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A STUDY OF SALT GRADIENT SOLAR POND IN THE TROPICS

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ABSTRACT

The energy generation potential of a salt gradient solar pond in Ile-Ife, Nigeria (7°28'13.41"N, 4°32'50.82"E), a tropical environment was experimentally determined from a laboratory scale model in this investigation. The laboratory scale model solar pond was constructed from a rectangular plastic tank with a cross- sectional dimension of 0.98m x 0.8m and a height of 1.0m.

The salinity gradient was achieved using the salinity redistribution method. Measurements of the temperature at depths of 0.2, 0.45, 0.75, 0.85 m from the base of the pond and ambient temperature were taken using type K thermocouples. Global radiation were taken during a period of 21 days of experimentation using a global radiation meter (Model GRM 100).

Results from solar radiation measurements showed that the average global radiation for the period of experimentation was 398.3 W/m^2. A comparison between the temperature profile obtained experimentally in the model pond and that obtained from theoretical relations showed good agreement. Theoretical determination of the available thermal energy collected in the experimental pond showed that the thermal energy obtainable from the pond was 24.3MJ. Results from the investigation shows that the utilization of the salt gradient solar pond technology could improve the energy access problem in the rural areas of Nigeria.

INTRDUCTION

A global rise in the temperature of the earth is undoubtedly real according to the Intergovernmental Panel on Climate Change, IPCC [1]. An increasing body of observations gives a collective picture of a warming world and other changes in the climate system [2]. The estimated temperature increase during the past century was between 0.4 and 0.8 °C with the 10 warmest years all occurring within the last 15 years [3]. The exponential growth of the global economy since 1860 is based mainly on fossil fuel consumption [4]. Developing clean energy resources as alternatives to fossil energy has become one of the most important tasks confronting modern science and technology, the reason for this strong motivation is to stop the increase in the temperature of the earth and the resulting climate change both of which have been largely linked to the combustion of fossil fuels. Further, there is a deep urge internationally to protect the ecological cycles of the bio systems of the earth [5]

Of recent, the world's interest in renewable sources of energy has been increasing in response to the challenges in the environmental and development areas [6]. Among a wide variety of renewable energy projects currently in progress, the utilization of solar energy is a very promising one because it is abundantly available everywhere in the world, it is also pollution free and even diffuse solar radiation can be harnessed for energy generation [5]. Solar radiation represents the largest energy flow entering the terrestrial ecosystem. Currently, there exist an extremely large variety of solar technologies. Nevertheless, the global utilization of solar energy is still small compared to the potential of this source [7].

In Nigeria, for decades, solar thermal has been constantly enjoying very high level utilization by rural dwellers for agricultural processing in purposes including drying of agricultural products such as grains, cassava(tubers or marsh),yam flakes, meat, fish, fruits, kernels, drying of manure, hides and skins, cooking and frying of agricultural products which are not preserved or sold raw. Other areas of solar energy utilizations include heating and lighting of animal pens, pumping of water and irrigation, food and vaccine storage [8]. In addition to these, solar energy has also found wide usage in Nigeria viz: solar street lightings, solar refrigerators, solar cookers, solar-powered water pumps, etc; different applications exist in the form of solar thermal and solar PV [9].

Solar ponds have been studied for many decades for their potential as collectors of solar energy [10]. Salt gradient solar ponds have received a great deal of attention and despite their apparent simplicity in concept, have provided a large number of interesting challenges from both theoretical and practical considerations. Solar pond physics and technology was pioneered by Tabor [11] and followed by others such as Weinberger, Rabl and Nielson, Zangrando[12, 13, 14]. Experimental studies of solar ponds have been reported by Shar among others [15], although these have been almost exclusively for the temperate northern climates. Many of the drawbacks and problems encountered with solar pond design and operation in northern cold climates are fortunately absent in the tropics especially in the equatorial tropics [16].

A salinity gradient solar pond is an integral collection and storage device of solar energy. By virtue of having built-in thermal energy storage, it can be used irrespective of time and season. Most of the solar ponds operated today, however, are artificial, simulating natural solar ponds but taking advantage of engineering technologies to advance their operation and application for practical purposes.

The salt gradient solar pond is typically 1–2 m deep and the bottom is painted black as shown in Figure 1. The convection currents that normally develop due to the presence of hot water at the bottom and cold water at the top are prevented by the presence of strong density gradient from bottom to top. This density gradient is obtained by using a high concentration of suitable salts such as NaCl at the bottom of the pond and negligible concentration at the top. The thermal conductivity of the salt solution, which is even less than that of stagnant water, decreases with the increase of salinity and thus acts as an insulating layer [17].

The salt gradient solar pond consists of three layers. The top surface layer is known as the convection zone (CZ) that is a zone of constant temperature and salinity. The thickness of this surface layer varies from 0.1 to 0.4 m and is formed due to upward salt transport, surface heating and cooling and wave-action [18]. It is a relatively thin layer which consists almost wholly of fresh water [20]. The temperature of this zone is near ambient.

The second layer is the non-convective zone (NCZ) with thickness ranges from 0.6 to 1.0 m, which acts as an insulating layer of the pond [18]. The density in the NCZ increases with increasing depth of the gradient layer. The thickness of the gradient layer depends on the desired temperature, solar transmission properties and thermal conductance of water. This is also known as the gradient zone and is regarded as the most important layer where salt content increases with depth. In the gradient layer, water cannot rise because water above it is lighter, neither can it fall because water beneath it is heavier. Thus the stable gradient layer suppresses convection and acts as a transparent insulator, permitting sunlight to go through to heat the water in the bottom but reducing the heat loss from the bottom layer to the upper layer [20].

The bottom or the third layer is a high temperature layer known as the storage layer or the storage zone. This layer has a constant temperature and salinity. Useful heat is usually extracted from this layer and its thickness depends on the temperature and the amount of the thermal energy to be stored [17].

In a study of global solar radiation in Nigeria, daily averages of 500W/m^2 and 360W/m^2 for the northern and southern parts of Nigeria, respectively, with a country wide average of 415W/m^2 were obtained [16], thus indicating that Nigeria has a great potential utilizing solar energy as an energy source. Solar pond technology can contribute significantly to the energy needs of Nigeria especially in the rural areas with very poor access to modern energy sources and services, and especially grid electricity.

Unfortunately, not much work has been carried out on solar ponds in the Nigerian context. The objective of this research is to provide experimental data on the performance of a solar pond in the tropics with Nigeria as a case study with the hope that the data provided will be an invaluable contribution to the development of this technology locally.

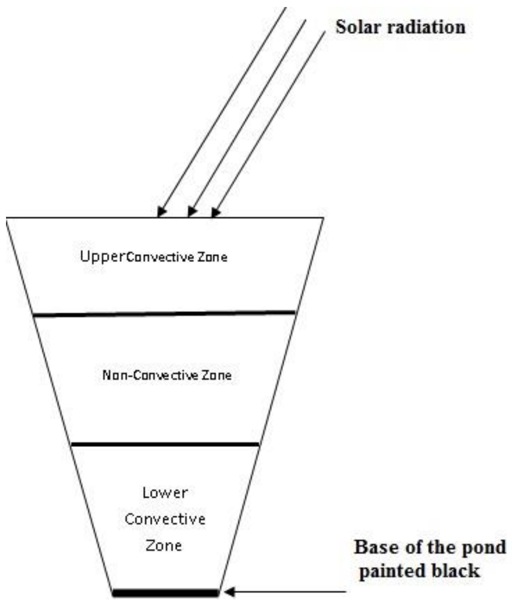

Figure 1: Diagram of the Salt Gradient Solar Pond

NOMENCLATURE

T	[K]	Temperature of the pond collection zone
T_a	K	Ambient Temperature
τ		Transmissivity
a, b		constants in the logarithmic absorption function of the solar spectrum in water
H	W/m^2	Solar irradiation
K_w	W/m^oC	Thermal conductivity of water
l_i	m	thickness of the insulation layer
r		Angle of refraction of solar radiation in water
S_o	W/m^2	Average power density withdrawn from the solar pond.
x	m	vertical coordinate
x_1	m	top of the non-convective zone
x_2	m	top of the heat storage zone
Q	J	heat content available in the pond
ρ	kg/m^3	density of salt water
V	m^3	volume of heat storage zone
T_{AMB}	°C	average ambient temperature
T_{ATT}	°C	average temperature attained

2.0 MATERIALS AND METHOD

The experimental set-up was located in the Mechanical Engineering Department building, Obafemi Awolowo University, Ile-Ife (7°28'13.41"N, 4°32'50.82"E), Osun State, Nigeria. The pond was a rectangular plastic tank located inside a metal cage to enhance rigidity when filled with water. The plastic tank was insulated with a 3mm thick organic synthetic fiber while the inner surface was lined with a black nylon (polyamide) to facilitate the absorption of solar radiation. The plastic tank surface area was 0.98m x 0.8m with a height of 1.0 m.

Four thermocouples were fixed on a side of the tank to measure the temperatures at different depths in the pond and the depth of each probe in the pond is as shown in Table 1 while another thermocouple probe enabled measurement of the ambient temperature.

Table 1.0: Height of Temperature Sensor from Bottom Level

Temperature Sensor	Height from Bottom Level(m)	Location in the Pond
T1	0.2	Heat Storage Zone
T2	0.45	Non-convective Zone
T3	0.75	Non-convective Zone
T4	0.85	Upper Convective Zone

Determination of Temperature and Density Distribution

The density variation in the pond was determined at the beginning and at the end of the experiment. Samples were taken from specific locations within the pond and the gravimetric method of density measurement proposed by Fynn and Short [21] was employed in the determination of density in this study. After the establishment of the solar pond, the initial temperature at the points where the thermocouple probes were located were taken and recorded. Also, the total solar radiation intensity was taken and recorded. The experimental set up was monitored for a period spanning 21 days. Measurements were taken between the hours of 8:00am and 6:00pm on hourly basis using a portable solar pyranometer.

From the daily averages of temperature data taken at the different zones of the experimental salt gradient pond, the temperature profile for each day was established. Similarly, from the daily averages of the hourly temperature readings in the heat storage zone of the pond, a graphical plot of the temperature in the heat storage zone of pond throughout the period of experimentation was obtained. Temperature of the ambient air was also taken throughout the duration of the experiment.

Estimation of Temperature Profile in a Salt Gradient Solar Pond

Using equation 1 as proposed by Bryant and Colbeck [22], the temperature in the heat storage zone was calculated enabling comparison with the experiment data. A similar procedure was employed using equation 2 given by Kooi [23] for evaluating the temperature analytically in the gradient zone which again enabled comparison with the experimental data.

$$T = T_a + \frac{\tau H}{K_W}[\{a + b\ln(\cos r) + b\}(l_i - 1) - b l_i \ln l_i] - \frac{S_o\,(l_i - 1)}{K_W} \qquad (1)$$

$$T(x) = -\frac{Hb}{K}(x\ln x - x_1 \ln x_1) + \Big[T(x_2) - T(x_1) + \frac{hb}{K}(x_2 \ln x_2 - x_1 \ln x_1)\Big]\left(\frac{x - x_1}{x_2 - x_1}\right) + T(x_1) \qquad (2)$$

Ould Dah *et al.*[24] established that the ambient temperature and the temperature at the upper convective layer in a solar pond are most times within the same range; our experiment provided data to validate this assertion.

Determination of Thermal Energy within the Salt Gradient Solar Pond

The thermal energy was determined in the experimental salt gradient solar pond using equation :

$$Q = \rho V C_P\,(T_{ATT} - T_{AMB}) \qquad (3)$$

RESULTS AND DISCUSSION

Solar Radiation Measurement

From the hourly average during the (daylight) period of experimentation the average solar radiation in Ile-Ife (7°28'13.41"N, 4°32'50.82"E) for the period of experimentation was found to be 398.3 W/m^2

From samples taken at various depths in the salt gradient solar pond both at the start and at the end of the experiment, the density profile at these two periods appears in Figure 2 below. At the start of the experiment, the density of brine in the heat storage zone was 1.2 g/cm^3, which decreased gradually to 1.002 g/cm^3 at the surface, while the density of brine varied from 1.19 g/cm^3 in the heat storage zone of the pond to 1.007 g/cm^3 on the surface at the end of the experiment.

A comparison between the density profile at the start and end of the experiment shows that the density of brine in the heat storage zone at these two periods are significantly different. At the start of the experiment, the density of brine was higher and fairly uniform throughout this zone, while the density of brine was lower and non-uniform at the end of the experiment. The density gradient in the gradient zone is obvious at the start of the experiment where the slope at this zone is more pronounced than other zones; while at the end of the experiment, the slope of the density profile in the gradient zone is less pronounced than at the start of the experiment. This is attributed to the diffusion of salt molecules from the heat storage zone into the gradient zone.

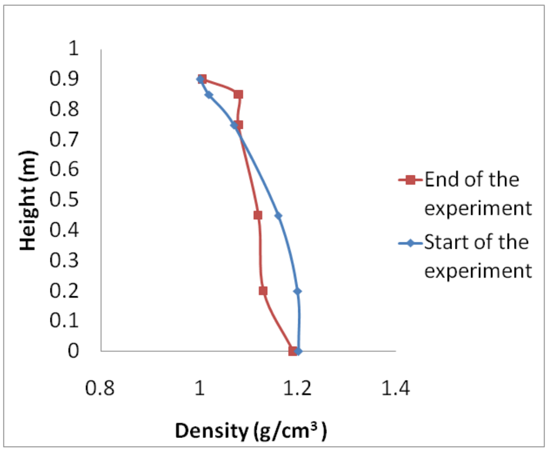

Figure 2: Density profiles at the start and the end of the experiment.

Development of Temperature Profile

The daily average temperature at the different levels of the pond was used to generate the temperature profile in the pond for all the days in which the experiment was carried out as shown typically in Figure 3. The temperature profile was fully established after four days of experimentation. Although the temperature at the heat storage zone of the pond started increasing considerably from an average reading of 29.5°C on the second day of experiment to 36.7°C on the third day, it was observed that there was no significant temperature variation in the gradient zone of the pond on the second and third days.

After the profile was established on the fourth day, subsequent observations revealed that the pond started accumulating heat gradually throughout the first week of experimentation. It was observed that the average temperature in the heat storage zone increased steadily from 41.9°C to a maximum average value of 56°C on the eleventh day of the experiment and that the temperature gradient in the pond remained relatively stable with very slight variations occurring throughout the days of experimentation.

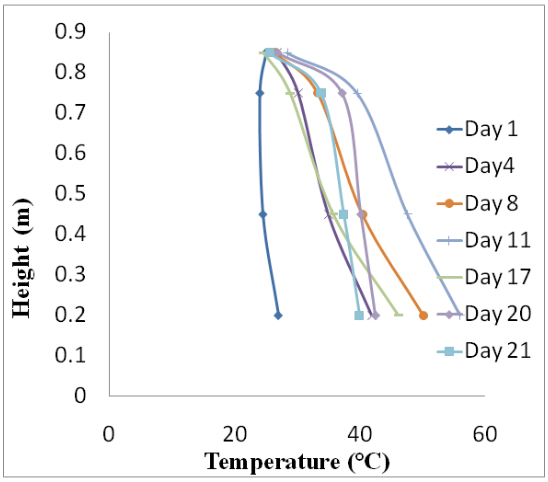

Figure 3: Temperature profile development in the pond

Temperature Development at the Upper Convective Zone, Heat Storage Zone and Gradient Zone

Figure 4 shows the history of temperature evolution at the upper convective zone and in the heat storage zone while the mean temperature in the gradient zone appears in Figure 5. As seen in Figure 4, the temperature in the heat storage zone increased steadily every day until it reached the highest point of 56°C on the 11th day of experimentation. A gradual decline was observed until the 13th day before the temperature in this zone began to rise again. The temperature decline noted in the heat storage zone coincided with a reduction in the amount of solar radiation received during this period. From Figure 4, the temperature of the upper convective layer appears to be fairly uniform, reaching a maximum of 30°C on the 9th day but generally between 25-30°C throughout the days of experiment.

Figure 6 shows the temperature in the upper convective layer in relation to the ambient temperature. It is observed that the temperature development in both cases follow a similar

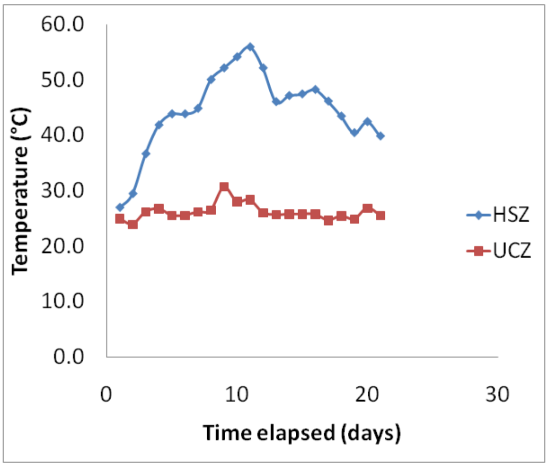

Figure 4: History of temperature profile at the upper convective zone (UCZ) and heat storage zone (HSZ)

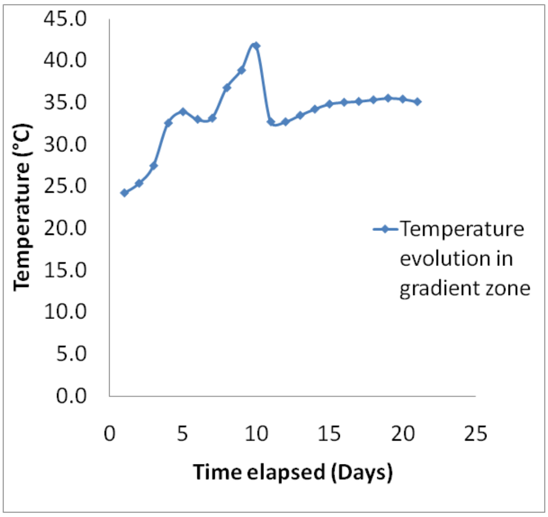

Figure 5: History of mean temperature profile at the gradient zone

pattern and that the ambient temperature at any point in time is only slightly higher that the temperature at the upper convective layer as earlier noted.

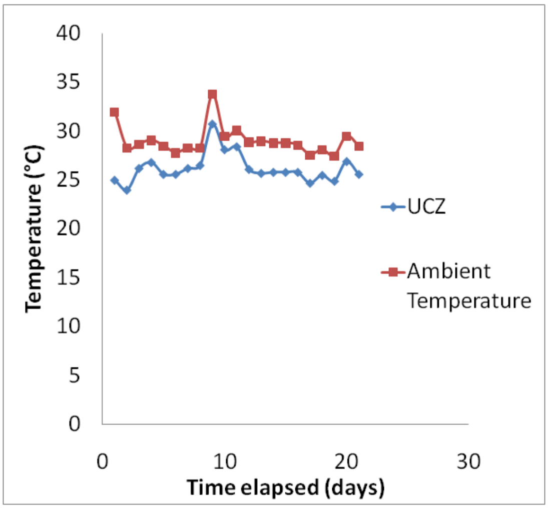

Figure 6: Comparison of the temperature at the upper convective zone (UCZ) and the ambient temperature

Estimation of Temperature Profile in the Salt Gradient Solar Pond

Equation 1 was used to calculate the temperature of the heat storage zone. Figure 7 shows a comparison of the experimental data and calculated temperatures at the heat storage zone using equations 1. At the start of the experiment, the calculated values were higher than the measured values but as the experiment progressed, both values approached one another by the 9th day of experimentation. It is important to note that the values obtained are greatly influenced by the solar radiation recorded for each day. Days 14 to 18 were cloudy and this resulted in little amount of solar radiation experienced during this period. Although the temperature measured during this period was not increasing significantly as seen in the graph, the pond still retained heat thereby resulting in a higher measured temperature as compared with the calculated temperature.

Determination of Thermal Energy within the Salt Gradient Solar Pond

The thermal energy accumulated within the experimental pond was determined using equation 2.4. The surface area of the experimental pond is 0.784 m^{2}while the depth of the heat storage zone is 0.4m. The density of brine in the heat storage zone is taken to be 1200kg/m^3. The average ambient temperature and average heat accumulated in the heat storage zone of the solar pond throughout the days of experiment were designated as the temperature of the heat sink and heat source respectively. The heat source and heat sink temperatures were 44.5 and 29.1°C respectfully while the specific heat capacity of saturated salt water is 4187 $^{J}/_{kg.K}$ ([25] Using these values, the heat accumulated within the pond was calculated to be 24.3MJ using equation 3.

A comparison between the average daily thermal energy accumulated in the heat storage zone of the solar pond and the total energy available on the surface of the pond is as shown in Figure 8.

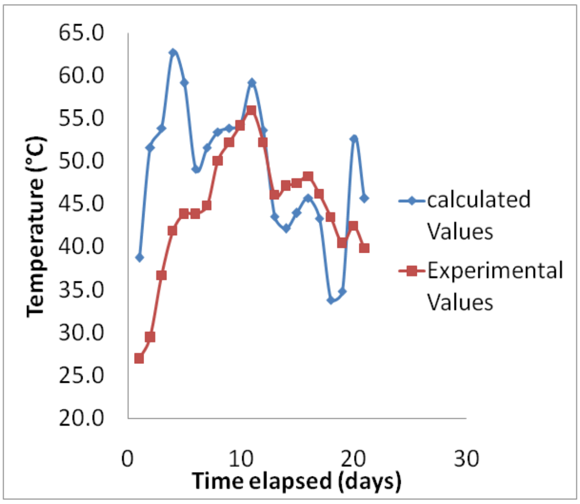

Figure 7: Comparison between measured and calculated temperatures for the heat storage zone of the experimental pond

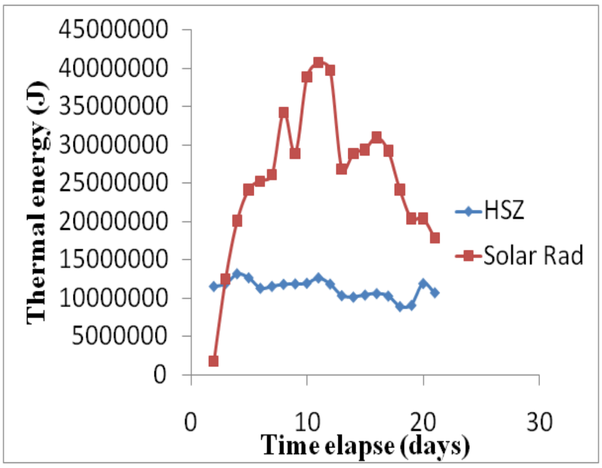

Figure 8: Average daily thermal energy plot of energy accumulated at the HSZ and the energy of the solar radiation at the surface of the pond UCZ of the pond

CONCLUSION

This research work has considered the thermal behavior of a salt gradient solar pond as a solar collector and thermal storage system in the tropics; it was observed that the temperature profile was fully established in the pond after first four (4) days of the experimentation; the existence of salt diffusion from the heat storage zone to the surface zone was noticed. A comparison of the experimental data obtained with data from the theoretical relations show good agreement. The average temperature in the heat storage zone throughout the period of the experimentation was much higher than the average ambient temperature during the same period and at no point in time was the ambient temperature higher than the temperature in the heat storage zone of the experimental salt gradient solar pond.

The study therefore concluded that even the south western part of Nigeria typified by Ile-Ife enjoys a reasonable amount of solar radiation which can be harnessed and utilized for thermal heating by utilizing a salt gradient solar pond.

REFERENCES

[1] IPCC "Climate Change 2007: Synthesis Report, An Assessment of the Intergovernmental Panel on Climate Change".

[2] IPCC "Fourth Assessment Report: Climate Change", 2001, Working Group I of the IPCC.

[3] EPA, United State Environmental Protection Agency (EPA), 2001, http://www.epa.gov/globalwarming.

[4] J. Marion, N. Nsakala, G. Timothy, and B. Alain, "Controlling Power Plant Co_2 Emissions: A Long Range View", ALSTOM Power Plant Laboratories, 2006, 2000 Day Hill Road, Windsor, CT 06095, USA.

[5] Y. Hamakawa,"Recent Advances Of The Photovoltaic Activities In Japan", Phys. Status Solidi B, Vol 194,1996, pp 15–29. doi: 10.1002/pssb.2221940104.

[6] A. Demirbas, "Global Renewable Energy Projections", Energy Sources, Part B; No 4, 2009, pp 212– 224

[7] J. Gale, "Overview of Sources, Potential, Transport and Geographical Distribution Of Storage Possibilities", 2002, IPCC Workshop on Carbon Capture and Storage, Regina, Canada.

[8] J. Yohanna., V. Umogbai. Solar energy potentials and utilization in Nigeria agriculture. JEnviron Issues AgricDevCtries 2010;2(2–3):10–21.

[9] S. Ohunakin, M. Adaramola, M. Oyewola, and R. Fagbenle. "Solar energy applications and development in Nigeria : Drivers and Barriers", Renewable and Sustainable Energy Reviews, An Elsevier Journal, Volume 32, April 2014, pp. 294-301.

[10] Y. Keren, H. Rubin, J. Athinson, M. Priven. and G. Bemporad " Theoretical and Experimental Comparison of Conventional and Advanced Solar Pond Performance", Solar Energy, Vol. 51, No. 4, 1993, 255–270.

[11] H. Tabor "New Sources of Energy", Solar Energy, Earlier Report at U.N. Conf., 7. Rome, 1963, pp. 189.

[12] H. Weinberger "The Physics of Solar Ponds", Solar Energy, Vol. 8, No. 2, 1964, pp 45–56.

[13] A. Rabl and C. Nielsen, "Solar Ponds for Space Heating", Solar Energy, Vol.17, 1975, pp. 1–12.

[14] F. Zangrando, "Salt Gradient Solar Ponds", Ph.D. Thesis, 1979, University of New Mexico, Albuquerque, New Mexico.

[15] S. Shah, T. Short, and R. Fynn, "Modeling and Testing of Salt Gradient Solar Ponds", ASME Paper, 82-WA/Sol-25, 1982, Phoenix, Arizona.

[16] R. Fagbenle, "Solar Energy Utilization in Nigeria", Nigerian Journal of Renewable Energy, Vol. 3, 1993, pp. 813.

[17] H. Garg, "Advances in Solar Energy Technology" Collection and storage systems", 1987, 259ff.

[18] A. El-Sebaii, M. Ramadan, S. Aboul-Enein, and A. Khallaf, "History of the Solar Pond: A Review Study", Renewable and Sustainable Energy Reviews 15,2011, pp. 3319– 3325.

[19] H. Kurt, H. Fethi and A. Korhan, "Solar Pond Conception - Experimental and

Theoretical Studies", Energy Conversion & Management, Vol. 41, 2000, pp. 939-951.

[20] J. Srinivasan, "Solar Pond Technology", Sadhana, Vol. 18, 1993, pp. 39-55.

[21] R. Fynn and T. Short, "The Salt Stabilized Solar Pond for Space Heating-A Practical Manual", 1983, OARDC special circular.

[22] H. Bryant and I. Colbeck, "A Solar Pond in London?" Solar Energy, Vol. 19, 1977, pp. 321-322

[23] C. Kooi, (1979), "The Steady State Salt Gradient Solar Pond", Solar Energy, Vol. 33, 1979, pp. 37-45

[24] M. Ould Dah, M. Ouni, A. Guizani and A. Belghith, "The Influence of the Heat Extraction Mode on the Performance and Stability of a Mini Solar Pond", Appl Energy, Vol. 87, 2010, pp. 3005–3010.

[25] B. Schober, "Membrane Stratified Solar Pond." M.Sc. Thesis in Energy Systems, 2011, Department of Technology and Built Environment, University of Gavle, Sweden.