CONSTRUCTION AND ANALYSIS OF A SALT GRADIENT SOLAR POND FOR HOT WATER SUPPLY

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Abstract
Solar pond technology is being used in this world for the past many years, yet this technology has to prove its effectiveness in energy starved country like Pakistan and resolve energy crisis of the country. This research discusses basic principles of solar pond design, construction of a prototype solar pond, thermal energy extraction from the solar pond and cost benefit analysis of this technology for industrial sector in Pakistan in the form of a case study.

Keywords: Solar Pond, salt Gradient, heat extraction, renewable energy, green energy

1. Introduction

Pakistan is facing worst energy crisis in history. The natural gas reservoirs of the country are fast depleting with the passage of time and the gap between electicity need and supply of the country is increasing every year as shown in the figure 1 [1].

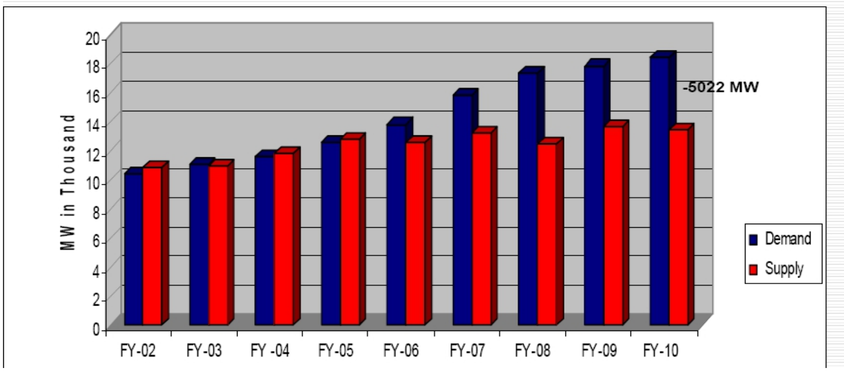

Figure 1: Annual rise in gap between electricity demand (left cells) and the supply (right cells) of Pakistan [1].

The alternate solar energy resources, such as Solar PV cells at large scale (~ MW), are not yet competitive in the market due to their low efficiency and high cost. So there is a dire need for a reliable and cost effective solution to the present energy crisis of the country. Solar thermal energy is one of the main source of clean energy which is abundantly available especially in country like Pakistan. The country receives about 5.45 kWH/m^2day of solar radiations on average [1] and one efficient way to trap this solar energy is solar pond technology. This solar pond technology, as compared with other methods of using solar thermal energy for power generation, is more efficient especially for the utilities where direct thermal energy is required such as for heating / drying purposes in many industrial processes. In all these processes where industrial need is of only the thermal energy and not the electricity, solar ponds can cheaply fulfill the industrial demand without the need of expensive conversion of solar energy into electricity generation. Thus increased efficiency in the use of solar energy can be ensured by skipping the inefficient step of first converting solar thermal energy into useful electricity and then using the expensive electricity, to produce hot water or hot air, for many industrial processes. The estimates obtained in this research shows that although the solar pond technology needs relatively large initial investment (~ $ 200,000/-) but has an investment return period of about 12 months for medium to large industries requiring hot water for production processes. Similar studies can be done for industrial processes requiring hot air for drying purposes instead of hot water.

2. Solar Pond Technology

In an ordinary natural pond, about 30% solar radiations reaches a depth of about 2 meters. Despite this significant amount of energy, the overall temperature of an ordinary pond remains uniform throughout the pond due to density driven gradients activated by convection heat transfer within the pond. In such ponds the energy going into the water at bottom of the pond gets wasted away because the water at the depth attains thermal equilibrium by mixing with heavy and colder water in upper layers of the pond and forming a natural circulation loop. In this loop lighter but hotter water rises to the upper surfaces of the pond and the heavier but colder water at the upper surface moves down. Thus the solar energy in the pond spreads out and the average temperature of the water in the natural pond does not change more than few degrees from the ambient. However, in case of a solar pond, a method is devised such that the hot water in the bottom layers remains heavier than the cold water at the upper layers and therefore does not form a convection circulation loop to rise up. Thus, when the solar energy is incident upon the solar pond, it is trapped in the hot bottom layers, called lower convective zone (LCZ) of the pond. To achieve heavier (increased density) water in the bottom of the pond, several organic or non organic material can be used. However, abundantly available table salt is more often added to LCZ (bottom most layers) of the pond to increase the density of water at the bottom. The salt concentration is gradually decreased in the preceding upper layers. The topmost upper layer, known as upper convective zone (UCZ) has the least concentration of salt to achieve a perfect solar pond containing several intermediate layers, known as non convective zone (NCZ) of water with gradually increasing density from the top to the bottom of the pond. So the hot water at bottom of the pond is preserved through the formation of different convective zones, in the form of a thermal energy reservoir from where this thermal energy can be extracted using differnt types of heat exchangers [2]. There are two common methods practiced worldwide to extract the trapped solar thermal energy from the solar pond. First method involves direct pumping out of hot saline water in the LCZ from one end of the pond and exchanging its thermal energy through an heat exchanger outside the pond. The same saline water is circulated back to the LCZ at the other end of the pond. In this method, special design considerations are taken to ensure minimum disturbance of the bottom layers so as to avoid convection currents resulting in mixing of layers. The other method uses an un-mixed type heat exchanger embedded permanently in the LCZ of the solar pond. Any suitable fluid with high heat capacity is circulated through this heat exchanger to extract the heat only, without physically disturbing the bottom layer of the pond. However, on the surface, the system requires another heat exchanger for transportation of the thermal energy to the process site. In this study, the second method of heat exchanger has been applied. In the initial phase, the constructed pond is only tested for several days for the formation and retention of different zones in the pond, by regularly measuring their respective temperatures as well as densities. In the second phase, the required heat exchangers are designed and installed, one inside the pond (IHE) and the other external to the pond (EHE) for the extraction of heat. In the end, this paper discusses the results of temperature measurements and economic assesment is made for its proposed use as a source of hot water supply for the industrial need.

3. Design and Construction of an Experimental Solar Pond

An experimental salinity gradient solar pond with a total volume of 2.4 m^3 is designed and constructed at NUST (34° 3' 48" North, 71° 59' 37" East) Pakistan with the base area of 1 m^2. Each wall of the pond is 1.28 m deep into the soil but inclined at an angle of 12^o to increase the exposed surface area of the solar pond at the top. This arrangement ensures more solar energy per volume of the pond and yet maintaining its structural stability. The standard single brick wall construction of the pond has a cemented plaster of

1.6 cm thick and is further insulated by 30 cm thick layer of sand at the outside all around the pond to reduce heat losses to the surrounding soil. On the inside of the walls, a 0.5 mm polypropylene sheet is used to prevent

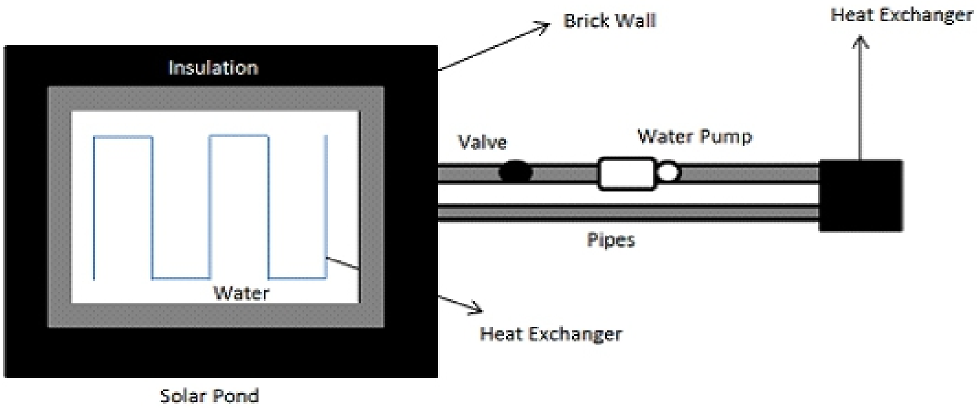

Figure 2: Schematic of Solar Pond

seepages of saline water through the cemented walls into the soil. The complete schematic of the solar pond is shown in figure 2. Temperature sensors are then placed in each zone i.e. UCZ, NCZ, & LCZ of the solar pond as well as on the outside heat exchanger, to measure their respective temperatures. Hydrometer is used to verify the density of saline solution in each zone.

4. Solar Thermal Energy Calculations

The variation in solar radiation during 365 days of a year can be calculated by following expression

$$Io = Isc\left[1 + 0.034\cos\left(2\pi\frac{n}{365.25}\right)\right] \quad (1)$$

where, I_0 is the extraterrestrial (outside the atmosphere) irradiance on a plane perpendicular to the Sun's rays (W/m^2). I_{SC}, the solar constant for the earth (1367 W/m^2), is the average extraterrestrial insolation at the edge of the atmosphere, and ‘n‘ is the day of the year such that for January the 1st, n = 1.

Most solar power calculations use I_0 as the starting point because, for any given day of the year it is the maximum possible energy obtainable from the Sun at the edge of the Earth's atmosphere. The annual variation of I_o when plotted using equation (1), is shown in figure 2. The dash line shows the value of solar constant, I_{sc} [3].

To obtain the total solar power entering the earth atmosphere, the earth presents a semi-hemispherical disc of area A to the Sun at any given time.

Therefore the maximum total amount of extraterrestrial insolation incident on the Earth is simply given by

$$H = I_o \times A. \qquad (2)$$

where, H is the total solar insolation on earth.

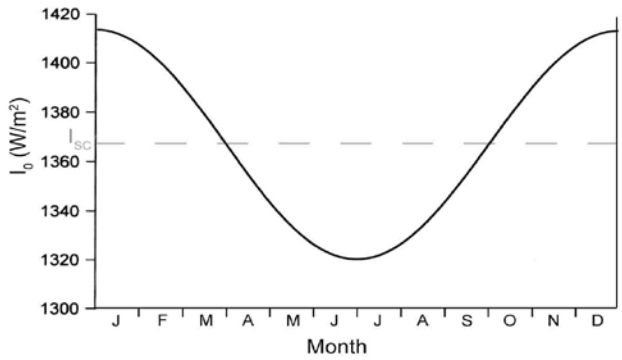

Figure 2: The variation in I_0 over the course of a year. The dashed line shows the value of the solar constant (Isc).

However, while entering through the atmosphere, only 70% of the solar power is able to reach the surface of the earth and the rest is reflected back. The average solar influx estimated from the above calculation over the solar pond is about 5.25 kWh/(m^2 day). Further more, for a conservative estimate, it is assumed that the Sun is only at an appreciable strength on an average 7 hours in the day (as is likely in more northerly latitudes) [3]. This makes the solar pond in this research of about 750 W maximum capacity. However, not all the energy is able to penetrate into the dept of the pond. It is estimated, usually from the logrithmic function of declining light intensity in the water [4], that only about 40 % of the energy is able to get into the LCZ due to reflections of sun light from the UCZ surface interface with air and other attenuation effects. Thus, the solar pond reservoir constructed in this study (1.96 m^2) has LCZ of about 300 W thermal capacity that is available for extraction.

5. Salt Concentration Gradient

The salt solution of various densities is formed in the mixing tank, one after another, and then transported to solar pond by the help of an electric motor & pump unit, as shown in figure 3

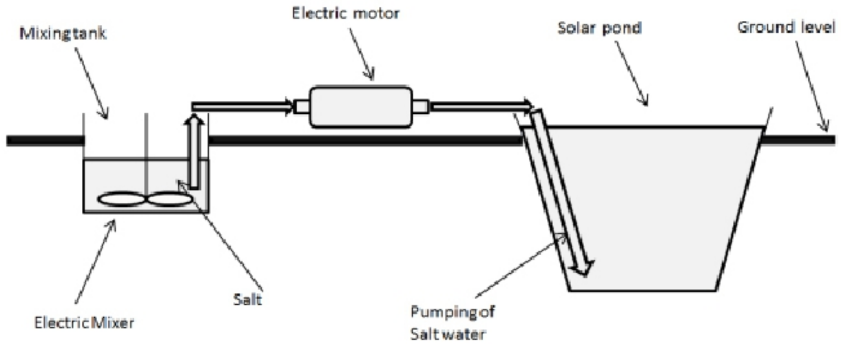

Figure 3: The schematic of salt concentration gradient formation in solar pond

At first the solution with high density (high salt concentration) for the LCZ is prepared and let it settled at the bottom of the pond before sprinkling the next layer on top of it. Three distinct zones of saline solution are formed in the solar pond with the LCZ having the highest density. The NCZ being the intermediate zone consists of series of layers of different but lesser densities decreasing from bottom to top in this zone, as shown in figure 4. The NCZ acts as a transparent insulator where it permits solar energy to pass through but inhibits the heat trapped in bottom layer to travel up. The UCZ, is formed at the end and therefore has the lowest density with the temperature of the UCZ reaching closer to ambient. Also, it is this layer which is directly affected by winds, rainfall and environmental effects, and therefore needs special care.

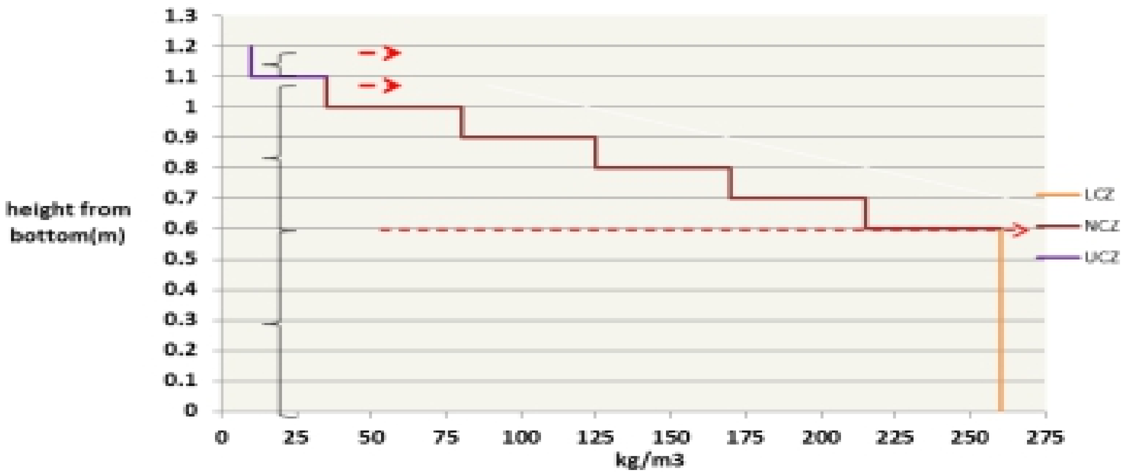

Figure 4: Variation in salt concentration along the height of pond, showing three distinct zones of saline concentration

6. Salt Selection

There are different factors that affect the selection of appropriate salt for the solar pond. Diffusion rate and temperature dependant solubility of salts in water are very important selection variables. Other than the technical reasons, the cost, availablity, and the environmental pollution are the main factors that one must consider for the selection of the salt. For this research selection of NaCl as the salt for the solar pond is discussed below as it is relatively friendly with nature, cheaply and abundantly available.

a) **Salt Diffusion**: The NaCl has a low diffusion rate as compared to other salts which results in slow movement (diffusion) of NaCl through the gradient zones thus reducing the mixing of the layers. The diffusion coefficient of most salts commonly ranges from 10^{-4} to 10^{-6} m^2s^{-1} depending upon the temperature and type of salt, whereas the diffusion coefficient of NaCl varies between 1.59 $x10^{-9}$ to 3.2 $x10^{-9}$ m^2s^{-1} at temperatures varying between 25 ^oC and 65 ^oC respectively [4].

b) **Temperature Effect on the Solubility of Salt:** NaCl has a very slight change in its in solubility in water with the increase in temperature as compared to the other salts. The figure 5 shows the variation of solubility curves of different salts with temperature [5]. The solubility of NaCl in water remains nearly constant and increases only to less than 8% for the change in temperature from 0^oC to 100 ^oC, as shown in figure 5.

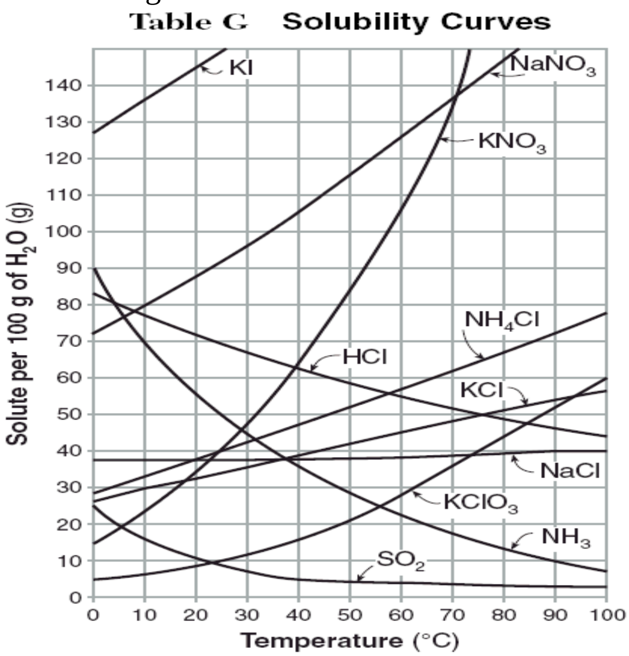

Figure 5: Variation of solubility of various salts with temperature [5]

7. Design of Internal Heat Exchanger (IHE)

Due to corrosive enviroment of the saline water in the LCZ, the material selection for internal heat exchanger needs careful attention. Commonly used Copper with high thermal conductivity appear to be the first choice, however, it is not suitable due to corrosion limitations. On the other end, polypropylene pipes are good corrosion resistent, however, they suffer from poor thermal conductivity and therefore would require unacceptably large surface area. Stainless Steel has good corrosion resistent properties and modest thermal conductivity and therefore has a good balance between the two opposing requirements. However, harsh saline environment requires that the complete heat exchanger be made from single pipe without any weld joints to avoid corrosion forming on the welded regions.

The size of the internal heat exchanger, or specifically the design length of the heat exchanger for a given diameter of the pipe can be estimated by using commonly used Log Mean Temperature Difference (LMTD) method, availble in standard heat transfer text books. It is common practice to represent the required surface area of the external heat exchanger for the desired rate of thermal energy extraction as given by equation 3.

$$A_s = \frac{Q}{U\,\Delta T_{lm}} \qquad (3)$$

where, ΔTlm is the logarithmic mean temperature difference of the internal fluid (at pipe inlet and outlet) with that of the surrounding hot water in LCZ, Q is the desired rate of thermal energy extraction, and U is the overall thermal conductance (W/m2.K) of the thermal path from the pond through the stainless steal pipe to the inner fluid [6].

8. Operation of Experimental Solar Pond

A schematic view of experimental heat extraction system is shown in figure 6. The system consists of inner heat exchanger (IHE) embeded in the LCZ of the solar pond (shown in the inset), pump and piping to allow the fluid to run through the IHE and an external heat exchanger (EHE). Three calibrated temperature sensors are placed inside the pond to measure the temperature of each zone for the desired duration of pond operation. Other sensors such as flow meters and temperature sensors, not shown in the figure, are also placed on the pipe outside the pond to measure the rate of heat extraction from the pond. The measurement of density (hydro-meter) helps in ensuring that the all zones exists in the pond to a satisfactory level of salt concentration.

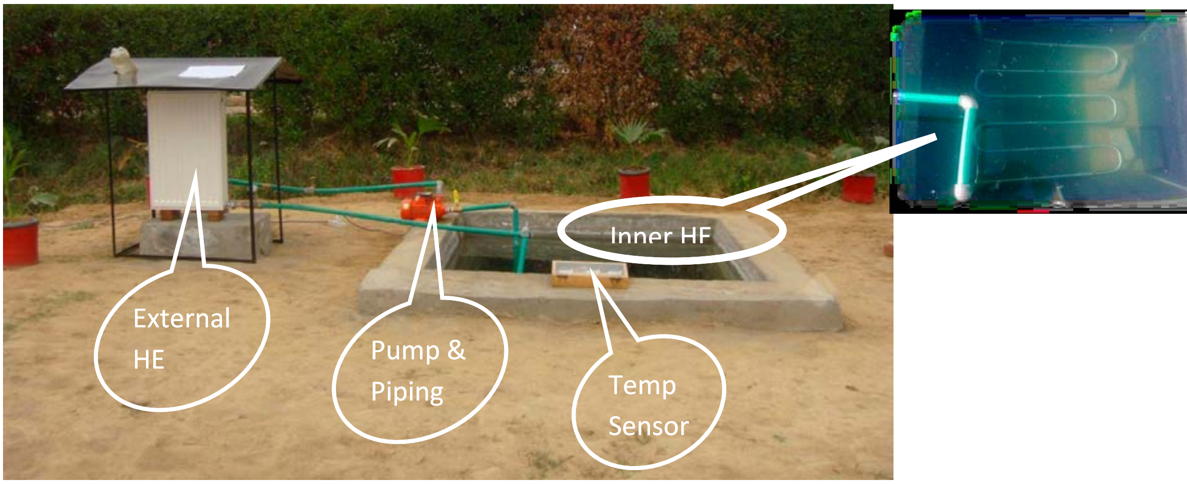

Figure 6: Schematic view of the experimental solar pond. Inner heat exchanger can be clearly seen (in the inset) embedded at the bottom of the pond in LCZ.

To appreciate the performance of a functional solar pond, the temperature data of its three zones are measured and recorded. Shown in figures from 7 to 9, are the daily average temperature data of the three zones UCZ, NCZ, and LCZ, respectively, inside the constructed solar pond recorded from 22 July, 2011 till 26 August, 2011. It may be of interest to note that this time of the year in Pakistan, is the peak moonsoon season which is also evident from some of the ups and downs in the temperature data in all the three figures (figure 7 to 9), but more pronounced especially in figure 7 of the UCZ, whose temperature is more closer to the ambient.

A steady rise in temperature is seen in all the three zones (figures 7 to 9)

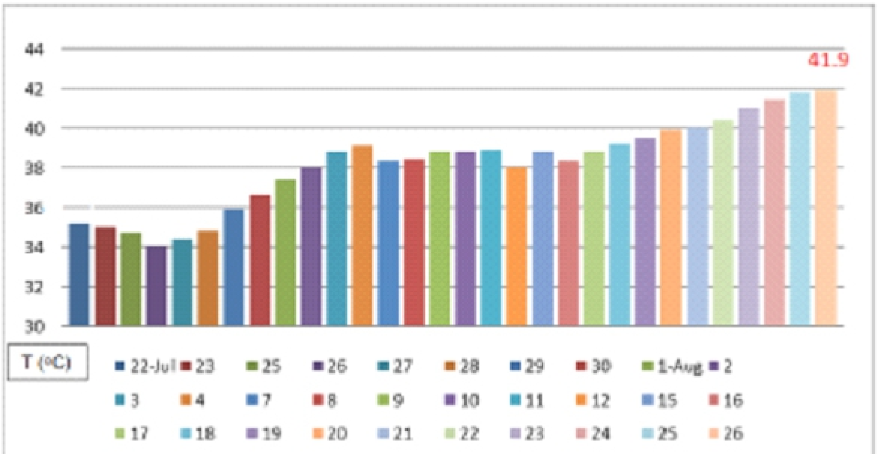

Figure 1: UCZ Temperature variations

since the functioning of the Solar Pond begins on 22nd July. This phenomena is commonly known as the chargining of the Solar Pond. After the Solar Pond reaches near to a full thermally charged level, the daily change in temperature with the rise and fall of the ambient temperature is seen lowest in the LCZ, then more in the NCZ, and even more pronounced in the UCZ. However, the maximum temperature reached in UCZ is 41.9 °C, as shown in figure 7, against the average recorded ambient temperature of 38.2 °C (not shown in figure). Thus, the UCZ is operating at about 4 degrees above the average ambient temperature of the day.

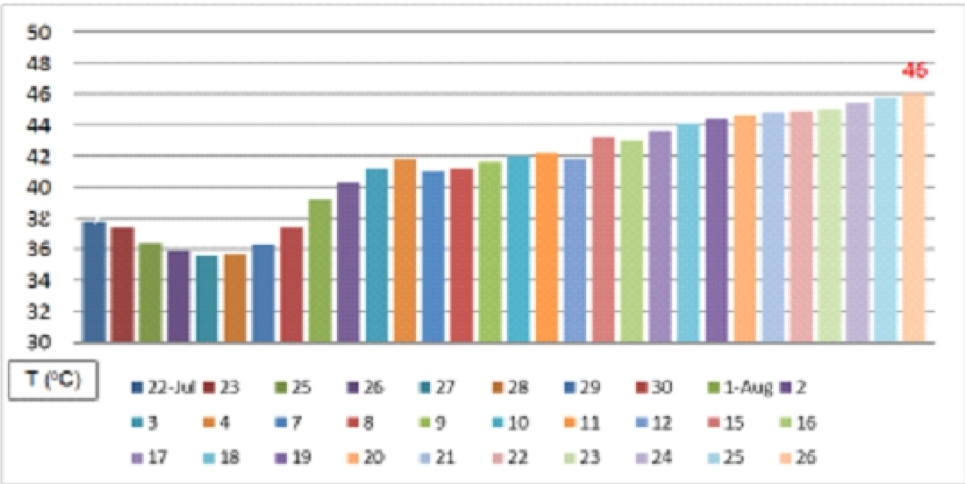

Figure 8: NCZ Temperature variations

As discussed earlier, the temperture variations of NCZ, as shown in figure 8, are less dramatic as compared with the UCZ, because of its more depth into the pond. However, corresponding to UCZ, the daily averge temperatures in this zone are about 4 to 6 degrees higher due to higher density at increased depth of this zone inside the pond.

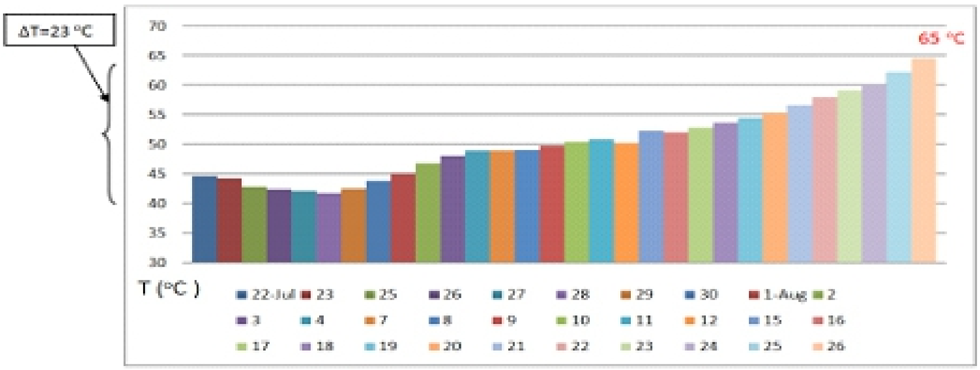

Figure 9: LCZ Temperature variations

9. Thermal Behavior of LCZ in Monsoon:

The thermal behavior of the Solar Pond in LCZ is shown in figure 9. It shows an appreciable increase in temperature on every sunny day varying with heat intensity on that day and slight decrease in temperature on rainy or a cloudy day. The maximum temperature drop of about 3.5 ^{o}C is observed from 23rd July to 27th July due to continuous rain for five consective days, which can be considered as one of the worst case senario in the operation of a Solar Pond. Special precuations are necessary against the falling rain and dust into the pond. Average temperature rise of the UCZ on a sunny day during the monsoon season vary from 1^{o}C to 3 ^{o}C. Maximum temperature of 65^{o}C is achieved by the end of the temperature measurement program against the ambient temperature of 38.2 ^{o}C on the same day and thus giving a temperture rise of about 27 degrees which is quite significant in terms of total thermal energy stroage considering the total mass of saline water in UCZ.

10. Industrial Case Study

There is a high demand of hot water in the industry where it is used either directly or for another process, such as in Textile, Leather tanning, Pasteurization, Paper, Paint, and Fertilizer, etc. The temperature requirement of the hot water in this industry varies from 50 to 90 ^{o}C. Usually the hot water boilers, operating on natural gas, are economical in practice as the electricity is an expensive solution and the industry simply can't afford due to high international competition of cheap products. However, with growing shortage of natural gas in the country, even this option is also quickly fading out. It is in this situation, that the Solar Pond technology is realized that can fill the gap of thermal energy requirement to either fulfill or atleast complement the energy need of industrial demand. In order to verify the scope of Solar Pond technology in Pakistan, a survey of existing industry in Punjab province of Pakistn is carried out. This survey indicates that in a sample size of 1800 factories, there are about 800 factories requiring hot water. This make about 44 % of total sample size. Out of these 800 factories, initially only three major industries, including Textile, Leather Ttanning and the Food Processing, has been chosen. This makes a target market of 31% in which leather industry takes about 32%, Textile is of 51 % and Food industry is of 17 % share. To fulfill the demand of this target market, it is estimated that a solar pond which is capable of providing hot water up to 80 ^{o}C during extreme summers and up to 45^{o}C in severe winters, is sufficient. The deficiency in case of temperature where hot steam is required near at 100 ^{o}C, the extra energy to bring the temperature from 80 ^{o}C from the solar pond to the required steam temperature, can be then provided by the natural gas.

UNITED TEXTILE MILLS Faisalabad, Pakistan	
CURRENT STATISTICS	
Water Heating Expenditure	110,000 USD/month
Hot Water Consumption	9.5 Million gallons/month
Cost Using Solar Pond Technology	
Solar pond sale price	280,000 USD
Maintenance Cost	6,000 USD/month
Expenditure using Solar Pond	47000 USD/month

Table 1: Cost analysis of a sample Textile Mill

To be more specific, Table 1 shows the monthly requirement of hot water of one of the textile mills in Pakistan alongwith the expenditure in US Dollars. It can be seen that even with modest conservative estimates, this demand of hot water can be fulfilled by the Solar Pond of about 2500 m^2 size. In this table, although the initial cost of Solar Pond seems excessive, however, given its lower monthly expenditure and minimal maintenance cost, the pay back period is about 2 to 3 years. Adding an year or two in this estimate as a factor of safety due to uncertainity in the Market, 4 to 5 years of payback time is still quite encouraging for any potential investor in this project.

11. Conclusion

In this research a small scale Solar Pond has been designed and constructed. The operation of this pond reveals that significant amount of solar energy can be stored in the UCZ of the pond which can be extracted through the installation of heat exchangers. The case study carried out in this research shows that the Solar Pond technology can be effectivly utilized to meet the energy requirements of such industry which requires hot water in their plant processes. The investment in Solar Pond by the industry will not only help them independence from the government gas load shedding program but also reduce their energy bill significantly along with small pay back period. Thus, it can be concluded that the Solar Pond Technology is a viable option, both technically as well as economically, for the industrial sector requiring hot water for their essential industrial processes.

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