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PREDICTION OF OPTIMUM TILT ANGLE OF FLAT-PLATE SOLAR COLLECTOR IN ABIA STATE NIGERIA

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ABSTRACT: Most solar collectors in Nigeria are mounted without consideration of optimum tilt angle for maximum solar radiation. To address the gap, a flat plate surface solar collector of area 0.15 m2, hinged on horizontal support for quick adjustment of inclination between 0 to 90o was fabricated marked out at 1o intervals on a telescopic leg graduated in degrees. Measurement of the solar radiation at varying degrees of inclination was taken between 12:00 noon and 2.00 pm for 4 days at clear sky hours, within the week of nth day of the year. The measurements were taken for each month of the year at Michael Okpara University of Agriculture, Umudike. Umuahia, Abia State, Nigeria, at each degree of inclination. The result showed that the optimum angle of inclination of a flat plate for maximum collection of solar radiation intensities for January to December were 9.5, 9.1, 3.0, 6.4, 9.9, 11.8, 9.0, 7.3, 3.1, 7.0, 10.2, and 11.8o respectively. The study also revealed that the average angle of inclination at which a flat surface solar collector can be mounted at a fixed position in Umudike is 8.14o. The analysis indicated that solar energy gain of 123,314.79 MJm-2, 39,041.24 MJm-2, and 25,610.84 MJm-2 for horizontal, Latitude angle of location and calculated fixed angle of inclination of the solar collector respectively. Comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface for trapping maximum solar radiation intensity indicated a high correlation (R^2) of 0.97.

Keywords: Solar energy, solar collector, optimum tilt angle, renewable energy, solar radiation intensity

1. INTRODUCTION

Solar radiation that floods the earth's surface on daily basis is renewable energy which can be harnessed into three primary uses by heliochemical, helioelectrical and heliothermal processes. On the earth, surface solar radiation is only effectively available in the day and mostly in the hours of clear sky weather. Nielsen (2005) stated that the sun releases 7,000 times more energy to the earth's surface than the current global energy consumption. He asserted that the energy intercepted by the earth over a period of one year is equal to the energy emitted by the sun in just 14 milliseconds and the solar energy reaching the earth surface is estimated at 3.2 million Exajoule (EJ) per year. Approximately 30% of solar energy received on the atmosphere is reflected in the space, while the rest is absolved by cloud, ocean, and land masses (Milburn, 2015). Nigeria lies within a high sunshine belt of the world, receiving between 3.5 and 7 kW/m^2/day from the coastal Latitude to the far North. Iwe (1998), Kaul and Egbo (1985) and Eke (2003) stated that solar radiation floods northern Nigeria all the year round at about 490 to 522.2 W/m^2.Chiemeka (2008) obtained the mean global solar radiation of Uturu, Abia State, Nigeria as 1.89± 0.82 kWh per day Global solar radiation within the region of Michael Okpara University of Agriculture, Umudike was found to be within the range of 1.99kWh to 6.75kWh (Nwokocha et al., 2009). Oko and Nnamchi (2012) applied calculation method using Micrsoft Excel to work on optimum collector tilt angle for Latitudes (4.86 to 13.02 ^{o}N. Fagbenle (2004) proposed that for Latitudes below 8.5 ^{o}N, the optimum tilt angle should be the Latitude plus 10^{o}. This radiation provides enough free solar energy source that can be harnessed by hilothermal process to raise the ambient temperature to a sufficient level that can efficiently dry sliced okra.

Bena and Fuller (2002), Sharma et al. (2009), Iloeje (1993) and Diemnodeke and Momoh (2011) indicated that solar energy trapped by solar dryers is now commonly used globally in drying and preservation of agricultural products. The uses of helio-electrical devices, which trap solar radiation on horizontal plane, are increasing world-wide. Houda and Khalid (2013) and Maduekwe (1995) reported various works done on solar energy-electrical devices. Since solar radiation is not always available at the desired quantity and time, the challenge is how to maximize available solar energy. It is an established fact that the solar radiation intensity falling on a horizontal flat surface, at a given time and location, increases with the increase in surface tilt angle at a solar hemispherical inclination (Artlet et al., 1999). This principle was applied by the following researchers to identify the optimum angle for maximum solar energy collection of the given locations (Chau,1982; Dang and Sharma, 1983; Morcos, 1994; Koray, 2006; Huseyin and Arif, 2007; Hamid et al., 2010). However, the dryers were not positioned at optimum tilt angle for maximum collection of solar radiation because such angles for Abia State had not been determined. The aim of this work was to predict the optimum angle of inclination for maximum collection of solar radiation using a flat plate collector for each month of the year in Umudike, Umuahia, Abia State, Nigeria. The optimum tilt angle was recommended for solar drying experiments within the locality. Before the study, most researchers base their collector tilt angle on assumptions.

2 METHODOLOGY

Theoretical approach and direct measurement method were employed in this work for identification of the optimum solar collector angle of inclination for collection of maximum solar energy at a given location.

2.1 Theoretical Framework

The total solar radiation that floods the space reaches the earth's atmosphere at a solar constant of 1367 W/m^2 (Collins, 2003). Solar radiation from the solar constant is received on a tilted solar collector surface as direct and diffuse solar radiation. The diffuse radiation is a component of diffuse radiation from the sky and the diffuse radiation reflected from the ground. From research, it is established that the solar energy trapped on a flat plate solar collector increases to a maximum point at the optimum inclination of the collector. (Tian, 2008) stated that the global radiation (I_t) incident on a south-facing collector tilted at an angle β to the horizontal surface can be calculated as given in equation 1.

$$I_t = I_{cb} R_b + I_{cd} \left(\frac{1+\cos\beta}{2}\right) + I_c \rho \left(\frac{1+\cos\beta}{2}\right) \quad (1)$$

Where：

I_t is total solar energy radiation incident on the top cover of a thermal solar collector truly facing south.W/m^2

$I_{cb}$is direct solar radiation component on a horizontal surface, W/m^2

$R_b$is Radiation tilt factor, dimensionless

I_{cd} is Diffused solar radiation on a horizontal surface, W/m^2

β is thermal solar collector tilt angle from the horizontal plane, degree

I_c is Total solar radiation on horizontal surface, W/m^2

ρ is diffused reflectance of the ground or surrounding, Dimensionless. Tian (2008) assumed ρ to be 0.2.

$$I_c = I_{cb} + I_{cd} \quad (2)$$

$$I_{cb} = I_o \tau_b \cos\theta_z \quad (3)$$

, I_o is beam radiation at clear sky on the horizontal surface of the earth (W/m^2). $\tau_b$is the atmospheric beam radiation transmittance (dimensionless), Θ_z is zenith angle (degree).

$$I_o = \int S_c \left(1 + 0.033\cos\left(\frac{2\pi dn}{365.25}\right)\right) dt \quad (4)$$

Where; S_c is solar constant (1367 W/m2), dn is the day counted from January first throughout the year (1-365), t is duration of sky clarity (s).

$$\tau_b = a_o + a_1 \exp\left(\frac{-k}{\cos\theta_z}\right) \quad (5)$$

The constants $a_o = r_o a$, $a_1 = r_1 ά_1$ and $k = r_k Ḱ$ for the standard atmosphere with 23 km visibility are calculated from the following relationship assuming that the observation altitude is less than 2.5 km:

a= 0.4237-0.00821(6.0- H)^2 (6)

$ά_1$= 0.5055+ 0.00595 (6.5- H)^2 (7)

Ḱ = 0.2711 + 0.01858 (2.5 – H)^2 (8)

Where, H is the altitude of location in kilometers. The correction parameters r_o, $r_1$and r_k are related to climate conditions, and for the tropical conditions are given as 0.95, 0.98 and 1.02 for r_o, r_1 and r_k respectively.

$$\theta_z = \cos^{-1}(\sin L \sin\delta + \cos L \cos\delta \cosh) \quad (9)$$

L is local latitude (degree), δ is declination angle of the sun at a given location (degree), h is the hour angle in the local solar time (degree).

$$R_b = \frac{\sin\theta_z \cos\theta_a \sin\beta + \cos\theta_z \cos\beta}{\sin\delta \sin L + \cos\delta \cos L \cos\omega} \quad (10)$$

$R_b$is the geometric factor (the ratio of beam radiation on the tilted surface to that on a horizontal surface), Θ_a is the solar azimuth angle (degree), ω is the solar hour angle (15 degrees per hour, zero at solar noon, morning negative, afternoon positive).

$$\theta_a = \cos^{-1}\left[\left(\frac{\sin\delta - \sin S_E \sin L}{\cos S_E \cos L}\right)\right] \quad (11)$$

S_E is the solar elevation angle

$$S_E = \cosh\cos\delta\cos L + \sin\delta\sin L \quad (12)$$

$$\delta = \sin^{-1}\left[\sin(23.45)\sin\left(\frac{360}{365}\right)(n-81)\right] \quad (13)$$

$$I_{cd} = I_o \tau_d \cos\theta_z \quad (14)$$

$$\tau_d = 0.2710 - 0.2939\tau_b \quad (15)$$

Where τ_d is the atmosphere transmittance of diffusion radiation.

2.2 Direct Measurement

A flat plate surface solar collector of dimension 0.5 m by 0.3m, hinged on a horizontal support was fabricated. The hinge gave the flat plate surface a freedom of adjustment of angle of inclination from 0 to 90 ^{o}, marked at the intervals of 1^o. The adjustment of 1^o increment was accomplished within the intervals of one second within which the solar radiation intensity had not changed. The adjustment for varying the angle of inclination was done manually. This was achieved by constructing telescopic support which enhanced quick and easy adjustment of the flat plate surface at the interval of 1^o. Following the assertion by Duffie and Beckman (2013), 90^o was chosen as the upper limit of inclination for this work. Provision for fixing solar radiation intensity measuring equipment was made on the surface of the flat plate in such a way that the total solar energy falling on the flat plate at the varying angle of inclination was captured. The system was mounted to slope towards south as recommended by (Farzad, 2013).
Measurements were taken between 12:00 noon and 2:30 pm for 4 days at clear sky hours within the week of n^{th} day of the year for each month of the year. At each degree of inclination, the solar radiation intensity was replicated three times and the average value was taken. The n^{th} day of the year is specified by (Arinze, 1981, MEC, 2013). The experiment was conducted in the Department of Agricultural and Bioresources Engineering, College of Engineering and Engineering Technology, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria. Geographically situated at latitude 05^{o}29 $^/$N, longitude 07^{o}33$^/$ E and altitude of 122m above sea level (Akanno and Ibe, 2005)

The flat plate surface solar collectors on horizontal and inclined positions are presented in Figures 1 and 2, respectively.

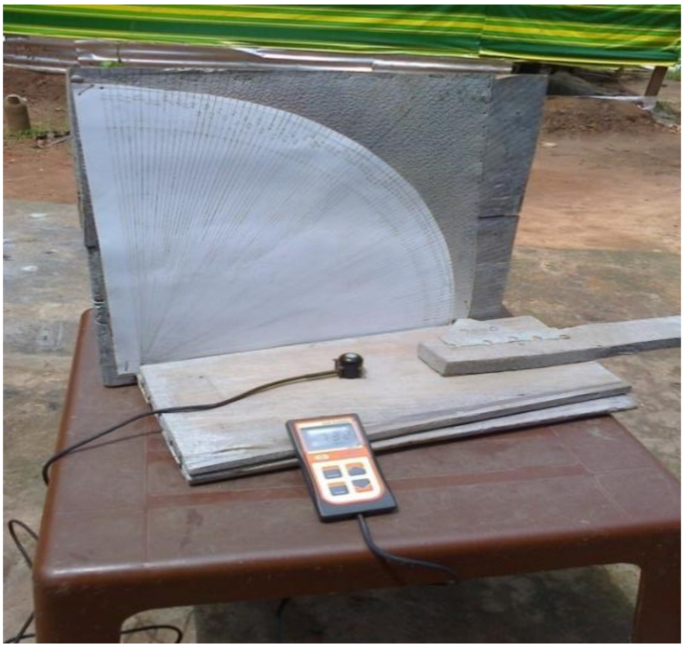

Figure 1. Flat plate surface solar collector with solar radiometer on horizontal position.

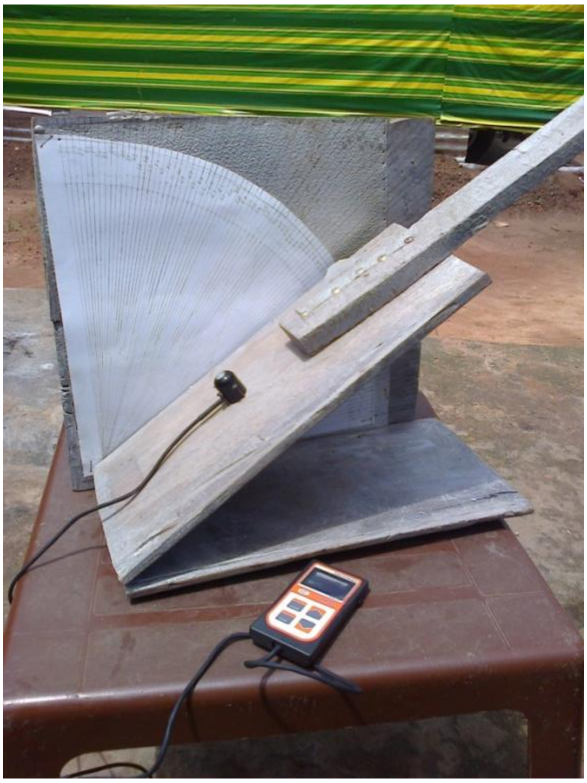

Figure 2. Flat plate surface solar collector with solar radiometer on an inclined position.

2.3 Instrumentation

A sensitive digital accurate and reliable total short wave and global radiation Pyranometer (Model MP-200), of sensitivity 1 % to 1750 W/m^2, was used to measure the total solar radiation intensity falling on the surface of the flat plate at varying degrees. Magnetic compass, Radio Isotope: H^3 of sensitivity 1 % to 360^o was employed to determine the cardinal position of the flat plate and to ensure it was truly facing south.

3. RESULTS AND DISCUSSION

3.1 Directly Measured Solar Energy Radiation Intensity Intercepted On Flat Plate Surface

Results from directly measured solar energy radiation intensity on horizontal and inclined surfaces, for each month of the year are shown in Figures 3 and 4 respectively, while the result from the calculated values using the given formulas is shown in Figures 5, 6 and 7. For clarity four months are represented in each figure.

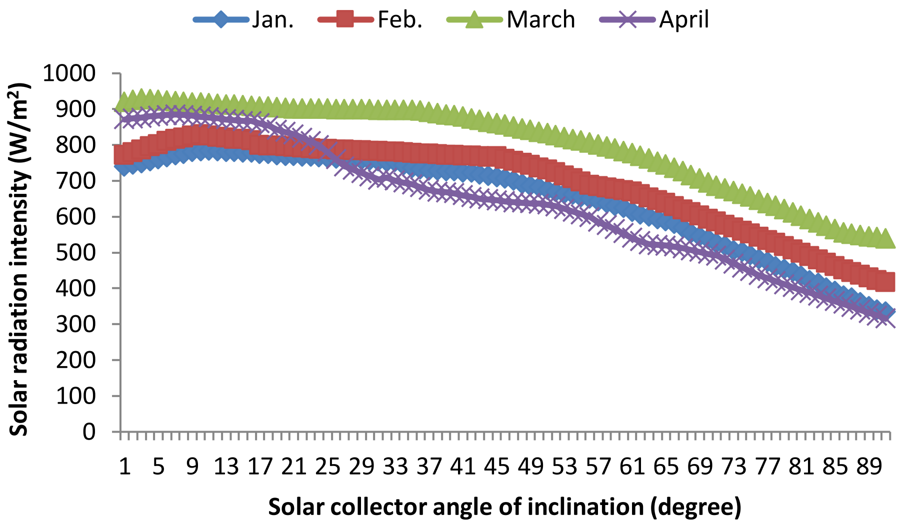

Figure 3. Response of calculated solar radiation intensity intercepted on flat plate surface at varying angles of inclination.

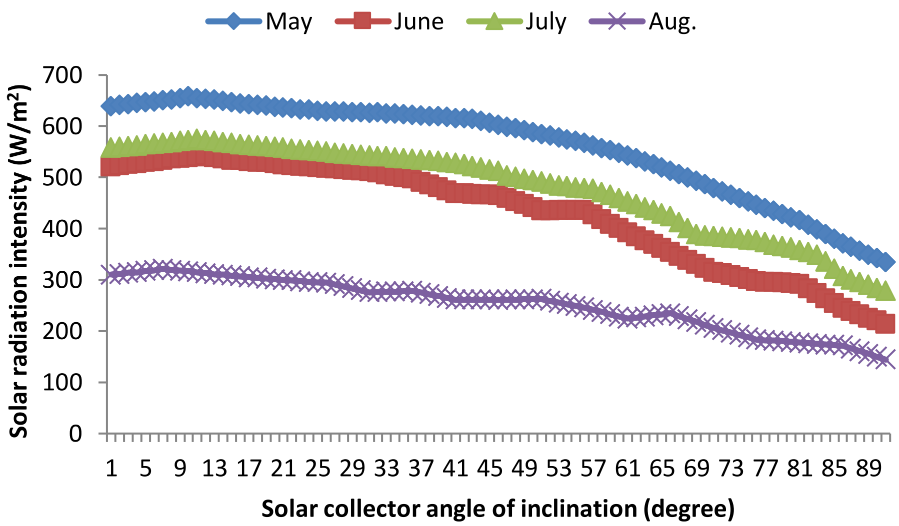

Figure 4. Response of calculated solar radiation intensity intercepted on flat plate surface at varying angles of inclination.

3.2 Solar Energy Radiation Intensity Intercepted On Flat Plate Surface

It was observed that the measured and the calculated solar energy radiation intensities incident on the flat surface increased from horizontal position of 0^o to a certain angle of inclination, after which, further increase in angle of inclination of the flat surface resulted to decrease of the trapped solar energy radiation intensity. The result also indicated that the optimum angle for catching maximum solar energy radiation on a flat plate surface varies with the months of the year as shown in Figures 5, 6 and 7.

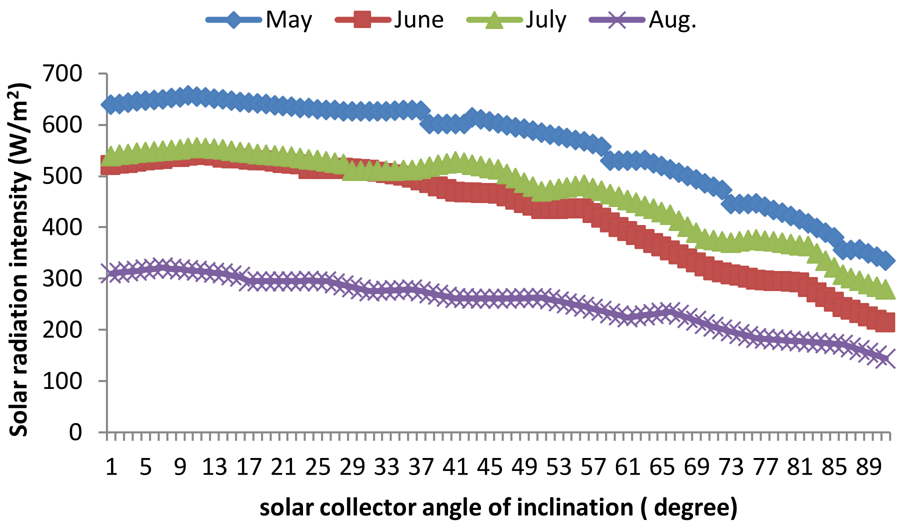

Figure 5. Response of measured solar radiation intensity intercepted on flat plate surface at varying angles of inclination.

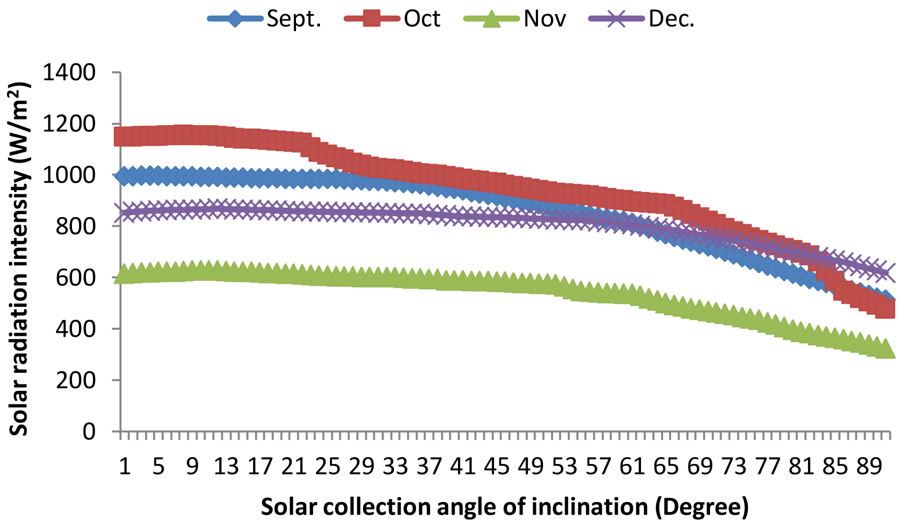

Figure 6. Response of calculated solar radiation intensity intercepted on flat plate surface at varying angles of inclination.

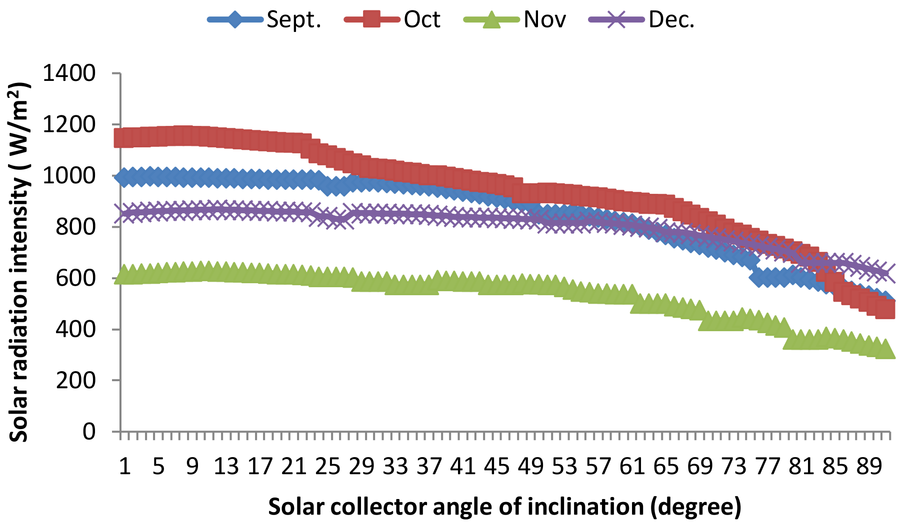

Figure 7. Response of measured solar radiation intensity intercepted on flat plate surface at varying angles of inclination.

3.3 Comparison Of Measured And Calculated Solar Radiation Intensity Intercepted On Flat Plate Surface

The predicted optimum tilt angle of inclination of a solar collector plat plate surface and that of the directly measured were compared and the result presented in Figure 8.

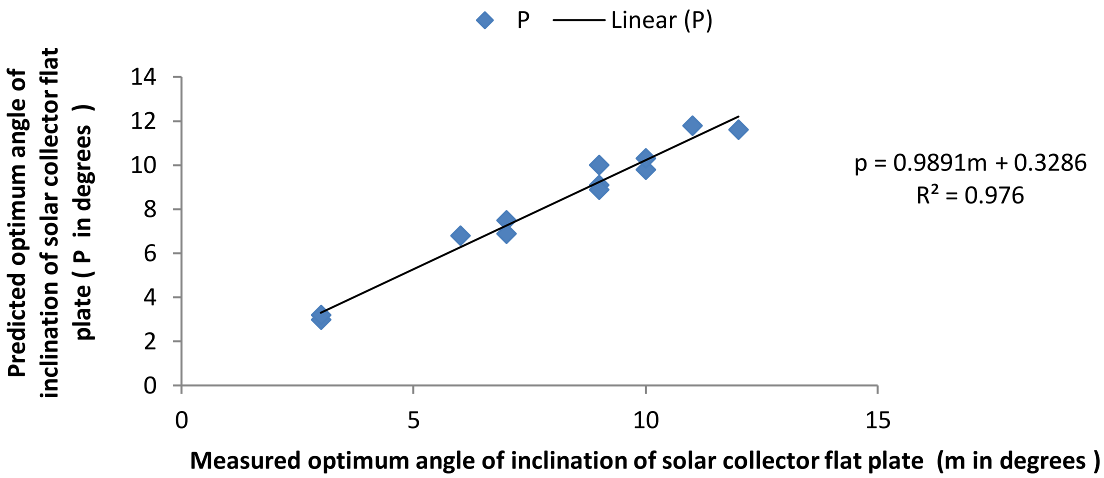

Figure 8. Comparison of the predicted and measured optimum tilt angle of inclination of a solar collector flat plate surface.

Where p is the predicted optimum angle of tilt for a solar collector float that meaning.

Where m is the measured optimum angle of inclination for a solar collector, flat plate (m in degrees

Comparison of the measured and predicted optimum tilt angle of inclination of a solar collector flat plate surface for trapping maximum solar radiation intensity for each month of the year indicated a high correlation with R^2 equal to 0.97. It also showed that at 95% probability level, there was no statistically significant difference between the predicted and measured values. The highest optimum angle of inclination of a flat surface in Michael Okpara University of Agriculture, Umudike (MOUAU), Umuahia, Abia State, Nigeria for trapping maximum solar radiation intensity was 11.8°. Months of January, February, June, July, November, and December experienced high angle of inclination for trapping maximum solar radiation. This might be because of the earth's tilt of 23.47° north at the Tropics of Cancer and 23.47 ° south at the Tropics of Capricorn on June 21st and December 22nd, respectively. Within these periods the sun is further away from UMUAU, Umuahia and the other regions in the Tropics generally. On the other hand, the lowest optimum angle of inclination of a flat surface in UMUAU, Umuahia, for harnessing maximum solar radiation intensity was 3° in the months of March and September. These are the periods of equinox when the sun is observed to be directly overhead at the Equator on March 21st and September 23rd.

It was found in this work that during the spring and autumn equinox the optimum angle for maximum solar energy collection in Umudike is very close to its Latitude angle. It can from this report be assumed that locations in the Tropics, near equator, will have their optimum angle of inclination of flat plate surface for collection of maximum solar energy close to their latitude angles, during the equinoxes. Besides, the earth's tilt angle, the sun's azimuth angle created by the revolution of the earth around the sun might have equally contributed to the varying optimum angle of inclination with time.

Table 1 gave the average values of measured and calculated parameters at 4.4 sunshine hours per day (Agro-Climatic Data, 2007) when a flat plate collector was located at horizontal, Latitude of location and at optimum angle of inclination for collection of maximum solar energy.

3.4 Analysis Of The Measured And Predicted Solar Energy On Tilted Flat Plate Surface

Table 1. Average values of measured and predicted solar radiation intensities and energy gain for a flat plate solar collector varied tilt angle of inclination.

Y	A_1	A_{OA}	A_H	A_L	A_C	SA_{OAH}	SA_{OAL}	SA_{OAC}
Jan.	9.5	784.5	739.5	773.5	780	21,851.28	5,155.92	1,964.16
Feb.	9.1	830	770.7	813.5	825	26,535.56	7,383.42	2,237.40
Mar.	3.0	921.6	920	920.6	919	785.66	491.04	1,276.7
Apr.	6.4	893.4	871	884	881.5	10,644	4,466.88	5,654.88
May	9.9	658	638.9	649	654	9,378.86	4,419.36	1,964.16
Jun.	11.8	542	520.6	532	537	10,169.28	4,752	2,376
Jul.	9.0	576	539.6	566.9	570.8	17,873.86	4,468.46	2,553.41
Aug.	7.3	323.2	310	320.2	318	6,481.73	1,473.12	2,553.41
Sep.	3.1	996.3	994.2	995	993.5	997.92	617.76	1,330.56
Oct.	7.0	1156	1147.5	1154	1154.4	4,173.84	982.08	982.08
Nov.	10.2	629	615.7	624	627	6,320.16	2,376	950.40
Dec.	11.8	869	852.5	864	865.4	8,102.16	2,455.2	1,767.74

Where, Y is month of the year; A_1 is average value of optimum angle of inclination for collection of maximum solar radiation (degree); A_{OA} average value of solar radiation intensity on optimum tilt angle for collection of maximum solar radiation ($W \cdot m^{-2}$) ; A_H is average value of solar radiation intensity on horizontal level ($W \cdot m^{-2}$) ; A_L average value of solar radiation intensity on flat plate solar collector tilted at the angle of Latitude of location ($W \cdot m^{-2}$); A_C is average value of solar radiation intensity on flat plate solar collector tilted at mean value of monthly optimum tilt angle of inclination ($W \cdot m^{-2}$); SA_{OAH} is monthly average solar radiation energy gain at optimum tilt angle of inclination when compared with the solar radiation energy collected at horizontal level (kJm^{-2}); SA_{OAL} is monthly average solar radiation energy gain at optimum tilt angle of inclination when compared with the solar radiation energy collected at angle of latitude (kJm^{-2}); SA_{OAL} is monthly average solar radiation energy gain at optimum tilt angle of inclination when compared with the solar radiation energy collected at fixed angle (kJm^{-2})

The analysis from Table 1 showed that when the flat plate surface was adjusted from horizontal (0^o) to Latitude angle of location (5.48^o), calculated fixed angle (8.14^o) and predicted optimum angle of inclination for each month of the year, an average annual increment the result indicated that 2.90 %, 0.90 % and 0.58 % solar radiation intensity for horizontal, Latitude angle of location and calculated fixed angle respectively were achieved, when compared with the yearly average solar radiation intensity harnessed by flat plate on the predicted optimum angle of inclination for each month of the year. These percentage increases amounted to annual average solar energy gain of 123,314.79 MJm^{-2}, 39,041.24 MJm^{-2} and 25,610.84 MJm^{-2} at no extra-cost, other than positioning the solar collector at the identified optimum angle of inclination. The average angle of inclination a solar flat surface collector should be mounted at fixed position is found to be 8.14^o. This agrees with the findings of Chow and Chan (2004) who stated that solar collectors in around coastal regions would be mounted with a tilt angle greater than the Latitude by 2.8^o for annual optimum angle of inclination for maximum solar radiation energy collection.

4. CONCLUSIONS

The optimum angle of inclination for maximum collection of solar energy radiation intensity was found to vary with months of the year. The angle was dependent on the Latitude and Azimuth of location. Optimum angles of inclination at which solar panels can be mounted to guarantee maximum collection of solar energy radiation intensity for each month of the year were identified. It wasobserved that solar flat plate collector can be fixed permanently in Umudike and other locations of similar geographical specifications at 8.14^o. The optimum angle of inclination showed solar energy gain at no extra-cost, when compared to what is obtainable when the solar collector is positioned at the any desirable angle of inclination.

5. RECOMMENDATIONS

Since the optimum angle of inclination varies with the month of the year, solar collectors should be mounted on telescopic legs for easy adjustment of the collectors to the determined optimum angle of inclination for the month in question. For locations near Equator in the northern hemisphere, it is recommended the flat plate solar collectors would be mounted with a tilt angle greater than the latitude by 2.66^o, truly facing south.

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