analysis of the pond was carried out theoretically and experimentally.

III. RESULTS AND DISCUSSION

1. Theoretical Design of Solar Pond for Cost Estimation

The design of a solar pond in the region of Guntur of latitude 16.30N and Longitude 80.46E has been considered for study. The following table refers to the climatic condition of a Guntur.

Table I : Weather data in the selected region

Month	Solar Radiation (kWh/m^2)	Ambient Temp. (^{0}C)	Wind Speed (m/sec)	Relative Humidity (%)
Jan.	4.70	29	3.29	76
Feb.	5.54	31	3.57	76
Mar.	6.28	33	3.78	75
Apr.	6.53	35	4.42	73
May	6.05	38	4.53	67
Jun.	4.81	36	5.23	67
Jul.	4.17	34	5.22	74
Aug.	4.27	33	4.99	77
Sept.	4.53	33	3.47	79
Octo.	4.35	32	3.15	81
Nov.	4.53	30	3.74	78
Dec.	4.47	29	3.64	75

The following configuration was as summed for design of solar pond and to perform thermal analysis.

1. Upper convective zone depth = 0.1 m (0.3 ft), salt concentration = 0.5 kg salt/m^3 brine (0.03 lb salt/ft^3 brine). This is a fixed assumption.
2. Non-convective zone depth = 0.6 m (1.96 ft), salt concentration varies from 0.5 - 208 kg salt/m^3 brine (0.03-13 lb salt/ft^3 brine).
3. Storage zone depth = 0.8 m (2.26 ft), salt concentration = 208 kg salt/m^3 brine (13 lb salt/ft3 brine).

The cost for construction and running of solar pond is much less than that of the conventional system of flat plate collectors. The cost of a solar pond is, however, strongly dependent on-site-specific factors such as the local cost of excavation and salt. The thermal performance of a solar pond is also dependent on issues such as solar irradiation, ground thermal conductivity and water level depth.

Rao et al. (1989) and Hull et al. (1989) have provided a detailed analysis of the various components for estimation of costs of a solar pond. Hull et al. (1989) estimated the cost of a large solar pond (area greater than 100,000m^2)to be around US \$10/m^{2}and that of a small solar pond (area around1000m^2) to be around US \$ 50/m^2, wherein the cost of salt represents 50% of the total cost of a small solar pond and more than 75% of the total cost of a large solar pond. The cost of the solar pond per square meter can be estimated by using the following relation.

C_{sp} = 2.546 (C_1 +C_2) + 0.675C_3 + 1.3C_4 + 0.456C_5 + 0.0415C_6+ 0.124C_7 + 0.021C_8 + 0.085C_9 + C_{10}.

The following data was considered for cost estimation of solar pond for the assumed geometric and climatic conditions. The values of different components isC_1 = excavation charges (1000 Rs/m^3); C_2 = water charges (600Rs/m^3); C_3 = salt cost (1940 Rs/tone); C_4 = liner cost (2200 Rs/m^2); C_5= cost of clay lining (500Rs/tone) ; C_6 = cost of bricks (Rs 1/brick) ; C_7= cost of cement (800 Rs/bag) ; C_8 = cost of sand (600 Rs/m^3); C_9 = cost of brick lining (600 Rs/m^3); C_{10} = cost of wave suppresser (400 Rs/m^2).The total estimation of the cost is Rs. 9640($198). Therefore the cost per square meter of solar pond may be obtained around $ 1 per square meter.

2. Thermal Analysis of Solar Pond

The thermal performance of a solar pond gives the rate of absorption of the incident solar radiation by zone, and gives the temperature distributions of different zones based on assumptions. Analysis of an experimental solar pond is generally complicated because of the differences of inner and outer conditions viz. pond dimensions, salty-water solutions, insulation, zone thicknesses, shading area of the layers, transmission and absorption characteristics for the layers. Table II gives the data obtained from the analysis of solar pond, and the results shows that the temperature of the UCZ is a maximum with 34.83^{0}C in May, a minimum of 25.15^{0}C in January. Similarly, the temperature of the NCZ is observed to be a maximum of 34.83^{0}C in May, a minimum of 25.18^{0}C in January, while the temperature of the LCZ is observed to be a maximum of 52.68^{0}C in May, a minimum of 41.01^{0}C in January.

Table II : Temperatures in solar pond.

Month	Ambient Temp. (^{0}C)	UCZ Temp. (^{0}C)	NCZ Temp. (^{0}C)	LCZ Temp. (^{0}C)
Jan.	29	25.18	33.14	41.01
Feb.	31	27.72	35.83	44.53
Mar.	33	29.41	37.11	46.55
Apr.	35	31.64	39.54	48.19
May.	38	34.83	42.38	52.68
Jun.	36	32.14	40.91	49.73
Jul.	34	30.76	38.12	47.39
Aug.	33	29.65	37.56	46.32
Sept.	31	27.54	35.43	44.56
Oct.	32	28.87	36.12	46.83
Nov.	30	26.45	34.32	43.34
Dec.	29	25.56	33.43	42.89

Table III gives the following data were obtained by analyzing the solar pond based on the literature mentioned in the previous sections. The results shows that the energy efficiency of the UCZ has a maximum of 3.18 in June, at NCZ this value is observed to be 10.87, while at LCZ is observed to be a maximum of 23.89. The LCZ usually have high temperatures thus higher efficiencies are obtained.

Table III : Energy Efficiencies of solar pond in three different zones

Month	UCZ Efficiency (%)	NCZ Efficiency (%)	LCZ Efficiency (%)
Jan.	1.01	3.18	9.94
Feb.	1.25	3.94	10.11
Mar.	1.45	4.64	10.41
Apr.	1.96	5.14	12.81
May	3.18	10.87	23.89
Jun.	3.10	10.23	20.01
Jul.	2.98	10.01	19.76
Aug.	2.65	9.89	18.87
Sept.	2.45	9.10	17.19
Oct.	2.26	8.67	16.89
Nov.	2.11	8.32	16.01
Dec.	1.87	7.76	14.32

Table IV shows the details of the exergy efficiency from the analysis; the value of exergy efficiency of the UCZ is maximum as 3.15 in month of May and for NCZ it is observed to be a maximum as 10.24, and for LCZ it is observed to be a maximum as 20.14. Exergy is a measure of the actual potential of a system to do work, energy that has a high convertibility potential is said to contain a high share of exergy. Exergy efficiencies are observed to be low for each zone of the pond because of small magnitudes of exergy destructions in the zones and losses to the surroundings.

Table IV : Exergy Efficiencies of solar pond in three different zones

Month	UCZ Efficiency (%)	NCZ Efficiency (%)	LCZ Efficiency (%)
Jan.	1.01	2.68	9.28
Feb.	1.09	3.15	9.86
Mar.	1.26	4.28	10.01
Apr.	1.70	5.18	11.21
May	3.15	10.24	20.14
Jun.	2.1	9.91	19.89
Jul.	2.95	9.34	18.78
Aug.	2.67	8.85	17.34
Sept.	2.5	7.91	16.12
Oct.	2.15	7.12	15.45
Nov.	2.01	6.98	14.18
Dec.	1.91	6.12	13.01

Fig.1 shows the trends of energy efficiency for the three zones during the year. The energy efficiencies are lower during the cooler months, and are higher during the warmer months. The LCZ efficiencies are observed to be higher than the corresponding UCZ and NCZ efficiencies.

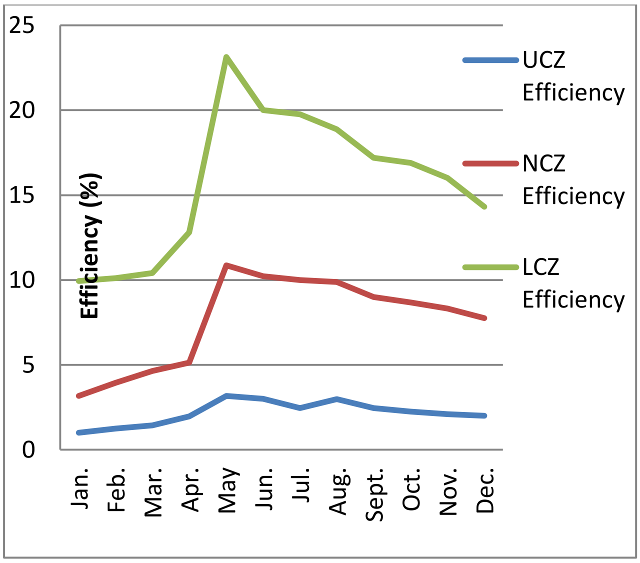

Figure 1: Variations of energy efficiencies of the solar pond in a year

Fig. 2 shows the trends of exergy efficiency during a year for the three zones. The exergy efficiency values are lower during the cooler months, and are higher during the warmer months. The LCZ efficiencies are observed to be higher than the corresponding UCZ and NCZ efficiencies. Comparison of energy and exergy efficiencies for the zones over the year shows that the differences between energy and exergy efficiencies are small during the cooler months and large during the warmer months.

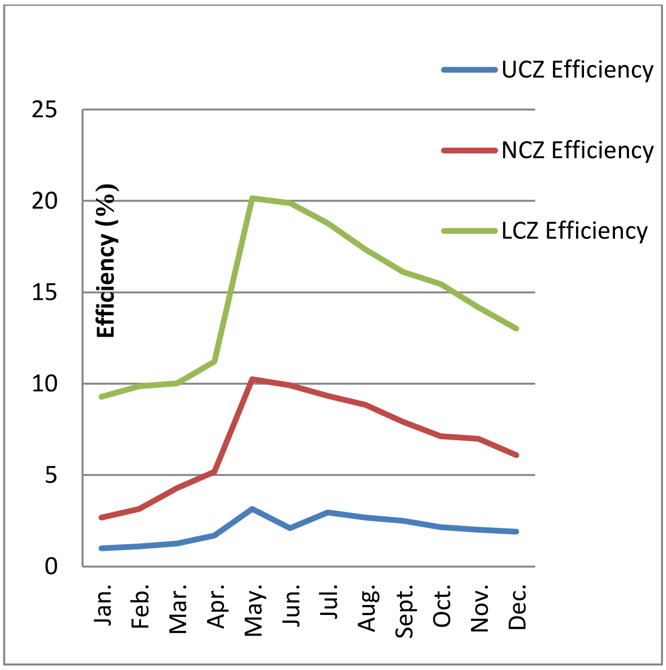

Figure 2: Variations of exergy efficiencies of the solar pond in a year

IV. CONCLUSION

In the view of energy demand the 'exploration of solar energy' is the key topic of interest. The direct solar heating systems can signify wide range of applications. The solar pond is one among the potent solar direct heating system. Much study is needed on energy conversion in solar pond. More insight towards simulation of energy transfer in solar pond can provide better understanding. Present analysis gives the value of thermal efficiency of pond to be 23.89% at a particular time for selected climatic conditions. The cost analysis of construction of solar pond was also presented and the value is observed to be 1$ per square meter area.

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