Thermal Performance of a Salt Gradient Non-Convective Solar Pond in Subtropical Region Climatic Conditions

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Abstract. Renewable energy is becoming a significant source of energy due to the intensification in crude oil prices and the upsurge in greenhouse effects due to burning of fossil fuels. With only finite source of fossil fuel and exponential increase in the demand of power because of increase in human population, power generation from renewable energy promises a sustainable future for the mankind. Solar energy can be harnessed to meet our energy needs for a sustainable future. After the remarkable hike in oil prices numerous countries began to do an extensive research and development to utilize solar energy. There are many methods to trap solar energy, but an effective one was by using solar pond. Solar pond is an unnaturally constructed pond in which large temperature can be maintained in the lower convective zone by the way of higher salt concentration and by preventing natural convection so these ponds are termed as salt gradient solar pond. In this current research a salt gradient solar pond is designed and developed. Further the Thermal Analysis and Performance of the same model has been done in Vizag Climatic Condition. The same model can be utilized for generating sensible and latent heat for room heating and industrial heating applications. Moreover, electrical power can be generated by using suitable heat exchanger and working medium of low boiling point values such as ammonia.

Keywords: Salt gradient solar pond, thermal efficiency, hot wire anemometer, solar power meter.

1. Introduction

Many researchers have been studied in both experimentally and analytically on thermal performances of solar pond based on different designs at numerous climatic conditions. Bezir Nalan et al [1] has created a salt gradient solar pond of surface area of 12.25m$^2$ area of the trapezoid cross-section pond was 1.7 m$^2$ and having a depth of 0.5 m. and a depth of 2 meter. The Thermal Efficiency was investigated for each zone theoretically and numerically. The pond was covered on the surface to minimize the thermal losses at the top during night time and also to increase the efficiency of the pond. Thermal analysis was carried out both theoretically and experimentally. P. Sarath Kumar et al [2] investigated the solar pond with PCM storage in which it was concluded that by adding Al$_2$O$_3$ with PCM improves the heat transfer coefficient along with heat storage capacity. Jimmy Leblanc et al [3] has fabricated a solar pond and introduced a novel system for extracting heat and thus the efficiency. Experimental studies of the system are studied and a close agreement with theoretical studies is found.
out. This study showed that an overall efficiency of about 55% can be increased with heat extraction from NCZ comparatively conventional way of extraction from lower convective zone. Jeffrey A Ruskowitz et al [4] has carried out an experimental investigation on the salt gradient solar pond and found out the suppression of evaporative losses and solar energy collection. The transparent material over the solar pond reduces the wind flow across the surface thus resulting in a decrease in UCZ-NCZ interface thereby increasing efficiency. A.A. Hill et al [5] in England has fabricated a solar pond porous material and investigated its linear instability in the lower convective zone (LCZ). It was found that the solar pond made of porous materials has more stability than the normal one. M.M. Ould Dah et al [6] has fabricated a mini solar pond of 0.64m² and the performance and stability of it was carried out experimentally and numerically. In the experimental study it was observed to reach 54°C quickly after 20 days. G.S. Gunasegarane [7] has found out that for a monthly average solar radiation was 180 –270 W/m2 available, the optimum thickness of the three zones were determined from the study UCZ, NCZ and LCZ values were 0.2m, 1.3m and 0.9m respectively. 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. Sathish Dhandapani et al. [8] in Tamilnadu has fabricated a portable solar pond with common salt (NaCl) and pebbles and investigated experimentally. D. Sathish et al [9] has built a portable solar pond with an area of the trapezoid cross-section pond about 1.7 m² and having a depth of 0.5 m. The Investigation has resulted that the maximum average storage temperature of NaCl salt was observed as 43°C and for coal cinder was 37°C. NaCl salt showed a better storage performance in comparison with the coal cinder one as more energy is stored due to presence of salinity profile. Jiansheng wang et al [10] constructed a mini trapezoidal shaped solar pond and analysed its energy efficiency at different zones. It was found that the energy efficiency is maximum at the lower convective zone compared to other zones. Francisco Suarez et al [11] has fabricated and investigated a small scale solar pond and this has revealed that the results can be used to investigate the experiment performance of large scale solar pond and main issues that can decrease the thermal performance of the system . Ahmad Aizaz et al [12] has designed and fabricated a small scale solar pond. The experimental analysis was carried out and revealed that this technology can be used to meet the energy requirements of Pakistan. Jobanputra Deepak P et al [13] has designed and developed a solar pond and validated its performance as a laboratory model. Qi Wu et al [14] has investigated the solar pond and found that the heat storage capacity increases the heat extraction efficiency. With the experimental results obtained the heat extraction efficiency is observed to be 40.3% more. Gautam Saini et al [15] has experimentally investigated the effect of a translucent separator (glass) above LCZ which decreases the diffusion of salt from LCZ to NCZ and maintain the stability of salt gradient for a longer period of time. When there was no glass above LCZ then the gradient of salt start diminishing after one week and heat loss start increasing rapidly due to convection current. But if using a transparent 5 mm glass above LCZ than rate of diminishing salt gradient was very less and temperature maintain for a longer time period. The salt concentration in top of UCZ due to salt diffusion after 15 days was 8% without using glass and 4% with using glass. So this is a significant difference in salinity by using a glass above LCZ for maintaining the salt gradient for longer period of time. Ni Ni Aung et al [16] has investigated the research work numerically and experimentally with insulated solar pond throughout day and night time. The new setup was performed on a SGSP to be used for desalination. The data for daily temperature distributions, solar radiation and ambient temperature is collected from 16th of January until 16th of March 2017. The maximum storage temperature reached 305.55 K after two months of the filling process. Mohammad Reza assari et al [17] has fabricated two like solar ponds with circular cross sectional area 0.54m² and two layers of pebbles and ball bearings as permeable medium are used. At the end of the experiment, the temperatures of LCZ of mixed medium and conventional are found out to be 75°C and 71°C. L.C. Ding et al [18] has investigated on a concept of passive electric power generation by using temperature gradient existing between LCZ and UCZ by using thermo electric devices which convert the heat in the lower convective zone to equivalent amount of electricity. Najam-ul-Hassan Shah et al [19] investigated the solar pond at lower convection zone for heat extraction. MATLAB code was used for
numerical simulation. Finally, it was found to have more efficiency. Assad H. Sayer [20] has investigated a theoretical model of a solar pond considering upper, lower and non-convective zones. The temperatures at the upper and lower zones are considered. The result was validated against the already established ponds.

2. Development of Model

A salt gradient solar pond is a modified form of ordinary solar pond by creating gradient of salt to suppress the convection current. It is a cheaper method for utilizing the solar energy without creating any pollution. There are three zones in a salt gradient solar pond as lower convection zone (LCZ), non-convection zone (NCZ), and upper convection zone (UCZ). LCZ is the lower zone of solar pond with highest concentration and used to store the heat energy from solar radiation. NCZ is the heart of solar pond because it suppresses the convection current due to the existence of the density gradient and helps out to store thermal energy. UCZ is consisting of very small salt concentration or fresh water. UCZ covers the NCZ and protect from external disturbance such as wind, dust, raindrop etc. Heat is stored in the LCZ and useful heat can be extracted by using the different types of heat exchanger. The working model of the solar pond of rectangular basin having dimension of (0.9 × 0.6) m² in cross section and 0.4m in deep has been developed by conventional carpentry process with appropriate design specification. The entire body structure of the model was used commercially used plywood except top surface. The interior of it was covered with galvanized sheet painted with black paint to enhance the absorptivity and proper attention was focused to make it leak proof. The inlet section of it was made of a poly vinyl pipe (PVC) of 12mm diameter to pour in the brine solution and covered a cap. Furthermore, a heat exchanger made up of copper tube of 5mm diameter in helical coil was rested at the lower zone of the solar pond which acted as an internal heat exchanger. The diameter of helical coil was of diameter 100mm. A 4mm Transparent Glass is used to place over the solar pond setup which decreases the diffusion of salt from LCZ to NCZ and maintain the stability of salt gradient for a longer period of time. To measure the incident solar radiation flux density a solar power meter was used. To observe the variation of solar radiation affected by air flow velocity a hot wire anemometer was adopted. The complete specifications of the experimental set up is given in table 1.

Table 1 Complete Specifications of investigational setup

| S. No | Component | Items | Technical Specification |
|-------|-----------|-------|------------------------|
| 01    | Basin     | Plywood | (2000×1700×25) mm     |
|       |           | Galvanised Iron Sheet | 1mm                |
|       |           | Glass    | (900×600×4) mm         |
|       |           | Salt     | 14 kg                 |
|       |           | paint    | 200 ml                |
|       |           | PVC pipe | 12 mm                 |
|       |           | Copper Pipe | 5 mm               |
| 02    | Solar Power meter | Sensor | High sensitivity silicon photodiode |
|       |           | Spectral Response | 400–1100nm           |
|       |           | Range    | 0–2000 W/m²(0–634 BTU/ft².h) |
|       |           | Accuracy (at 23°C, 60% RH) | ±10W/m²(±3BTU/ft².h) or ±5% |
|       |           | Resolution | whichever is greater |
|       |           | Angular Accuracy | Cosine corrected < 7% (angle <60°) |
|       |           | Tilt Angle Range | 0°- 90°          |
|       |           | Sample Time | Approx. 0.4 second |
|       |           | Operation Temp. & Relative Humidity | 0°C–50°C (32°F–122°F), Less than 80% RH |
3. Experimental Procedure

The primary objective of the research work is:

- To trap the thermal energy out of the incident solar irradiation.
- To extract the heat energy from the lower storage zone by using an internal heat exchanger.
- To investigate the thermal performance of the system based on climatic changes.

The real experimental set up is shown in figure 1. Similarly the solar power meter and the hot wire anemometer are shown in figure 2 and 3 respectively. The system consists of internal heat exchanger (IHE) embedded in the LCZ through which the fluid is circulated through pumping. Digital temperature sensors are used to measure the upper and lower convective zone temperatures.

![Figure 1 Real Picture Captured during the preparation of Brine Solution](image)
The location and positioning of solar pond is very important for carrying out the experiments. The location with maximum exposure to sun radiation is selected. The experimental salt gradient solar pond set up is placed and experimentation is carried on the terrace at Mechanical Engineering Department in Raghu Engineering College, Visakhapatnam city which is situated on south east coastal part of India with a latitude and longitude of 17.68° N and 83.21° E where maximum sun exposure and water supply are easily available. The salt gradient solar pond is made up of rectangular shape with dimensions 0.9m by 0.6m with a depth of 0.4 m. The brine solution is prepared with 80 litres of water and 14 kg of common salt worked as thermal storage medium. The salt concentration was maintained 25% in lower zone consisted of 40 liters of water. A PVC pipe of 12mm diameter is used to add the brine solution of lesser concentration to the upper zones so that the brine solution in the lower storage zone doesn’t get disturbed. The top of solar pond is covered by 4 mm thick transparent glass to prevent from the evaporation losses, wind disturbances and rainfalls. Experimental reading was collected daily from 9.30 am to 3 pm for 3 consecutive days starting from 21-02-2019 to 23-02-2019. A measurement system had been installed for recording the experimental data. Two digital temperature sensors with range of -50°C to +110°C temperature range and ±0.1°C accuracy were used to measure the upper zone air temperature and lower zone brine solution temperature for the required duration of pond operation. As we studied from literature review that more heat gets trapped in the lower zone, the temperature sensor is placed in the lower zone and only the mass of lower zone brine solution is considered during mathematical calculation and analysis. Two other temperature sensors are also used: Firstly, to measure the atmospheric air temperature and the other sensor placed on the pipe outside to measure the amount of heat extraction from the solar pond. Solar power meter was used to find the intensity of solar radiation of pond’s surface. Hot wire anemometer is used to measure the wind velocity from the surrounding.

4. Result and Analysis
The day wise analysis and recorded data is given in this section.
It has been observed from the figure 4(a), the Solar Radiation was increased from 9:30 am until it reached a maximum radiation of 942.5 W/m² at 1:00 pm, at which lower zone brine solution temperature is 47.8°C and then it started decreasing gradually.

From the above figure 4(b), we can get to a conclusion that the temperature of the lower zone brine solution kept on increasing till it reached a maximum temperature of 50.5°C at 3:00 pm because the energy is being incident on the system continuously.

As seen from the figure 4(c), the storage efficiency was maximum between 11:00 am and 12:00 pm and there after the storage efficiency goes on decreasing because the amount of heat incident decreased gradually after 12:00 pm. The ambient air temperature has started to decrease as soon as the wind velocity started to increase.
Figure 5(a) Variations of Global radiation with respect to time on 22.02.2019

Figure 5(b) Variations of Lower Zone Temperature and Storage Efficiency with respect to time on 22.02.2019

- Total amount of energy incident during the day was 8603.6 kJ
- Total amount of energy absorbed during the day was 4067.3 kJ
- Total amount of energy extracted during the day was 1601.1 kJ
- Efficiency of heat extraction is 39.36%

Figure 5(c) Performance analysis with respect to time on 22.02.2019

It has been observed from the figure 5(a), the Solar Radiation was increased from 9:30 am until it reached a maximum radiation of 940.1 W/m² at 12:30 pm, at which lower zone brine solution temperature is 46.1°C and then it started decreasing gradually.

From the above figure 5(b), we can get to a conclusion that the temperature of the lower zone brine solution kept on increasing till it reached a maximum temperature of 50.7°C at 3:00 pm because the energy is being incident on the system continuously.

As seen from the above figure 5(c), the storage efficiency was maximum between 11:00 am and 1:00 pm as the average maximum global radiation (940W/m²) was observed during that time. The ambient air temperature was found to be maximum i.e. 41.3°C and then it started decreasing corresponding to increase in wind velocity.
It has been observed from the figure 6(a), the Solar Radiation was increased from 9:30 am until it reached a maximum radiation of 773.9 W/m² at 12:00 pm, at which lower zone brine solution temperature is 46.3°C and then it started decreasing gradually.

From the above figure 6(b), we can get to a conclusion that the temperature of the lower zone brine solution kept on increasing till it reached a maximum temperature of 51.3°C at 3:00 pm because the energy is being incident on the system continuously.

As seen from the figure 6(c), the maximum storage efficiency was found to be maximum at 12:00 pm and a gradual decrease in storage efficiency is recorded since more amount of heat is extracted during the final hours of the experimentation and a corresponding decrease in global radiation was noted. The minimum wind velocity during the experimentation days (3.024 km/hr) was noted on the same day at 11:00 am.
As seen from the above graph, the maximum average global radiation of 942.5 (W/m$^2$) was recorded on February 21, 2019 at 1:00 pm. The minimum average global radiation of 528.7 (W/m$^2$) was recorded on February 21, 2019 at 9:30 pm. As seen from the figure 7(b), the maximum Wind Velocity was recorded on February 22, 2019 with 27.36 km/hr at 1:30 pm. The minimum wind velocity of 3.024 km/hr was recorded on February 23, 2019 at 11:00 am.

From the figure 7(c) it is clear that the amount of Heat Extraction is more on 23 February as compared to previous days because the temperature of the lower zone brine solution increased at a faster rate since there are no fluctuations in the climate on 23, February compared to day 1(i.e. 21 February), day 2(i.e. 22 February) where we had witnessed sudden changes like cloudy weather during the initial hours of the day.

5. Conclusion
From the Experimentation procedure, the results obtained are as follows:

- The maximum solar radiation 942.5 (W/m$^2$) was recorded on 21, February 2019 at 1:00 pm and the minimum solar radiation of 528.7(W/m$^2$) was recorded on the same day 21, February 2019 at 9:30 pm
- The maximum wind velocity was recorded on February 22, 2019 with 27.36 km/hr at 1:30 pm and The Minimum Wind Velocity of 3.024 km/hr was recorded on February 23, 2019 at 11:00 am.
• The maximum lower zone brine solution of was recorded on the last day of experimentation i.e., 23, February 2019 at 3:00 pm.
• The maximum storage efficiency was recorded on 23, February 2019 at 12:00 pm and minimum storage efficiency was recorded on 22, February 2019 at 9.30 am
• The amount of heat extraction was comparatively more on 23, February 2019 compared to previous days.
• The storage efficiency of the system after reaching its maximum value, undergoes a gradual decrease even though energy is being incident on it. This is due to the reason that the system here is an open system and cumulative value of heat incident and heat stored were taken into consideration during experimental calculation and analysis.
• The amount of heat extraction can be improved by increasing the number of heat exchangers in the set up.

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