A STUDY OF SOLAR RADIATION, STORAGE AND APPLICATIONS IN NIGERIA

Osadolor Orlando Odia
Mechanical Engineering Department,
Faculty of Engineering and Technology,
Ambrose Alli University, Ekpoma, Nigeria
Email: odiaoo@hotmail.com

ABSTRACT

The paper investigates the availability of solar energy in Auchi, a town in Nigeria located between longitude 6°15' East of the GM line and latitude 7°02' North of the Equator using photovoltaic solar cells and arrays of thermal solar collectors. The study proved that energy in excess of 64,202W/m^2 is available for use. The study further shows that solar energy could be stored in form of heat energy for over 12 hours using a bed of pebbles while temperature as high as 126°C were recorded with thermal collectors without concentration. Also, 64ml of steam was condensed from a 180mm x 130mm solar collector steam generator.

Keywords: Solar energy, photovoltaic cells, thermal collectors, pebbles, temperature, steam

INTRODUCTION

The use of fossil fuels has been blamed for global warming, as when coal, gas and oil are burnt, they release harmful gases, which trap heat in the atmosphere and cause global warming. Consequently, efforts to control CO_2 emissions should be directed at cutting the demand for fossil fuels as its increasing use will result in the increased concentration of CO_2 and other greenhouse gases, GHGs, in the atmosphere as released by burning fossil fuels. Though it is scientifically difficult to predict the relationship between global temperature variation and GHGs concentrations, reducing the dependence on fossil fuels, will not only protect our environment but will also prolong the life span of these wonderful natural resources while encouraging and promoting the development and penetration of renewable energy sources to accelerate the shift towards sustainable consumption and production. However, renewable energy already contributes as much as 20% to the global energy demand [1-4] and over two-thirds of this comes from biomass, mostly in developing countries. Whereas existing renewable energy technologies (RET) could play a significant mitigating role in the present world energy cum environmental crisis, the economic and political climate will have to change for more meaningful contribution.

The application of heat energy to cooking and domestic heating dates back to the creation of man. Wood was the first major source of energy and remained so way into the eighteenth century. The discovery and application of coal very rapidly replaced wood in domestic appliances, that is, cooking and heating, in mostly the present developed countries. Presently, gas dominates domestic cooking and heating in these same countries. In African and most Asian countries, wood fuels has been, is and will continue to play a significant role in meeting the energy demand for cooking, water and space heating[4-6]. Wood fuels consumption remains a principal contributor to the rate of wood removal in Africa as it is estimated that over 92% of the total wood harvested in Africa goes for energy purposes. Despite the new developments in the breeding of wood, the rate of consumption of wood for energy purpose still constitutes a challenge to tropical forests that are now becoming denuded of trees[5-8].

The design, location, construction and operation of most engineering facilities have been markedly affected by the concern for the environment. This is of particular concern to the energy industries as most forms of energy production and use are potentially damaging to the environment[9, 10].

Solar energy has been a dependable source of energy and today more than 90% of rural dwellers of the technologically developing countries still rely on the sun as a source of energy for: Drying foodstuff – rice, maize and millet, (ii) Processing of hides and skin, (iii) Drying and processing of medicinal leaves and roots, (iv) Warming of bathing water, (v) Space heating and warming, etc[11,12]. Solar powered appliances with improved efficiency are also now being designed and used in the form of solar water heater, solar dryer and solar cooker, etc. Homes are also now being designed to benefit maximally from solar energy and equipped with solar panels. Its application to modern equipment demanding high energy concentration is also being considered under solar cars, airplane and space craft[13-18]. The utilisation of solar energy depends on the availability of sunshine. It is estimated that the areas lying between latitudes 35°N and 35°S of the equator enjoys at least 3000 bright sunshine hours annually[13] and that most parts of Nigeria enjoy sunshine in excess of 10 hours on a really good day in the dry season. It is, however, gladdening to know that some giant strides have been taken in the development/utilisation of solar energy. For example, in the areas of direct conversion to electricity, water heating and drying, solar energy has been well developed and works are still being done in these areas[5,9,17]. The major setback of solar energy as a source power is its incessant availability. An adequate storage facility is, therefore, necessary for a solar powered system to function appropriately. A number of materials will work as storage media in many solar heating systems; but three are generally more efficient and reliable. These are the materials that most consistently meet the criteria for solar storage and deliver heat to it application points at a desirable temperature cheaply. There is no best heat storage material, but rather each has a characteristic that makes it the most desirable[9,12]. The solar collector is the most essential component of most solar energy-powered equipment. The efficiency at which each collector converts solar energy into other forms of energy and the energy into which the solar energy is desired to be converted, which depends on the intended application determines the type of collector that should be used.

OBJECTIVE

This study is directed at improving the designs that can assist in the building of solar collectors that may be applicable to drying, warming and homes and small industrial equipment. It will also provide information by providing accurate data for designs. Auchi, the study centre, is located on longitude $6^{o}15'$ East of the Greenwich Meridian (GM) line and latitude $7^{o}2'$ North of the Equator. A little inter and/or extrapolation of the results of this study will make it fit for designs in the aforementioned zone. The study will also attempt to provide insights into the design and construction demands of the systems.

METHODOLOGY

The apparatus for the photovoltaic system consists of modules of photovoltaic solar cells arranged in a panel. 36 photovoltaic cells each of 55mm diameter and power of 0.3W are arranged in 6 modules and used to give a total cell area of $0.109m^2$. The control panel provides means for measuring the power available through recording the current and voltage displayed or by applying some electrical resistance to the energy. The apparatus includes an accumulator (wet cell). The energy stored in the accumulator was used to run an electric motor loaded by applying some known dead weights, which provides some measurable torque at some speed. For the thermal solar systems, eleven thermal solar collectors were designed and constructed for the purpose of this experiment. Two were simple plain collectors with one painted black. Eight other collectors were constructed with matrix of different sizes of pebbles:- two have matrixes of 25cm diameter pebbles- one painted black and the other plain. Similarly, 50cm, 75cm and 100cm diameter pebbles were used to build two collectors each- one plain while the other painted black. These collectors were used to determine the solar energy storage ability and capacity of pebbles and the effect of size on their storage performance. The eleventh collector was designed as a heat exchanger using solar radiation to increase the temperature and consequently the internal energy of water. A single copper tube is coiled several times inside the collector box so that water passing through gets heated gradually until it attains boiling point before entering the steam chamber. Aluminium fins are attached to the tubes to enhance its thermal performance. Also, to improve radiation heat transfer, the surface on which the pipes are laid, the pipes and fins are all painted black. This surface is laid on a woollen insulation and held on a wooden background. All sides of the box containing the pipes are surrounded by plywood. Covering the top with two layers of glass completes the collector.

With these types of collector, the useful energy q_u delivered to the working fluid can be estimated as:

$$q_u = mC_p(T_{fout} - T_{fin}) \quad (1)$$

Where: m = mass flow rate through collector, C_p = specified heat at constant pressure of water

The energy balance can then be assessed by considering.

$$I_cA_c\,\tau_s\alpha_{sc} = q_u + q_{loss} + de_c/dt \quad (2)$$

Where: I_c = solar irradiation of collector surfaces, A_c = collectors surface area, τ_s = effective solar transmittance of collector covers, α_{sc} = solar absorption of the collector surface, q_u = useful energy gained by collector, q_{loss} = rate of heat loss to surrounding, de_c/dt = raet of internal energy storage in the collector

The instantaneous efficiency of the collector

$$\eta c = qc/AcIc \quad (3)$$

Can be achieved by taking the average efficiency η_{css} given in equation 4.

$$\eta_{css} = \int_o q_u dt / \int_o A_c I_c dt \quad (4)$$

Over the period of one month. Thus the rate of heat transfer to the working fluid Q (x, y) can be expressed as:

$$Q(x, y) = U_c[T_c(x, y) - T_a]\, dxdy \quad (5)$$

Where: U_c = overall unit conductance between plate and ambient air, T_c = local collector plate temperature, T_a = ambient air temperature. With aluminium plate of uniform thickness, t, the above equation can be modified to:

$$d^2T_c/dy^2 = U_cT_c/Kt - (T_a + SI_s)/U_c \quad (6)$$

The boundary conditions will demand that at the centre between any two ducts, y = 0 and dt/dy = 0.

At the duct, the plate temperature is $T_c = T_b\,(x_o)$ where $T_b[x_o]$ is temperature at the fin base.

Putting $m^2 = U_c/Kt$ and $\phi = T_c - (AT + \alpha_sI_s/U_c)$

Then, $d^2\phi/dy^2 = m\phi$ (7)

for which $d\phi = 0$ at $y = 0$ and a solution will yield $\Phi = c_1 \sinh my + c_2 \cosh my$ (8)

Applying the boundary conditions, solving and arranging:

$$q_{total}(x) = 2\omega\eta_f = [\alpha_sI_s - U_c(T_b(x_o) - T_a)] \quad (9)$$

By including the energy impinging on the duct directly, the total heat transfer to the water is:

$$q_u(x) = (IID)h_c[T_b(x_o) - t_f(x_o)] \quad (10)$$

Mass flow through the collector can be determined with the collector efficiency taken as:

$$\eta_c = q_u/A_cH_t \quad (11)$$

Where: H_t = total radiation on a tilted surface

Now,

$$H_t=[H_bR_b+H_d(1+\cos S)+(H_d+H_b)(1+\cos S)PL/2] \quad (12)$$

Hence,

$$q_u=\eta_cA_c[H_bR_bH_d(1+\cos S)+(H_d+H_b)(1+\cos S)PL/2] \quad (13)$$

Tables for collector efficiencies at various inlet temperatures are available [3]. The mass flow rate, G, can now be extracted from:

$$GC_p/U_1 = F_1 \quad (14)$$

Where F1 is the flow factor, which can also be obtained from tables [3]. Hence, $G = U_1F_1/C_p$, U_1 being the overall heat loss coefficient. Thus,

$$G\ \alpha\ U_1F_1 \quad (15)$$

The performance of the solar collector can be described by an energy balance equation that indicates the distribution of incident solar energy into useful energy gain and various losses.

That is:

$$q = A_c\,\{HR_b\,\gamma\alpha\} + \{HR_b\gamma\alpha\} = q_u + q_r + q_s \quad (16)$$

For the solar collector unit, the efficiencies are obtained as follows:

$$\eta_H = \frac{Q_u / A_c x100}{H} \quad (17)$$

$$\eta_D = \frac{\Sigma Q_u / A_c x100}{\Sigma H} \quad (18)$$

Total heat loss per unit area is the sum of heat loss from the top, bottom and sides of the collector, thus;

$$q_l = q_t + q_b + q_s \quad (19)$$

Where q_t, q_b and q_s are loss form top, bottom and side respectively. This expression can be put in terms of overall heat loss coefficient U as:

$Q_1 = U_1 (t_p - t_a)$ (20)

t_p = plate temperature, t_a = ambient temperature.

The overall heat coefficient U is given as:

$$U_1 = \frac{k}{x} + \left[\frac{Nc}{\frac{344}{Tp}\left(\frac{(Tp-Ta)}{Nc+F}\right)^{0.31}} + \frac{1}{hw} \right]^{-1} + \frac{\eta(Tp+Ta)\left(Tp^2+Ta^2\right)}{\Sigma p + 0.425Nc(1-\Sigma p) + \frac{(2Nc+f-1)-Nc}{\Sigma p}}$$

Where:

$F = (1.0 - 0.04hw + 5.0x10^{-4}h^2w)(1+0.558Nc)$

Nc = Number of glass cover, k= thermal conductivity

x = insulator thickness, Tp = absorber plate temperature

Ta = ambient temperature

RESULTS AND DISCUSSIONS

The measurements usually commenced by 6.30am and concluded by 6pm daily. Therefore, initially the current was very low but rose steadily as the sun rises. By adjusting the reception and incident angles, readings were taken at intervals of half an hour. The measurements were taken for one full year beginning from January 3rd 2009, to cover the two seasons in Nigeria (wet and dry seasons). Whereas solar energy is evidently more intensive during the dry season, the agricultural products that needed to be dried are harvested during the wet season. Thus, while the industrialists will maximise their solar powered equipment during the dry season, the agriculturists will need their equipment during the wet season. The results show that the available energy grows rapidly from 10am (Nigerian time) and reaches its peak at about 12 noon. It remains there through to 3pm and thereafter starts decaying and dies out at about 7pm. This is depicted in Fig. 1. It was observed that "tracking" actually enhances the intensity of the energy by up to 30% between 7am and 11am, and between 3pm and 7pm, between 11am and 3pm, tracking is of very little importance. The results show that there are very little or no variations in the daily intensity whereas a marked variation is recorded with a change in season. For example, from Fig. 1, the energy available for a day in February manifests marked variation in availability and regularity as distinct from energy availability for June with an evident difference in regularity and availability. The almost perfect dome shape of November and December availability, are examples of cloudless days.

Auchi town in Edo State, which was used for the investigation, does not represent the highest point of concentration of solar energy in Nigeria; as the northern part of the country presents a clearer sky, longer dry season and less interrupted environment. Solar energy can, therefore, be harnessed and utilised in Nigeria to benefit particularly the rural dwellers. For example, from the data collected on February, the energy available per square metre at 12 noon was 10.5/0.101 = 96.33W/m^2. However, the efficiency at which the photovoltaic solar cell converts photon into electricity is about 15%(6 – 16), hence, the energy in the photons reaching Auchi in Nigeria located in longitude 6^{o}15' East of the GM line and 7^{o}02' North of the equator at the particular cloudless time amounted to 98.33/0.15 = 655.53W/m^2. The solar constant has been predicted to be about 1,353W/m^2(6) and bringing into consideration the effect of the solar reflectance which varies from 0.1 for dark earth through 0.2 for concrete, 0.3 for lawn, 0.4 for sand to about 0.7 for snows or ice(2,6,13). The result is satisfactory as it yields a solar reflectance of 0.475 for the location which is actually a natural mixture of sand, gravel and lawn.

Figs. 2 and 3 depict the behaviour of the thermal collectors. It can be noticed that the plain, unpainted plate collector was able to raise the temperature to over 110^{o}C. Fig. 2 shows that the temperature, T_C, of the flat plate collector rose quickly and also quickly clash to ambient conditions. The temperatures of the pebble bed systems rose gradually and reach their peak at about 1500GMT. The Figure 3 shows that the collector with the 25mm diameter pebbles exhibited a lot of instability, getting to the peak but looses heat faster than the 50mm, 75mm and 100mm diameter pebbles. The 100mm diameter pebbles showed better stability and greater heat storage capacity. For the painted pebbles as shown in Fig. 3, the 75mm diameter pebbles proved to be better than even the 100mm diameter pebble as it exhibited better stability. The plain painted collector shows how much heat can be made available from solar energy in the tropics as the temperature rose to as much as 126^{o}C. The eleventh thermal solar collector actually generated steam. The steam generated from this equipment can be used for different purposes such as water distillation, steam jet refrigeration, rice parboiling or other similar industrial processes. The steam generated was condensed and measured; and the experiment showed the 180mm x 130mm collector generating as much as 64ml of condensed steam.

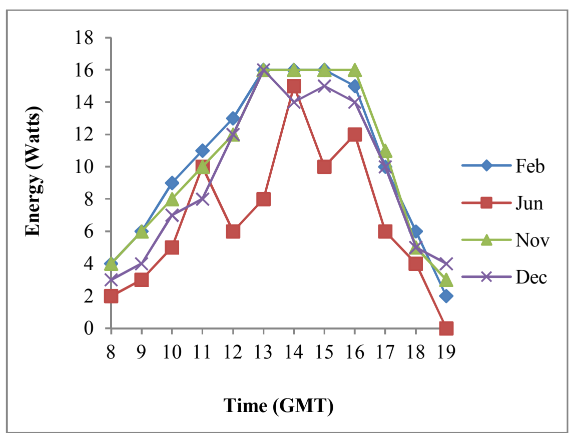

Fig. 1: Energy – Time Graph for Photovoltaic Panel

that tracking does not significantly affect the intensity of the energy.

Solar energy is one of the renewable sources of energy. Though efficient harvesting is still a problem, the greatest limitation of solar energy application is its incessant availability necessitating extensive storage facilities. This work has further proved that pebbles could provide reasonable storage capacity for a fairly reasonable period of time, as it was able to store solar energy at over 80^0C for about 12 hours. The pebble bed storage facility is, therefore, good as a house warming device.

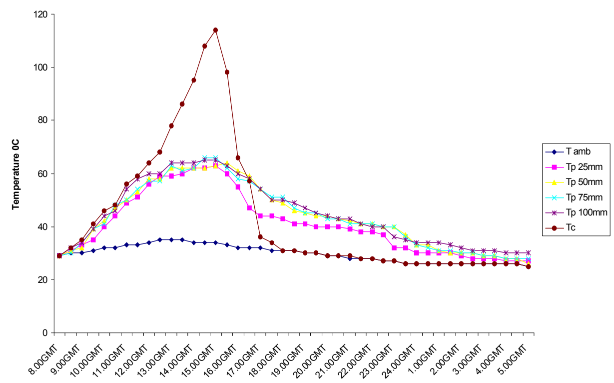

Fig. 2: Temperature-Time Graph for Unpainted Pebbles

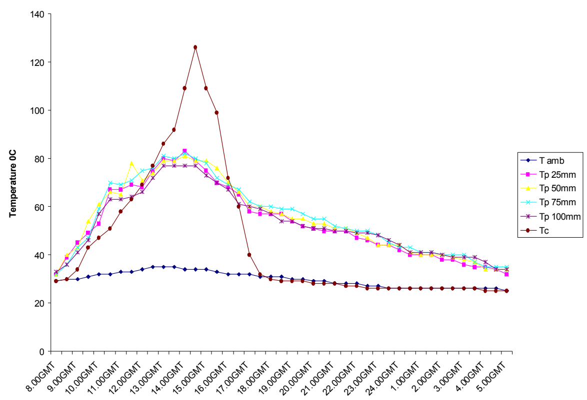

Fig. 3: Temperature-Time Graph for Painted Pebbles

CONCLUSION

The availability of solar energy in Nigeria and other countries living within the same geographical zone, particularly African countries is tremendous. However, the larger part of it pours to waste daily. Attempts at harvesting and utilising this noble source of energy for different domestic and industrial activity will be a worthy appropriate technology for African countries. Water distillation, Steam Jet Refrigeration and rice parboiling among others are areas were solar energy can be profitably utilised in Africa. Further; the experiments have shown that:

a. The energy available in the wet season is enough to effect the drying of grains and to carryout some domestic and industrial activities.
b. Machines can be designed to use solar energy to advantage in Nigeria, e.g. solar dryers, for agricultural produce, solar cookers, solar air conditioners, etc, using information provided in this work.
c. Solar energy availability in Nigeria could have intensity as high as 64,202W/m^2 during the dry season.
d. Tracking is necessary in the mornings and in the evenings, however,
e. Between 11am and 3pm (Nigerian time), the rays from the sun are approximately vertically downwards so

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