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Long Term Stability of an Experimental Insulated-Model Salinity-Gradient Solar Pond

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Abstract**—**Per capita energy usage in any country is exponentially increasing with their development. As a result, the country's dependence on the fossil fuels for energy generation is also increasing tremendously creating economic and environmental concerns. Tropical countries receive considerable amount of solar radiation throughout the year, use of solar energy with different energy storage and conversion methodologies is a viable solution to minimize the ever increasing demand for the depleting fossil fuels. Salinity gradient solar pond is one such solar energy application. This paper reports the characteristics and performance of a thermally insulated, experimental salinity-gradient solar pond, built at the premises of the University of Kelaniya, Sri Lanka. Particular stress is given to the behavior of the evolution of the three layer structure exist at the stable state of a salinity gradient solar pond over a long period of time, under different environmental conditions. The operational procedures required to maintain the long term thermal stability are also reported in this article.

Keywords—Salt-gradient, solar pond, solar radiation, renewable energy.

I. INTRODUCTION

BEING a country situated in the equatorial belt, Sri Lanka receives a substantial amount of solar radiation throughout the year. Therefore, a considerable amount of research work has so far been carried out and are still in progress to develop different solar energy conversion systems to mitigate the country's dependence on fossil fuels for energy generation [1]-[5]. Research work has been done to study the impacts caused by environmental effects on existing salt pan solar ponds and optimal insulation requirements for the small scale experimental solar ponds [6], [7].

At present, several solar energy conversion systems are being used to provide electricity in some of the remote areas where the electricity power from the national grid is not available and also to replace the electrical energy being used from the national electricity grid. Majority of these conversion systems are based on photovoltaic cells and these systems are also being used to reduce the electricity demand from the national grid by implementing a hybrid system. Energy storage and conversion based on salinity gradient solar ponds is another highly exciting area of viable renewable energy applications where a considerable amount of research work has been done [8]-[12]. Necessity, motivation and potential prevail for significant expansion of the salinity gradient solar pond as a renewable energy source. Earlier research works suggest that the solar pond technique has a good potential to store solar energy in the form of heat [13]-[16]. This has become one of the most economical and environmental friendly methods for collecting and storing solar radiation with high storing capacity [17]-[19].

Operation of a salinity-gradient solar pond is based on its ability to develop a non-convective zone in the middle, thus substantially reducing the heat loss via convection from the bottom region where the thermal energy is stored [6]. At stable conditions, a salinity-gradient solar pond consists of three separate layers known as upper convective zone (UCZ) at the top, non-convective zone (NCZ) in the middle and lower convective zone (LCZ) at the bottom of the pond. Fully saturated high density salinity water (brine at 27 baume ≈ 1.23 g cm^{-3}) remains at the bottom while keeping the low density solution (almost fresh water) at the top region. Salinity of the middle zone increases from that of the top fresh water layer up to the maximum in the saturated high density brine at the bottom layer thus, forming a stable downward salinity gradient with the depth. In high density and low density regions convective currents can occur because these two layers are homogeneous with constant salinity in each case. Convective currents are inhibited across the middle zone by the downward positive density gradient thus, preventing heat dissipation upward from the bottom where solar radiation is trapped and stored in the form of thermal energy. This situation arises due to the fact that the upward buoyant force on heated liquid mass is compensated by the downward gravitational effects on its high-density nature keeping the liquid mass unmoved with no effective resultant force in the vertical direction. The dominant mechanism of heat loss from the bottom region is, therefore, thermal conduction either through the middle layer to the upper layer or through the walls to the outside atmosphere.

II. SOLAR POND STRUCTURE

The first thermally insulated salinity-gradient solar pond at the premises of the University of Kelaniya was commissioned in 2012 for experimental analysis with a volume of 3.0 x 2.0 x 2.0 m^3 and insulated walls having 10 cm thick Styrofoam sheets. Thermal insulation capacities of this solar pond have been analyzed thoroughly, covering both experimental and theoretical aspects [7]. This solar pond had to be decommissioned after about one year of successful operation due to some other development process at the University. However, with the experienced gained from the first solar pond, an improved second solar pond was constructed at a

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different location of the University where there is a better solar influx. The second solar pond has thermal insulation properties very similar to those of the first solar pond of which details are provided in [7], but have slightly different dimensions 3.45 x 2.25 x 1.5 m^3. In this study, it is focused to analyze the long term behaviour and changes of temperature and salinity profiles of the newly started small-scale experimental salt-gradient solar pond at the University of Kelaniya in western Sri Lanka.

III. Results and Discussion

A. Formation of Temperature Profiles

This salt-gradient solar pond was initially filled nearly up to 70 cm with concentrated brine having a salinity of 26 baume (≈ 1.22 g cm^{-3}) and afterwards the system was left undisturbed. Temperature measurements were carried out every other day, in the morning time, to determine the full temperature profile and the results are shown in Fig. 1, where two consecutive reading sets give a comparison of how the temperature variation occurred during a period of two consecutive days thus, indicating the behaviour of solar pond, particularly in absorbing solar radiation and also the overall heat loss from the pond during the said period until it reaches its thermal stability. The energy accumulation with the absorption of solar radiation occurs only during the day time with the availability of solar flux but the heat loss is a continuous process throughout the day. Except the thermally insulated walls, the upper surface of the pond is open to the outside environment allowing continuous natural evaporation and also accumulation of rainwater during rainy periods. Data logging started from 13th October 2014, just three days after the addition of heavy brine and information of Fig. 1 illustrates the initial stages of the formation of temperature gradient of the solar pond and how the pond gradually reaches towards its stable stage.

The temperature of the fresh water layer at the top of the pond was almost equal to that of the ambient at the data logging time. Cloudy mornings had relatively lower ambient temperatures than sunny mornings. Information from Fig. 1 reveals that the formation of the salinity gradient in the middle region of the pond starts at a height of around 50 cm from the bottom and the temperature at this height keeps increasing up to a maximum of 52.0 ˚C after two weeks time, under these filling and environmental conditions. During this time period, daily average of the absorption of solar energy by the pond is greater than daily average of the heat loss, resulting in an accumulation and storing of thermal energy at the bottom region of the solar pond.

The last temperature profile observed on 28th of October indicates that the pond has reached its stable stage and provides an approximate estimates of the zones as follows. The UCZ is above 80 cm, the NCZ is from 50 cm to 80 cm and the LCZ is from the bottom to 50 cm. According to Fig. 1, the characteristic features of a typical temperature profile of a thermally stable salinity gradient solar pond are clearly visible about 18 days after the initial filling under the given circumstances. Highest temperature of 52.0 °C was recorded in the middle of the LCZ, with an average rate of solar energy accumulation that corresponds to an average temperature increase of 1.3 °C/day. The relatively smaller value of the temperature observed very close to the bottom of the pond, as compared to the recorded maximum temperature, indicates that the heat loss by thermal conduction through the bottom wall has some significant influence on the temperature of the deeper-most layer of the pond.

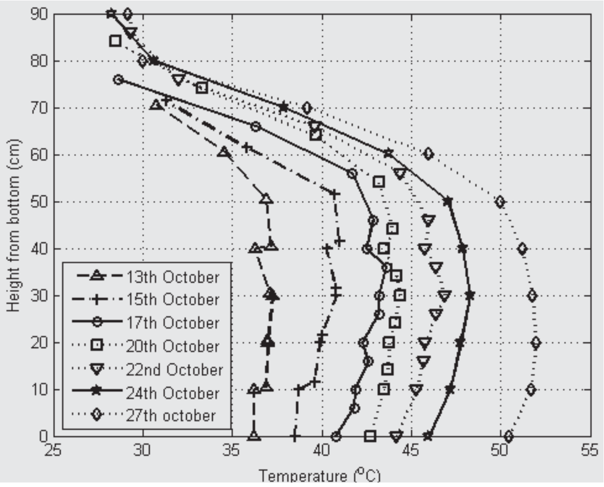

Fig. 1 Variation of temperature profiles along the vertical height of the pond within a time duration of two weeks until the stability stage is reached

After the pond became its thermally stable conditions, daytime raining with cloudy skies occurred at the beginning of November which prevented or reduced substantially the solar radiation influx to the pond during the day time and therefore the net heat gain was always observed to be negative during this period. As the rainfall persisted during most of the daytime, for several days, the pond had to be closed at 2:00 pm on 31st October in order to prevent overfilling. It was opened again on 5th November from 7:30 am to 4:00 pm for thermal charging with the availability of solar radiation at the pond site. Temperature profiles in Fig. 2 illustrate the behavior of the solar pond during the time duration of daytime rainy period that was experienced after the pond reached its thermal-stable conditions.

The solar pond was completely covered with an opaque metal cover from 3rd November 11:00 am to 5th November 7:30 am. The bottom temperature in the morning of 4th November was measured to be 46.4 ºC which afterwards dropped to 45.2 ºC within the next two days with the covers on. During this particular time period there was no significant solar energy input to the pond. It can be seen from the data in Fig. 3 that the whole profile is shifted to the left due to no energy input to the system. Average temperature drop in each zone is as follows; LCZ 1.4 ºC, NCZ 2.1 ºC and UCZ 1.0 ºC. The predicted temperature profile using average zonal temperature values calculated from the observed 4th and 5th November plots is also shown in Fig. 3 by the dashed line which is in good agreement with the actual data. Average density of each zone increases with the salt concentration. Calculated values of power loss in each zone are tabulated in Table I.

TABLE I
CALCULATED VALUES OF POWER LOSS IN EACH ZONE OF THE SOLAR POND

Zone	Thickness	Volume (m3)	Density (kg/m3)	Mass (kg)	C (kJ/kg.ºC)	Delta T (ºC)	Energy (kJ)	Power (kW)
UCZ	0.2	1.55	1008	1564.42	4.153	1	6497.020	0.075
NCZ	0.5	3.88	1157	4489.16	3.583	2.12	34099.480	0.395
LCZ	0.4	3.10	1186	3681.34	3.303	1.4	17023.271	0.197

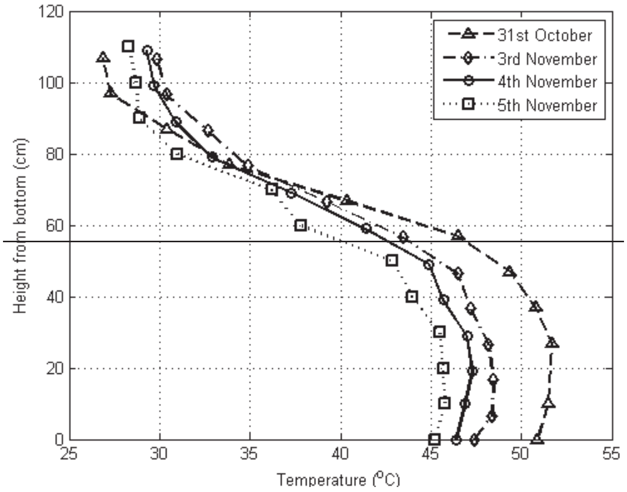

Fig. 2 Variation of temperature profiles along the vertical height of pond within a time duration of daytime rainy season with and without solar radiation influx

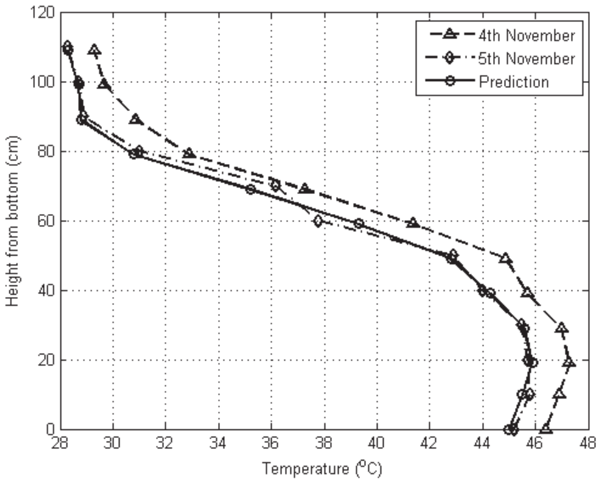

Fig. 3 Comparison between predicted temperature profile and observed one using measured average zonal temperatures

It can be seen from the observed data that the highest rate of thermal energy loss is from the NCZ, as compared to those of other two zones. Since there are no convective currents within the NCZ, heat energy is not transferable from one place to another by convection. However, a heat loss can be occurred through NCZ to the UCZ and through the surrounding walls to the outside atmosphere by conduction. This conductive heat loss is greater from NCZ to UCZ due to the negative temperature gradient than that from the LCZ to the NCZ between which a temperature gradient does not exist.

Obviously, the heat loss through the walls by conduction is greater from the LCZ to the outside than that from the NCZ to the outside through its walls because the wall area is less and the temperature difference is also less in the latter case. However, a greater power loss observed from the NCZ indicates that the dominant energy loss mechanism from the pond is by heat conduction through NCZ to the UCZ from where the heat is lost to the outside atmosphere through both convection and conduction. The heat conduction from the pond to the outside environment is minimized by having a thick Styrofoam layer of thermal insulation in the walls [7]. Total power loss of this solar pond is estimated to be around 680 W under these conditions. Fig. 4 illustrates temperature profiles observed daily in the morning within a period of consecutive four days of March, 2015 under better operating conditions for a solar pond where a maximum temperature of 60.0 ˚C was recorded in the bottom region.

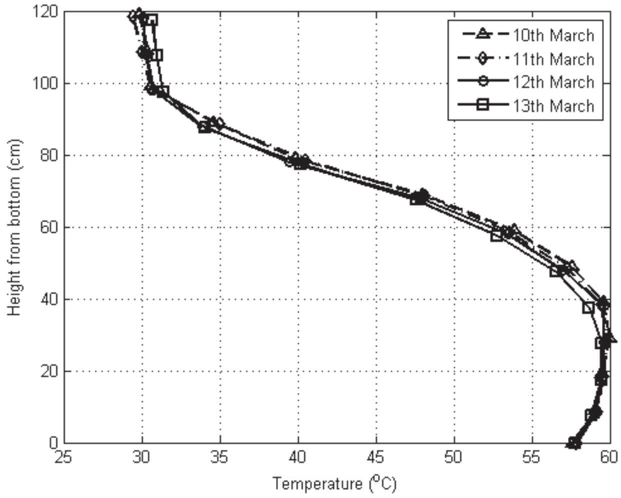

Fig. 4 Temperature profiles at the stable stage of the solar pond under better operating environmental conditions

B. Long Term Stability

The temperature profiles observed in the mornings of 31st October and 3rd November indicate that the maximum temperatures in the bottom region keep decreasing due to unavailability of solar radiation with overcast conditions thus showing a negative overall heat gain. Under these conditions, the ambient temperature was also observed to be at a lower value and the continuous heat loss by heat conduction from the bottom region through the middle NCZ to the UCZ and also through the walls seems to be the dominant mechanism of energy loss from the pond.

The temperature profiles obtained in the mornings of 4th November and 5th November were measured with minimal solar flux into the pond. However, information in Fig. 2 reveals that even at these negative heat gain conditions, the zonal structure of the pond remains intact and with the availability of solar flux, it will have the potential to come back again to a highly effective thermal storage with a net positive gain of thermal energy. It is an interesting feature to notice that the layer between 65 cm and 80 cm of the pond keeps almost a constant temperature and this layer falls at the middle of the NCZ for all these temperature profiles. It can also be concluded that a substantial variation observed of the heat loss from the pond bottom can be due to the varying thermal conductivity of soil due to varying water content.

C. Power Loss

It can be seen that all the profiles illustrate almost a same pattern but 13th March profile is slightly shifted to the left due to overcast conditions with lower solar insolation on 12th March. According to Fig. 4, the thickness and the temperature of LCZ are 40 cm and 60.0 °C, respectively. Heat loss through the bottom wall to the outside soil medium due to conduction has made the temperatures of the layers close to the bottom wall relatively little lower than the average temperature of the LCZ. This situation is due to the fact that the salt concentration of the lower most layers is the highest, which are not replaced by the relatively low density brine from the upper layers of the same region thus reducing convective currents of brine in this particular region of the pond bottom. These conditions result in a slightly lower temperature at the very bottom of a solar pond than its maximum value recorded. Energy loss from the LCZ of the pond could be calculated by assuming that the average temperature from 20 cm to 40 cm is 60.0 °C and average temperature from 0 cm to 20 cm is 58.7 ºC. This implies that each day the pond bottom loses 8359 kJ or the energy loss from bottom is nearly equal to 97 W. This is almost half of the estimated energy loss of LCZ shown in Table I. It can be assumed that the other 100 W is lost due the conduction through the walls.

D. Evaporation Effects

Daily evaporation of water content from upper surface of the solar pond depends on several factors such as ambient temperature, humidity, wind speed etc. Surface evaporation area of this pond is 7.76 m^2 and the maximum rate of water evaporation observed was 39 kg/day. Energy requirement for this evaporation could be 88530 kJ/day by assuming that the latent heat of water is 2270 kJ/kg. This suggests that 1 kW maximum power loss from the pond surface is due to evaporation, which could vary from a minimum value up to this maximum under different environmental conditions. Energy loss due to water evaporation from the pond surface was further investigated using a transparent cover on the water surface. A polythene transparent sheet was made floating on the water surface of the pond so that there was no air trapped between the water surface and the sheet, and the effect of this situation is illustrated by the temperature profiles shown in Fig. 5. The morning temperature profiles were obtained for the consecutive two days of 22nd and 23rd of January, 2015 under normal conditions without covering the water surface.

The pond had been covered for the consecutive two days of 28th and 29th of the same month with the transparent polythene cover and the morning temperature profiles were observed and these two profiles are also shown together in Fig. 5 for the comparison. The ambient temperature of each day during the data collection was recorded respectively as 25.6 °C, 27.3 °C, 28.0 °C and 27.2 °C on 22nd, 23rd, 28th and 29th during the period. It was observed during the last two days with the cover that the water level in the solar pond remained unchanged, implying that the surface evaporation could significantly be controlled by the polythene cover. However, this mechanism seemed to slightly reduce the penetration of solar radiation into the pond. A fraction of the solar radiation seemed to have reflected at the surface by the polythene cover, and also the poor heat transparency through the covering material must have reduced the radiation penetration. Data collection was carried out around 7:30 am on all four days. It is clear that the cover has substantially reduced substantially the evaporative cooling of top layer suppressing the water evaporation from the upper surface as expected. However, a better performance of the pond is not achievable due to the negative factor coming from the heat transmission loss at the cover by the reflection of solar radiation.

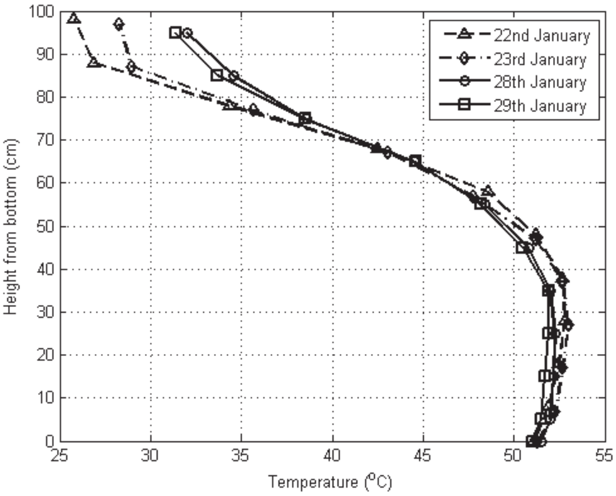

Fig. 5 Comparison of temperature profiles with and without a transparent cover on the pond's surface to investigate evaporation cooling of the upper fresh water layer

E. Maintenance of UCZ

It is an essentially important practice to maintain an appropriate quality of fresh water content of the UCZ for a better operation of the solar pond for longer durations of time under different environmental conditions. Adding freshwater to compensate for surface evaporation during the periods of no rain and removing excess water during the periods of

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continuous and heavy rain, appropriately in both cases, are essential operational procedures in order to maintain a constant water level of a solar pond which is being operated for long periods of time. Removing fresh water from the UCZ of pond was done using a thin siphon tube fixed at the required water level. Adding fresh water to the upper surface of the UCZ was accomplished when the water level dropped significantly, in both cases essentially without any turbulence to the liquid mass of the pond. The UCZ seemed to take two to three days to establish itself again after the addition of fresh water from the upper surface to overcome severe evaporation effects with no rain for longer durations of time. However, the overall solar pond stays at stable conditions as an accumulator of solar radiation thus storing relatively larger amounts in the bottom region under better environmental conditions such as occasional rains during night times and strong solar insolation with clear skies during day times for longer periods of time.

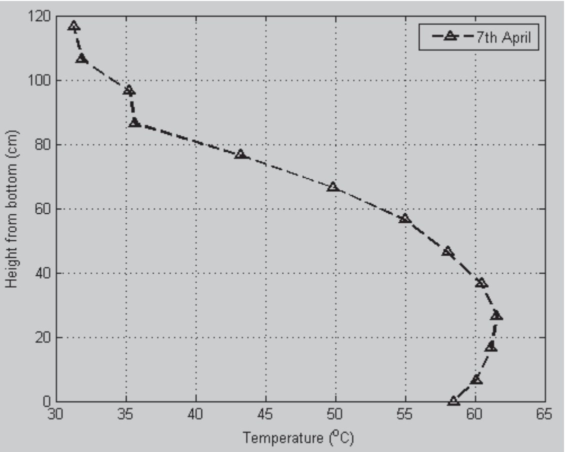

Fig. 6 Temperature profile that shows the maximum observed temperature in the bottom region of the solar pond

This situation is illustrated by Fig. 6 which shows a maximum temperature of 62 °C in the bottom region and this temperature profile was observed in the month of April, 2015 which is almost about six months after the initial filling of the pond with heavy brine in October of the previous year 2014. Most importantly this clearly suggests that the solar ponds when reached their stable stage can be operated as a solar energy accumulator and a powerful renewable energy source for moderate temperature applications for long periods of time without any additional filling with heavy brine.

Temperature variations of the top and the bottom regions of the solar pond over the entire time period of study have been plotted in Fig. 7. The information reveals that the bottom temperature was on the rise over the time since the initial filling except some downfall nature at several time intervals which is in fact due to the overcast environmental conditions with low solar insolation received at the pond site. The relatively large downfall in temperature of the bottom region at some time intervals were caused by very low radiation input due to overcast conditions that prevailed continuously for several days. During the environmental conditions with clear skies in day time and little rain in the night time always helped the bottom temperatures increase in considerable amounts. It is conclusively notable that the bottom temperature of a solar pond can be increased during a dry season with healthy solar insolation and by adding fresh water to the top of the UCZ in little amounts which also can compensate the water content that evaporates from the top surface. Also in Fig. 7, the temperature variation of the UCZ is plotted for the entire period of study spanning a total of seven months and the data show that the variation is minimal and having one to one relation with the outside temperature reflecting conventional slight environmental changes during the time period. These changes were caused by the oscillating weather conditions between dry and rainy atmospheric situations.

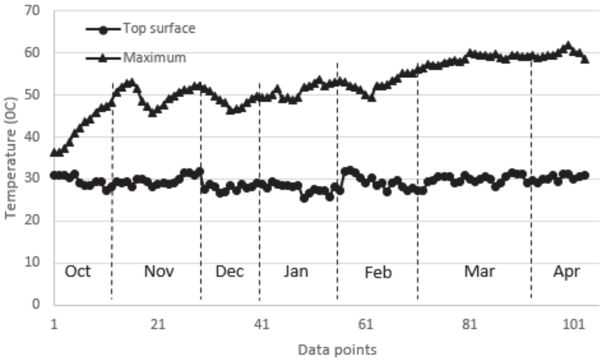

Fig. 7 Temperature variations of the top and bottom layers of the solar pond for a time span of eight months of operation under various natural environmental conditions

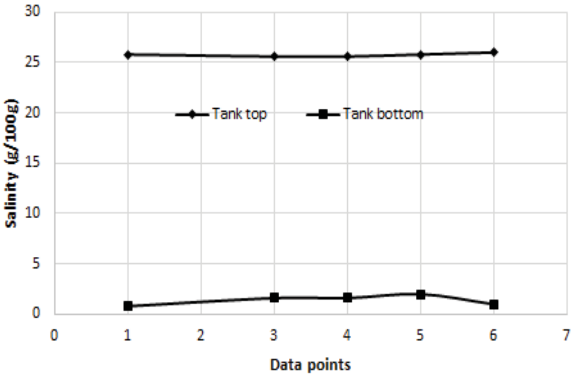

Fig. 8 Salinity variations of the top and bottom layers of the solar pond for a time span of six months of operation under various natural environmental conditions

The corresponding salinity variation of the top and bottom regions of the pond for the entire period of study was also monitored and is illustrated in Fig. 8. The top layer of the pond shows a very low salinity and a little variation throughout the time period as expected because this is the fresh water part of the system which gets refreshed by occasional rain that helps avoid the rising salinity due to evaporation at the top surface. The absence of rain for several weeks and the presence of high solar insolation with clear skies expedites the process of evaporation resulting in the decrease of water content of the UCZ helping the salinity to rise with time until the next rain which could compensate the situation controlling and maintaining the very low salinity of this top layer of the pond.

The variation of salinity of the bottom region of the pond was also monitored with time over the period of study, which is illustrated in Fig. 8 in comparison with that of the top layer in the same figure. At the initial filling, heavy brine of about 26 baume was brought from a nearby salt production site in a transport tanker, which was put up to about 75% of the total height of the pond. The data in Fig. 8 show that the salt concentration has increased by a little amount with time in the bottom region which could be due to the gravitational effects as the heavy brine in fact is prefer to be deposited at the bottom of the pond. The data also illustrate that the heavy brine at the bottom region can stay relatively a long time as it is without any dilution and diffusion up though the height, thus resulting in a long term stability of the zonal structure required to absorb and store solar radiation in the bottom region of the solar pond. Since this is a small-scale insulated model solar pond, the wind effects which could transfer kinetic energy in sufficient amounts from strong winds into the pond to destroy the zonal structure is minimal, thus supporting the long term stability [6]. As conclusive remarks, a solar pond of this type can be operated as multi-utility renewable energy source for relatively long periods and noticeably in a hundred percent environmentally friendly manner with almost zero natural hazards.

IV. CONCLUSIONS

Behavior of an insulated, small scale salinity gradient solar pond has thoroughly been analyzed over an extended period of time to identify the environmental conditions and operational procedures favourable for the sustainability the three layer structure of a salinity gradient solar pond. This study illustrates that once the pond is filled with high density brine initially, the subsequent addition of salinity water is not required for the maintenance of the thermal energy storing capability of the solar pond. Although the maximum temperature observed in the temperature profiles is around 60 °C during the period of study, it is very clear that achieving higher temperatures is possible if the pond is exposed to uninterrupted sunny days. Studies are currently underway for the development of a seawater desalination system that would extract energy from the solar pond in a completely environmentally friendly manner.

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