NON-CONVECTIVE SOLAR POND AS A THERMAL ENERGY SOURCE

ENGR. P.O. BABALOLA
B.Eng, M.Sc., MNSE, COREN
E-mail: phillip.babalola@covenantuniversity.edu.ng; phillgail@yahoo.com

DEPARTMENT OF MECHANICAL ENGINEERING
COLLEGE OF SCIENCE AND TECHNOLOGY
COVENANT UNIVERSITY
OTA

TABLE OF CONTENTS

ABSTRACT

Non-convective solar pond is a potential large surface area solar collector device. It has additional advantage of long term storage capacity.

It is a shallow body of water of about a meter deep containing dissolved salts to generate a stable density gradient (fresh water on top and denser salt at the bottom). Part of the incident solar radiation entering the pond is absorbed leading to temperatures near 100 ^{0}C without convection due to the density gradient.

The hot salt water can be used to drive turbine and electric generator with the use of suitable fluids, provision of process hot water for industrial and commercial purposes, space heating, air conditioning and hot water needs of community or individual apartment.

NOMENCLATURE

α	thermal diffusivity
k	thermal conductivity
ρ	density
C_p	specific heat capacity
m	mass flow rate
U	overall heat transfer coefficient
A	total heat transfer surface in contact with a fluid
q	source of thermal energy
t	time
UCZ	upper convective zone
NCZ	non convective zone
LCZ	lower convective zone
T	temperature
ΔT_{LM}	logarithmic mean temperature difference
Z	depth of the pond
H_S	surface insolation
E	ratio of radiation penetrating the water surface
i	angle of incident radiation (solar zenith angle)
r	angle of refracted radiation
η	efficiency

Conversion factors

$1.0\ W/m^2 = 0.317$ Btu/hr – ft

1.0 Langley (L_y) = 1.0 Cal. / cm^2

= $11.63\ W\text{-}hr/m^2$

1.0 L_y/min 698.0 W/m^2

CHAPTER 1

1.0 INTRODUCTION

1.1 WORLD ENERGY

Many sources of raw energy have been variously proposed or used for the generation of power. Only in few sources-fossil fuels, nuclear fission and elevated water-are dominant today.

A more complete list of sources of would include fossil fuels (coal, petroleum, natural gas); nuclear (fission and fusion); wood and vegetation, elevated-water supply, solar; winds; tides; waves; geothermal; muscles (human, animal); industrial; agricultural; and domestic wastes; atmospheric electricity; oceanic thermal gradient; oceanic currents.

These sources are superseded by fossil fuels due to the suitability of the thermal sources for practical stationary and transportation power plants. Features of acceptability include reliability, flexibility, portability, size, bulk, efficiency, maintenance and costs. Unfortunately, the world reservoir of fossil fuel will not be forever. It was reported that it will be exhausted around 2020(1). With the harmful effect to our ecosystem, coupled with the persistent energy crisis, it is necessary to look for alternatives like solar energy in this part of the world. Solar energy is renewable, pollution free, communitarian, conservable, decentralizable, adaptable and save. Fortunately, over 99.99% of the world energy sources are derived from the sun.

1.2 SOLAR ENERGY UTILIZATION

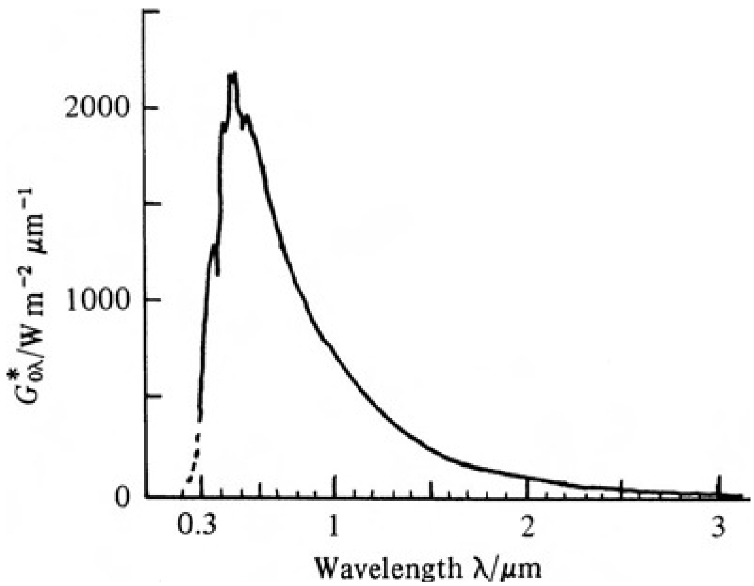

Figure 1. Extraterrestrial Solar Spectral Irradiance at sun-earth distance of one astronomical unit NASA/ASTM Curve. Solar constant=1353Mm^{-2}

Solar radiation reaches the earth's surface as short wave electromagnetic radiation in the wave length band between 0.3 and 3.0µm, its peak spectral sensitivity occurs at 0.48µm (figure 1). Total solar-radiation intensity varies from zero at sun rise and sun set to a maximum of about 1,070 W/m^2 at noon. This endless source of energy though it varies in magnitude and directly can be used in three major processes:

(1) **Heliothermal:** This involves the absorption and conversion of solar radiation into heat which can then be used for many applications. This is the process in which this paper is concerned.

(2) **Heliochemical:** In which the shorter wavelength can cause chemical reaction, sustain growth of plants and animal, converts carbondioxide to oxygen by photosynthesis and cause degradation and fading of fabrics, plastics and paints.

(3) **Helioelectrical:** In which part of the energy between 0.33 and 1.30µm can be converted directly into electricity by photovoltaic cells.

The development of solar energy devices to meet the domestic and industrial needs of man is no longer news. Major advancements are being reported all over the world even in regions considered unfavourable to solar radiation.

In this part of the world, we have enough insolation to justify the use of solar energy as a relatively cheap source of energy. On radiation climate (2-3), Nigeria falls into three major regions:

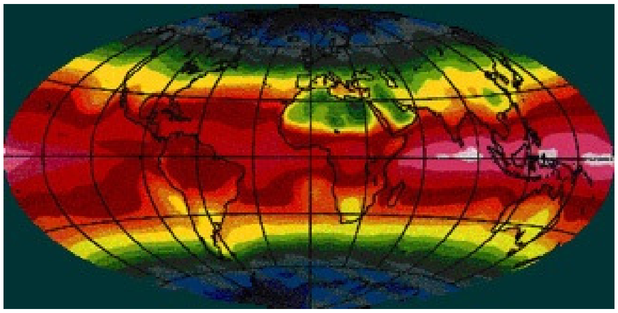

Figure 2 World annual average net radiation

(1) Very high radiation input, 18-17 Kly/month
(2) High radiation input, 16-14 Kly/month
(3) Upper medium radiation input, 13-12 Kly/month and very low wave fluctuation index (amplitude between the highest and lowest input)

The needs for solar energy may be to pump water for domestic, agriculture or industrial use, it may be for drying, it may be for comfort air conditioning, for water heating, generation of electricity and so on (4). Some of these needs could be met directly or indirectly with the use of solar ponds.

1.3 SELECTED RADIATION DATA

In Nigeria, mean annual values of radiation is between 140 Kcal. /cm^2 in Port Harcourt to 160 Kcal. /cm^2 in Kano.

Table 1: PERCENTAGE OF POSSIBLE SUNSHINE

STATION	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Bauchi	78	82	73	61	65	62	48	41	61	75	85	84	68
Benin	49	53	46	48	46	38	26	40	22	40	54	58	43
Enugu	57	61	51	52	52	42	32	27	32	47	60	63	48
Ibadan	56	59	53	49	49	41	24	19	25	45	58	59	45
Ikeja	50	57	53	52	45	32	23	24	25	41	55	56	43
Ilorin	64	67	63	56	55	49	34	29	34	51	64	68	53
Jos	85	83	70	58	54	53	39	33	47	66	84	88	63
Kaduna	78	79	72	66	62	55	39	32	47	68	81	83	63
Kano	77	78	72	68	70	68	59	48	65	80	84	80	71
Lokoja	67	69	62	54	55	47	39	33	41	54	69	70	55
Maiduguri	82	85	77	71	71	69	54	48	60	79	86	84	42
Markurdi	67	71	62	56	57	46	38	31	40	54	61	64	54
Minna	73	74	71	63	62	53	33	31	46	71	79	78	61
Pt. Harcourt	45	51	39	40	40	27	20	20	17	29	39	47	35
Sokoto	79	82	76	69	71	73	58	51	66	83	86	84	73
Yola	79	82	72	63	69	62	51	43	52	73	85	84	68

Source: World Survey of Climatology (5)

2.0 NON-CONVECTIVE SOLAR POND

A non-convective solar pond is a man-made black bottom pond or lake usually between 1m and 2m deep in which convection is discouraged with the use of saline water having increased concentration with depth. The saline water may be produced from Magnesium Chloride ($MgCl_2$), Sodium Chloride (NaCl), Sodium Sulphate (Na_2SO_4), Ammonium salts et cetera, inhibits free convection and through the solar radiation incident on the pond, a temperature gradient results with the bottom warmer (up to boiling point) than the top.

However, there are some natural lakes with this characteristic (6).

2.1 WHY SOLAR POND

A lot of solar collector devices are now known. However, none has succeeded in overcoming the periodicity problem of solar energy as solar pond. Solar pond is capable of storing energy for use in the black month (1-4 months depending on the Latitude) during the peak season in higher latitude (7). This is particularly useful in the northern part of Nigeria with extreme temperatures during the harmattan season. Energy stored in the afternoon can be used at night and the following morning.

Apart from the storage capacity, it has helped to overcome the limitation of other collectors to harness sufficient solar energy that can be used for power production (8), process heat (9), space heating (10), and desalination (11).

Here at home, it could be used to generate electricity to remote area that are yet to be connected to the national grid, process heating for industrial purposes and space heating for both domestic and industrial heating. Yearly occurrence of house burning in an effort to reduce the effect of cold harmattan haze can be reduced in the future. Also, the heat stored during the day can be used to power the generator side of an absorption refrigerator for comfort cooling.

2.2 A GLOBAL TREND

The inexhaustible nature of solar energy, coupled with availability, cheapness, cleanliness, non-destructive nature to the environment and renew fuel crisis of 1973 till date and subsequent concern about the availability of convectional fuel (fossil fuel) brought about a renew appraisal of solar ponds out of all other systems because of its storage capacity and large collector area.

Israel is the pioneer and forerunner of solar pond till date. Much theoretical and laboratory studies started as far back as 1958 and it has been established that pond operating temperature of 90^0C is feasible. Solar ponds had been successfully used to produce salt (12) and generation of electrical and mechanical power. Solar Pond Power Station (SPPS) at Et' Haaravah, Israel with a depth of 2.5m and area of $250,000m^2$ supplies 5.0MW of electricity for 3 hr/day in mid winter and 14 hr/day in mid summer(7).

Work began on solar pond in 1964 in Australia (13) and a temperature of about 63^0C was reported by at the bottom. Solar pond studies started in 1974 at U.S.A. and a temperature in excess of 100^0C was obtained in a location at New Mexico (14). Even in temperate region, where the insolation is generally low, solar pond had been proved to be a viable option for space heating in Spain (15) and London (16), former U.S.S.R., Chile, Argentina, India and Zambia also reported some advancement on solar ponds.

2.3 TECHNOLOGY OF SOLAR PONDS

2.3.1. LINING MATERIALS

The pond is lined at the bottom and sides with suitable material that must be impervious to the salt solution in the pond and ground water around the pond and secondly, be 'impervious' to the heat developed in the pond due to solar radiation. The ability to resist ultraviolet degradation and minimum mechanical strength is an added advantage. Compacted soil, plastic, elastomer and rivaseal (13), a patent laminated fabric (terylene cloth) impregnated with fibre-glass and coated on either side with bitumen are used today.

2.3.2 FILLING OF THE POND

Two different methods can be used to develop the salt gradient. One approach is to start with the most dense later (saturated brine solution) below and consequently floats denser layer on top up to the lighter layer (fresh water). Another approach is to start with the fresh water and then introduce denser layers at the bottom which will lift the lighter layers previously filled (13).

Atypical application of the first approach consists of partially filling the pond with high salinity brine and pumping of fresh water through a diffuser which is immersed in the upper portion of the existing solution. The diffuser is progressively raised to the surface either in continuous motion or in discreet steps of about 5.0 cm (17). The pond (figure 3) obtained can be categorized into 3 zones. The upper convective zone (UCZ) of low and uniform salt gradient at constant temperature that is very close to the ambient temperature. Convection is due to thermal cycling, wind action and the effect of both the temperature and salt gradient at it lower boundary. Immediately below the UCZ is the nonconvective zone (NCZ) with salt density increasing with depth. It serves as insulator and heat storage zone. It is known to effectively transmit incident solar energy to the storage brine below as its thickness is reduced and at the same time serve better as insulation for the storage brine as thickness increases. However, there is an optimum thickness for which the rate of energy collected is maximized (18). At the bottom of the NCZ is the lower convective zone (LCZ) with constant salt and temperature gradient. This is the heat collector, heat storage and heat removal medium. The bottom boundary is a black body. Figure 3.1 and 3.2 show the density and temperature gradient respectively.

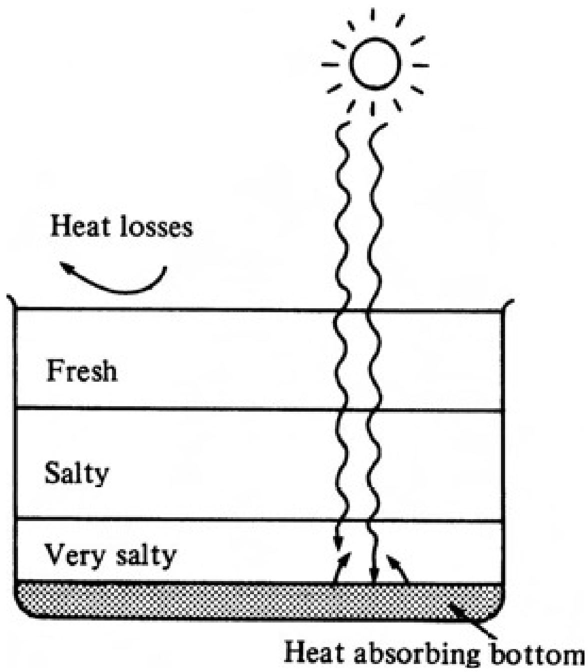

Figure 3. The Solar Pond

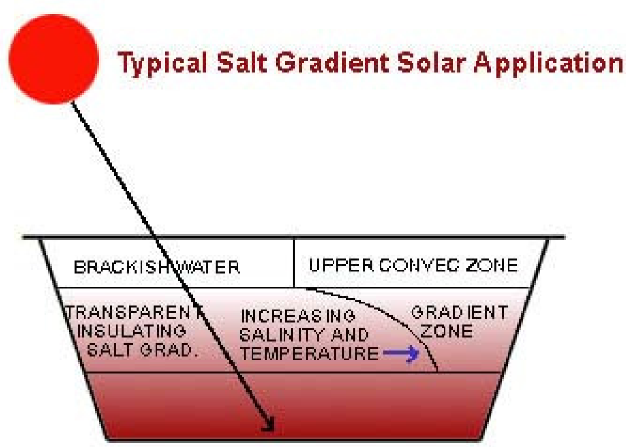

Figure 4. Density and temperature gradient

Due to diffusion (though very small indeed) of salt upwards from the higher to lower concentration, the salt gradient will be affected gradually. The rate of movement of salt flux upwards q_s is given by:

$$q_s = vs - k_s \frac{\partial s}{\partial z}$$

where k_s is the coefficient of salt diffusivity, v is the velocity, s is salt concentration and z is depth. Thus, if water is removed from the bottom of the pond to give v a value

$$v = \frac{1}{s}\left(k_s \frac{\partial s}{\partial z}\right)$$

then $q_s - 0$ and salt remain stationary in space. This is known as 'falling pond' concept (19). A flow system to carefully add salt to the bottom at the top had been developed (20).

Some recent pods used salt (e.g. borax or potassium nitrate) which exhibits a high increase in solubility with increase in temperature. The pond is filled with a saturated solution with left over at the bottom. When the pond is heated up, more salt goes into solution and convection does not occur (6). Even some are with transparent membranes that separate the layers. This pond does not even need salt at all (29).

Generally, inexpensive layer of transparent plastic over the water will suppress heat loss to the environment.

2.3.3 THERMAL ENERGY IN NON-CONVECTIVE SOLAR POND

Solar radiation incident upon a horizontal surface of the earth is a function of latitude, the day of the year, the time of the day and the atmospheric conditions. The energy is received as both direct and diffuse radiation and is distributed over the spectrum in the ultraviolet, visible, and infrared.
Fraction of the radiation reaching the surface of the pond will be reflected and the remainder that penetrate the pond result in thermal energy. This fraction in a day can be calculated from the following equations which are obtained from Fresnel's equation (22):

$$E - 2n(a^2 + b^2) \cos i \cos r$$

$$a = 1/(\cos r + n \cos i)$$

$$b = (\cos i + n \cos r)$$

where E is the ratio of radiation penetrating the water surface and incident upon a horizontal plane just below the surface to the radiation incident upon a horizontal plane above the water surface and incident upon a horizontal plane just below the surface to the radiation incident upon a horizontal plane above the water surface; *i* = the angle made by the incident radiation with the normal (solar zenith distance); n = indexes of refraction of the salt-water solution at the surface (≈1.33 for very dilute solution); and r = the angle made by the refracted ray with the normal.

From Snell's law: $\sin i = n \sin r$

Fraction of diffuse radiation $2\int_0^{\pi} E \cos i \sin i \, \partial i$

The solar zenith distance can be measured or calculated by

$$\cos i = \cos \emptyset \cos \delta \sin 2\pi (t-6)/24 + \sin \emptyset \sin \delta$$

t = time in hours (noon =12)

Ø = declination of the sun ≈

$\delta \sin 2\pi D/365.25$

δ_0 = declination of the sun at equinox

= 23 degree, 27 minutes

D = number of days

From Bonguer's law, transmitted radiation

$$q_\lambda^t = q_\lambda^i e^{-\alpha z}$$

Where q_λ^i is the intensity of the incident radiation of wavelength λ

α_λ is spectral absorption coefficient

z is the thickness of homogeneous absorber.

Therefore, the spectral transmittance (23) is

$$\tau_\lambda = q_\lambda^t / q_\lambda^i = e^{-\alpha_\lambda z}$$

and the spectral absorption coefficient is expressed by

$$\alpha_\lambda = \left(\frac{1}{s}\right) \ln \tau_\lambda$$

The heat transfer processes in the solar pond is governed by one-dimensional time-dependent heat conduction equation

$$\frac{\partial T}{\partial t}\rho c = \frac{\partial (K \frac{\partial T}{\partial z})}{\partial z} + q - q_s$$

in which ρ is the fluid density; c is specific heat of fluid; T is temperature; t is time; z is vertical coordinate; K is coefficient of heat diffusion; q is source of thermal energy and q_s is removal rate of thermal energy. A complete treatment is of course complex because of the large number of variables involved.

According to Hull (24), the thermal efficiency of solar pond is

$$= \alpha\tau = \frac{K\Delta T}{Z_{NCZ} H_s}$$

where ΔT is the temperature difference across the NCZ and H_S is the surface insolation.

3.0 APPLICATIONS

Various methods are employed to extract heat energy from the pond. This may be done by applying heat-exchanger equations:

$$q = m_c C_{pc}(T_{co} - T_{ci}) \quad (1)$$

$$q = m_h C_{ph}(T_{hi} - T_{ho}) \quad (2)$$

$$q = UA\Delta_c T_{LM} \quad (3)$$

subscripts c, h refer to cold and hot fluid,

i, o denote inlet and outlet

Another way is the use of hydrodynamic layer flow principle where by the hot fluid is removed at one end into a heat-exchanger external to the pond and then returns the solution to the other end of the pond.

Some applications of solar ponds are for heating and cooling of buildings, and power production.

Heat energy stored in the pond may be used for space heating during the harmattan season. The heat energy is transferred into Air Handling Unit (AHU) containing heat exchanger coil and fan that blows heated air into the space. This arrangement can be incorporated into office complex and estate in the future. Also, hot water can be extracted from the pond for domestic or industrial needs. A typical application is heating of greenhouse in U.S.A. (25)

Cooling can be achieved by absorption refrigeration system with generator heated with solar pond. The chiller side of the refrigerator will then be part of A.H.U.

With suitable fluid (Freons) and two heat exchangers-one on the upper cold water and one on the lower hot water, it is possible to operate a heat engine for power production (5). This is the most promising application of solar pond especially for small developing countries.

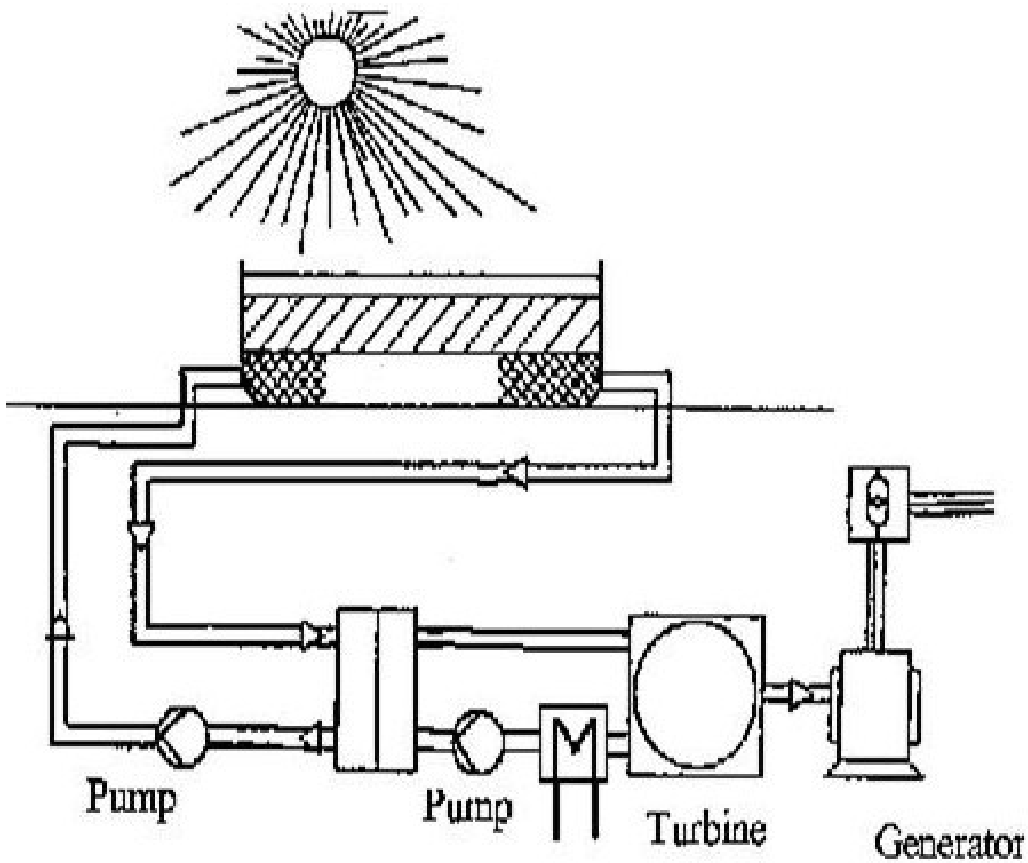

Figure 5. Schematic diagram of Solar Pond for power generation

REFERENCES

1. The illustrated Encyclopaedia of Science and Technology, Volume 7, New Caxton Library Services 1987. Published by Marshall Cavendish Limited, 58 Old Compton Street, London. Pp 903

2. W.H. Terjung, Global Classification of Solar Radiation. Solar Energy, 13, 67-81 (1970)

3. George O.G. Lof, J.A. Duffie, and C.O. Smith, World Distribution Solar Radiation, Solar Energy, 10, 27-37 (1966)

4. R.O. Onyeonwu, Commercialization of Solar Energy devices in developing countries-problems and prospects, Solar Energy, 19, 447-449 (1979)

5. World Survey of Climatology, Vol. 10, Climate of Africa (Edited by J.F. Griffiths). Elsevier Publishing Company, Amsterdam, Pp 185, 1972.

6. H. Tabor, Solar Ponds, Solar Energy, Vol. 27, No 3, Pp 181-195, 1981.

7. Encyclopaedia of Physical Science and Technology, Vol. 18, Pp 365

8. H. Tabor, Solar Ponds, Large-Area Collectors for power production, Solar Energy, Vol. 7, No 4, Pp 189-194, 1963.

9. H. Tabor and R. Matz, A status report on a Solar Pond Project, Solar Energy, Vol. 9, No 177, 1965.

10. A. Rabl and C.E. Nielsen, Solar ponds for space heating, Solar Energy, 17, 1975.

11. H. Tabor, Solar Ponds, Science Journal, 66 (1966)

12. R. Malt, E. Feist and M.R. Bloch, The production of salt by means of a solar pond, Inst. Of Chemical Engineers, London, Chem. Eng., Pp CE 81-87, April 1965.

13. T.R.A. Davey, The Aspendale Solar Pond. Rep. R15, CSIRO, Australia (1968).

14. F. Zangrando and H.D. Bryant, Solar ponds for residential heating, New Mexico Energy Resources Board, Grant ERB 161, 1976.

15. M.G. Velarde, J.A. Artiz-Cohen and M. Yustes, A solar pond for central Spain, Solar Energy, 34, 2, Pp 179-180, 1985.

16. H.C. Bryant and I. Colbeck, A Solar pond for London, S.E., 19, 321, 1977.

17. F. Zangrando, A simple method to establish salt gradient. Solar ponds, Solar Energy, Vol. 25, No 5, pp. 467-470, 1980.

18. J. Clair Batty, J. Paul Riley and Nitin K. Bhises, Optimum Thickness of the Non-convective zone in salt gradient solar ponds, S.E., 36, 1, 15 (1986)

19. Y.F. Wang and A. Akbarzadeh, A further study on the theory of a falling ponds, Solar Energy, Vol. 29, No 6, 557 (1982)

20. C.E. Niesen, A. Rabl, J. Watson and P.Weiler, Flow system for maintenance of salt concentration gradient in solar ponds. Test in isothermal pond, Solar Energy, Vol. 19, No 6, 763 (1977)

21. John R. Hull, Membrane stratified solar ponds, S.E., Vol. 25, No 4, 317 (1980)

22. H. Weinberger, Physics of the Solar Pond, S.E., Vol, No 6, 45 (1964)

23. S.B. Savage, Chapter on solar pond, Solar Energy Engineering (Edited by A.A.M. Sayigh). Academic Press, Inc. New York (1977)

24. John R. Hull, Calculation of Solar Pond Thermal Efficiency with diffusely reflecting bottom. S.E., Vol. 27, No 5, Pp 385-389, 1982.

25. Syed A. Shah, Ted H. Short and R. Peter Fynn, A Solar Pond-assisted heat pump for greenhouses. Solar Energy, Vol. 26, No 6, Pp 491-496, 1981.

Non-Convective Solar Pond as a Thermal Energy Source

~ 7f6a0279d53f23abed91425a67a0ae82.200x200 Non-convective solar pond is a potential large surface area solar collector device. It has additional advantage of long term storage capacity. It is a shallow body of water of about a meter deep containing dissolved salts to generate a stable density gradient (fresh water on top and denser salt at the bottom). Part of the incident solar radiation entering the pond is absorbed leading to...

Published at International Conference/ Workshop on Renewable Energy and Climate Change Mitigation, Covenant University, Ota, Nigeria, July 13-17, 2009.

Published in 2009

Download 272.32 kB

visit (http://www.scribd.com/doc/39657995/Solar-Pond-Scribd)

Babalola P.O.

BABALOLA Philip Olufemi » Dr. (Engr.) Babalola is a proven consulting engineer and have succeeded in turning many engineering ideas into reality all over the country, from design stage all through to project completion. He is teaching metallurgy, advanced engineering materials, internal combustion engines, fluid power systems, heat transfer, engineering law, engineering management, engineering entrepreneurship and... view full profile