

A Note on Significance of Solar Pond Technology for Power Generation

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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—Renewable Energy, Solar Pond, Energy Efficiency, Construction of Solar Pond.

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 now meet the all global energy needs to the most 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 may cut the pollutant emissions into the atmosphere. Exploration of solar energy plays an important role in developed and developing countries [1]–[9]. Solar ponds are the simplest and low expensive technologies for converting and storing solar energy. The solar pond has an ability to act both a collection and storage of solar energy [10]. Solar ponds may be operated at all latitudes, provides 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 to a certain depth, where 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.

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The temperature at the bottom of the pond goes near to 90°C, although the temperature at the top of the pond is usually around 30°C [12]. There are four basic types of solar ponds viz. (i) salt gradient solar ponds (ii) shallow solar pond (iii) salt-less convective 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 kind of non-convective solar pond [13]–[15]. The initiative of creating artificial solar ponds was proposed many researchers and many developments are in progress in this subject [1].

II. EFFICIENCIES OF SOLAR POND

Literature review provides the insight on solar pond; the incident onto the surface of the pond, A is the pond area and solar pond has low energy conversion efficiency in comparison to conventional direct solar heating systems. 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 are economical in many areas because of their low cost [16]. The solar pond thermal efficiency is useful energy over a given period of time to the total insolation for the area over that same period [17]. The relationship is expressed as follows.

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

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) is 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 is given as

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

where Q_{wa} , Q_{side} , Q_{solar} , Q_{down} in (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 1 to the total solar radiation 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 (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 (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 (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 (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 (11) can be respectively written as

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

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

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

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

A. Exergy Analysis of Solar Pond

The exergy efficiency of a solar pond may be defined as the exergy recovered from the system to the total input in the system. It may be expressed as

$$\eta_{Exergy} = \frac{E_{xr,system}}{E_{xti}}$$

The exergy balance for the UCZ can be written as follows:

$$E_{xsolar} + E_{xg,ncz} = E_{xr,ucz} + E_{xd,ucz} + E_{xa} + E_{xsw,ucz} \quad (22)$$

knowing that,

$$E_{xr,ucz} = E_{xti} - E_{xtl} = (E_{xsolar} + E_{xg,ncz}) - (E_{xd,ucz} + E_{xa} + E_{xsw,ucz}) \quad (23)$$

where E_{xti} is total energy input to the UCZ and E_{xtl} is the total exergy losses, including exergy destruction. Therefore, exergy efficiency can be written as

$$\eta_{E,UCZ} = 1 - \frac{E_{xd,ucz} + E_{xa} + E_{xsw,ucz}}{E_{xsolar} + E_{xg,ncz}} \quad (24)$$

The exergy balance for NCZ can be written as follows

$$E_{xr,ucz} + E_{xg,hcz} = E_{xr,ncz} + E_{xd,ncz} + E_{xl,ncz} + E_{xsw,ncz} \quad (25)$$

$$E_{xr,ncz} = E_{xti} - E_{xtl} = (E_{xr,ucz} + E_{xg,hcz}) - (E_{xd,ncz} + E_{xl,ncz} + E_{xsw,ncz}) \quad (26)$$

where E_{xti} is the total energy input to the NCZ and E_{xtl} is the total exergy losses, including exergy destruction. Therefore, exergy efficiency can be written as

$$\eta_{E,NCZ} = 1 - \frac{E_{xd,ncz} + E_{xl,ncz} + E_{xsw,ncz}}{E_{xr,ucz} + E_{xg,hcz}} \quad (27)$$

The exergy balance for the LCZ is

$$E_{xr,ncz} = E_{xd,hcz} + E_{xl,hcz} + 2E_{xsw,hcz} \quad (28)$$

$$E_{xr,ncz} = (E_{xd,hcz} + E_{xl,hcz} + 2E_{xsw,ncz}) \quad (29)$$

Therefore, exergy efficiency can be written as

$$\eta_{E,HSZ} = \frac{E_{xr,ncz} - (E_{xl,hsz} + 2E_{xsw,hsz})}{E_{xr,ncz}} \quad (30)$$

II. DEVELOPMENTS IN SOLAR POND SYSTEM

The modifications to the salt gradient solar ponds carried out 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 climatological situations [34]. Mehta et al. [35] analyzed the performance of a bittern-based solar pond with an area of 1600m² located in Bhavnagar, India. Many investigations have been done by different researchers on salt gradient solar pond [36]–[39]. Beziret al. investigated a salt gradient solar pond with a surface area of 3.5×3.5m² and a depth of 2m, for supplying hot water. They used a cover on the surface of the pond 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 [40].

IV. THEORETICAL DESIGN OF SOLAR POND FOR COST ESTIMATION

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

TABLE I
 WEATHER DATA IN THE SELECTED REGION

Month	Solar Radiation (kWh/m ²)	Ambient Temp.(°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
Oct.	4.35	32	3.15	81
Nov.	4.53	30	3.74	78
Dec.	4.47	29	3.64	75

The following configuration was assumed for design of solar pond

1. Upper convective zone depth = 0.1m (0.3 ft), salt concentration = 0.5kg salt/m³ brine (0.03 lb salt/ft³ brine).
2. Non-convective zone depth = 0.6m (1.96ft), salt concentration varies from 0.5 - 208kg salt/m³ brine (0.03-13 lb salt/ft³ brine).

3. Storage zone depth = 0.8m (2.26ft), salt concentration = 208kg salt/m³ brine (13 lb salt/ft³ brine).

The cost for construction and running of solar pond is much lower compared with conventional 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 [9]. A study gives that the cost of a large solar pond (area more than 100,000m²) to be around US \$10/m² and that of a small solar pond (area around 1000m²) to be around US \$ 50/m², 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 [9]. The cost of the solar pond per square meter can be estimated by using the following relation:

$$C_{sp} = 2.546 (C_1 + C_2) + 0.675C_3 + 1.3C_4 + 0.456C_5 + 0.0415C_6 + 0.124C_7 + 0.021C_8 + 0.085C_9 + C_{10} \quad (31)$$

The following data was considered for cost estimation of solar pond for the assumed geometric and climatic conditions. The values of different components is C₁ = excavation charges (1000 Rs/m³); C₂ = water charges (600Rs/m³); C₃ = salt cost (1940 Rs/tonne); C₄ = liner cost (2200 Rs/m²); C₅ = cost of clay lining (500Rs/tonne); C₆ = cost of bricks (Rs 1/brick); C₇ = cost of cement (800 Rs/bag); C₈ = cost of sand (600 Rs/m³); C₉ = cost of brick lining (600 Rs/m³); C₁₀ = cost of wave suppresser (400 Rs/m²). The total estimation of the cost is Rs. 9640(\$198). Therefore the cost per square meter of solar pond may be obtained approximately as \$ 1 per square meter.

V. 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°C in May, a minimum of 25.15°C in January. Similarly, the temperature of the NCZ is observed to be a maximum of 34.83°C in May, a minimum of 25.18°C in January, while the temperature of the LCZ is observed to be a maximum of 52.68°C in May, a minimum of 41.01°C in January.

TABLE II
TEMPERATURES IN SOLAR POND

Month	Ambient Temp.(°C)	UCZ Temp.(°C)	NCZ Temp.(°C)	LCZ Temp.(°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 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

Table III gives the data obtained by analyzing the solar pond based on the model mentioned in the previous section. The results show that the energy efficiency of the UCZ has a maximum as 3.18 in May, at NCZ this value is observed to be 10.87, and at LCZ it is observed to be a maximum as 23.89. The LCZ usually have high temperatures thus higher efficiencies are obtained.

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 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

Fig. 1 shows the trends of energy efficiency for the three zones during the year. The energy efficiencies are low during the cooler months, and are high during the warmer months. The efficiency values of LCZ are observed to be higher in comparison to values of UCZ and NCZ.

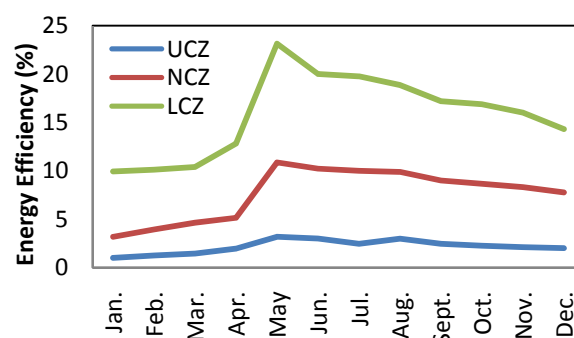


Fig. 1 Variations of energy efficiencies of the solar pond in a year

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

VI. CONCLUSIONS

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.

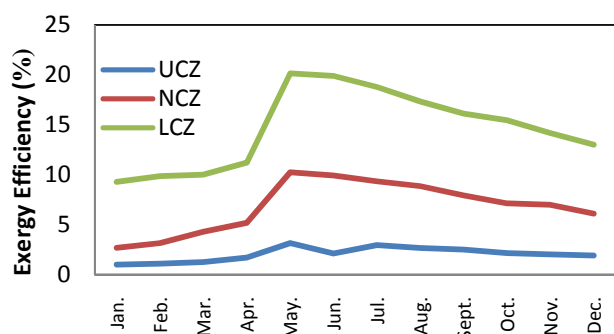


Fig. 2 Variations of exergy efficiencies of the solar pond in a year

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