Prediction of optimum angle of inclination for flat plate solar collector in Zaria, Nigeria

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Abstract: A flat plate surface solar collector of dimension 0.5 m^2, hinged on a horizontal support for quick adjustment of inclination from 0 to 90° was fabricated, marked out at 1° intervals on a telescopic leg graduated in degrees. Measurement of the solar radiation, varying degrees of inclination 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. The measurements were made for each month of the year in Zaria, Kaduna State, Nigeria. At each degree of inclination, the solar radiation intensity was replicated three times and the average value was taken. The flat plate was set truly facing south with an engineering prismatic compass. The result showed that the optimum angle of inclination of a flat plate for maximum collection of solar radiation intensities are 26.5, 24.5, 10.0, 19.5, 26.0, 30.0, 24.0, 21.0, 11.5, 19.5, 27.0 and 30.0°, in the months of January to December, respectively. This work also revealed that the average angle of inclination at which a flat surface solar collector will be mounted at fixed position in Zaria is 22.5°. The analysis indicated that when a flat surface was located at the predicted optimum angle of inclination for each month of the year, an average annual increment of 4.23% solar radiation intensity was achieved, when compared with the yearly average solar radiation intensity harnessed by the same flat plate collector on horizontal position, and under the same condition. This percentage increase amounted to annual average solar energy gain of 370,670 MJ/m^2, at no extra-cost, other than positioning the solar collector at the identified optimum angle of inclination. Comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface for trapping maximum solar radiation intensity for each month of the year indicated a high correlation with R^2 of 0.97.

Keywords: solar radiation, solar collector, angle of inclination, renewable energy, solar energy

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1 Introduction

Solar radiation that floods the earth's surface on daily basis is renewable energy which can be harnessed into three primary technical uses by helio-chemical, helio-electrical and helio-thermal processes. On the earth, surface solar radiation is only effectively available in hours of clear sky weather. Nielsen (2005) gave an expression for determination of the global horizontal solar radiation intensity in n^{th} hours of the day. Bena and Fuller (2002), Sharma, Chen and Nguyen (2009) and Iloeje (1993) 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. Thanailakis (1985) 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 angles for maximum solar energy collection of the given locations

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(Chau, 1982; Dang and Sharma, 1983; Morcos, 1994; Koray, 2006; Huseyin and Arif, 2007; Hamid, Farshad and Ashkan, 2010)

Eke (1993) asserted that awareness of the use of solar dryer for effective drying and preservation of agricultural products has been created to farmers in Zaria. However, the dryers were not positioned at optimum tilt angle for maximum collection of solar radiation because such angles for Zaria had not been determined. ZAR (2011) indicated that Zaria is geographically located in the Northern Guinea Savanna Zone of Nigeria, in the tropics, on latitude 11°7′48″N and longitude 07°41′8″E, at 661 m above sea level. Eke (2003) observed that the solar radiation that falls in Zaria, Nigeria on horizontal surfaces, on the average normally produces ambient temperature of about 28℃. However, in cloudless hot weather between the hours of 1:00 pm and 2:30 pm, in the months of March to May, the ambient temperature in Zaria usually rises up to 35℃. Eke (2003) asserted that the average horizontal solar energy radiation intensity flooding Zaria in Nigeria is 465.9 W/m^2 with 7.7 sun shine hours. Solar panels in Zaria are normally inclined at the angle corresponding to the latitude of location, which does not achieve maximum solar energy collection (Arinze et al., 1992). Hence the aim of this work is to predict the optimum angles of inclination for maximum collection of solar energy for each month of the year in Zaria, Kaduna State, Nigeria.

2 Materials and methods

2.1 Methodology

A flat plate surface solar collector of dimension 0.5 m^2, hinged on a horizontal support was fabricated. The hinges gave the flat plate surface a freedom of adjustment of angle of inclination from 0 to 90°, marked at the intervals of 1°. The adjustment of 1^o increment was accomplished within the intervals of 1 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°. Following the assertion by Duffie and Beckman (1974), 45° 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 toward south as recommended by Arinze (1981).

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). The experiment was conducted in the Department of Agricultural Engineering, Institute for Agricultural Research, Ahmadu Bello University, Samaru-Zaria, Kaduna State, Nigeria.

The flat plate surface solar collector on horizontal and inclined positions is presented in Figure 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

2.2 Instrumentation

A sensitive digital Haeni Solar Radiometer (Model 118), which measures total solar radiation intensity, was used to measure the total solar radiation intensity falling on the surface of the flat plate at varying degrees. Engineering prismatic compass was employed to determine the cardinal position of the flat plate and to ensure it was truly facing south.

2.3 Theoretical framework

The measured values were verified with the calculated values. Liu and Jordan (1960) in Obi (1984) developed an expression for calculation of incident solar radiation on a tilted flat collector surface truly facing south. The expression is shown in Equation (1) and was used in this work.

$$I_0 = I_r R_a + I_f \left(\frac{1+\cos b}{2}\right) + I_1 \left(\frac{1+\cos b}{2}\right) g \tag{1}$$

where, I_0 = total solar energy radiation incident on the top cover of a thermal solar collector truly facing south. W/m^2; I_r = direct solar radiation component on a horizontal surface, W/m^2; R_a = Radiation tilt factor, dimensionless; I_f = diffused solar radiation on a horizontal surface, W/m^2; b = thermal solar collector tilt angle from the horizontal plane, degree; I_1 = total solar radiation on horizontal surface, W/m^2; g = diffused reflectance of the ground or surrounding, Dimensionless. (The value of ground reflectance was given as 0.2 by Liu and Jordan (1960) in Obi (1984)).

The equation for R_a given in Equation（2）is based on the location of Zaria as earlier explained.

$$R_a = \frac{\cos(L-b)\cos d + \sin(L-b)\sin d}{\cos L \cos d + \sin L \sin d} \tag{2}$$

where, L = latitude of location, degree; b = solar collector panel tilt angle from the horizontal plane, degree; d = declination angle of sun.

Equation (3) which is a correlation equation given by Callares-Pereira and Rabi (1979) was used to calculate diffuse solar energy radiation (I_f) falling on a horizontal plane.

Thus:

$$I_f = [0.775 + 0.00653(W_s - 90) - [0.505 + 0.00455(W_s - 90)] \times \cos(115K_T - 103)] \tag{3}$$

where, W_s = Sunset hour angle for the typical day n of each month of the year; K_T = Clearance index.

The clearness index (K_T) was calculated using the expression given by Duffie and Beckman (1980) as shown in Equation (4):

$$K_T = a + b\left(\frac{S}{S_0}\right) \tag{4}$$

where, S = Measured sunshine hour; S_0 = Theoretical sunshine hour; a and b are constants given for Zaria by Ododo and Usman (1995) as 0.2 and 0.75, respectively.

The value of sunset hour angle and sun's declination for each month of the year for Zaria calculated in (Eke 2003) was used. Data for monthly average weather conditions for 40 years was collected from the Meteorological Unit, Institute for Agricultural Research, Ahmadu Bello University, Samaru- Zaria. The actual measured monthly average daily sunshine hour was employed to calculate the theoretical sunshine hour. The calculation was based on the formula presented by Duffie and Beckman (1980).

3 Results and discussion

Results from directly measured solar energy radiation intensity on horizontal and inclined surfaces, for each month of the year are shown in Figures 3 to 5. While the result from the calculated values using the given formulas are shown in Figures 6 to 8. For clarity four months are represented in each figure.

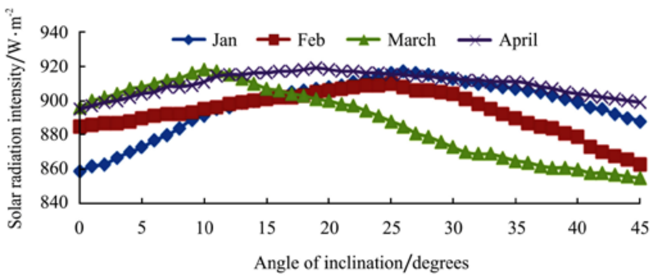

Figure 3 Responses of measured solar radiation intensity intercepted on flat plate surface at varying angle of inclination

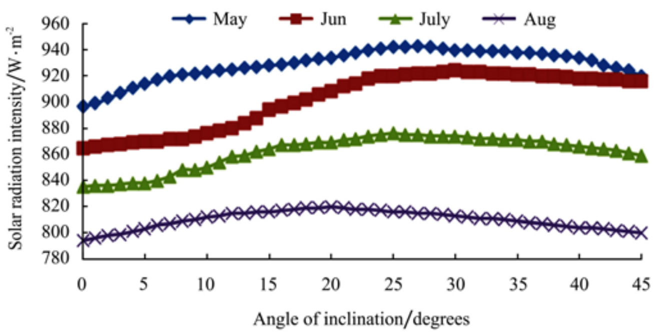

Figure 4 Responses of measured solar radiation intensity intercepted on flat plate surface at different angle of inclination

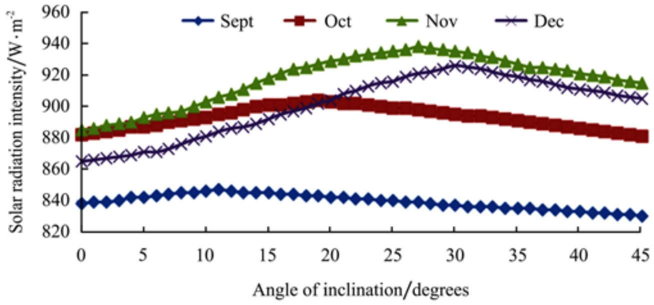

Figure 5 Responses of measured solar radiation intensity intercepted on flat plate surface at varying angle of inclination

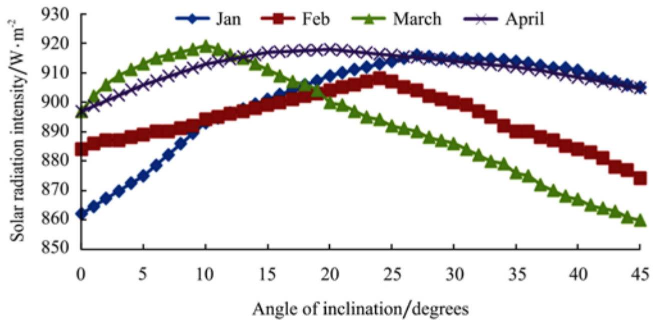

Figure 6 Responses of calculated solar radiation intensity intercepted on flat plate surface at varying angle of inclination

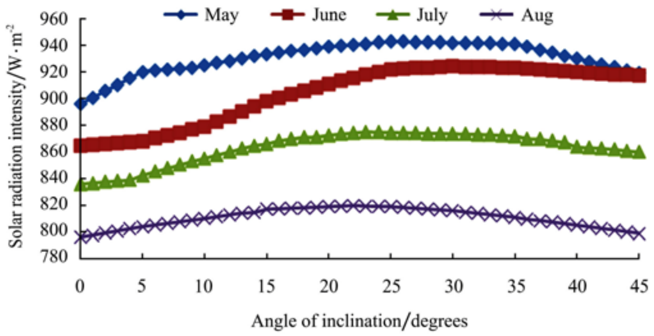

Figure 7 Responses of calculated solar radiation intensity intercepted on flat plate surface at varying angle of inclination

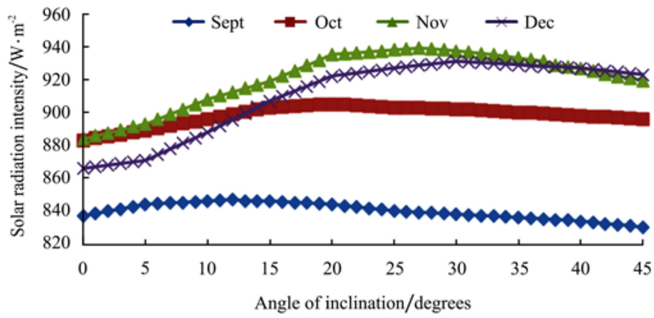

Figure 8 Responses of calculated solar radiation intensity intercepted on flat plate surface at varying angle of inclination

It was observed that the measured and the calculated solar energy radiation intensities incident on the flat surface increased from horizontal position of 0° to a certain angle of inclination, after which, further increase in angle of inclination of the flat surface resulted to decrease of the solar energy radiation intensity trapped. 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.

The calculated solar energy radiation intensity on an inclined surface and that of the directly measured were compared and the results presented in Figure 9.

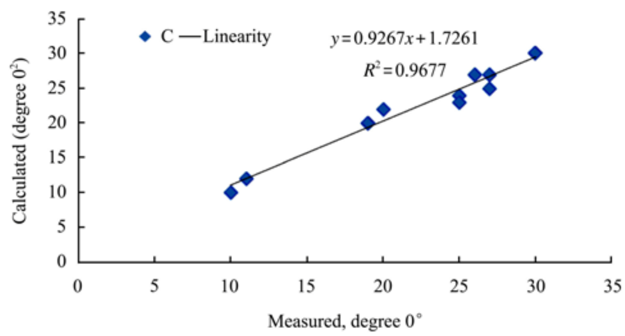

Figure 9 Comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface

Comparison of the measured and calculated optimum values of angle of inclination of a 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 statistical significant difference between the measured and calculated values. The highest optimum angle of inclination of a flat surface in

Zaria for trapping maximum solar radiation intensity was 30°. Months of January, June, November and December experienced high angle of inclination for trapping maximum solar radiation. This might be as a result 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 Zaria and the other regions in the Tropics generally. On the other hand, the lowest optimum angle of inclination of a flat surface in Zaria for harnessing maximum solar radiation intensity was 10° in the months of March and the month of September also had low degrees of inclination. 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 Zaria is approximately equal to its latitude. 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 at their latitudes, 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 7. 7 sun shine hours per day, when a flat plate collector was located at horizontal position and at optimum angle of inclination for collection of maximum solar energy.

Table 1 Average value of measured and calculated solar radiation intensity and energy gain for a flat plate collector

Month of the year	Average value of optimum angle of inclination /degree	Average value of solar radiation intensity on horizontal level (0°) /W · m^{-2}	Average value of solar radiation intensity on optimum angle of inclination/W · m^{-2}	Solar radiation intensity gained at optimum angle of inclination/W · m^{-2}	Horizontal monthly average solar radiation energy generation /KJ · m^{-2}	Monthly average solar radiation energy generation gained at optimum angle of inclination/KJ · m^{-2}
an	26.5	860.5	916.5	56.0	739,444.86	48,121.92
Feb	24.5	884.5	909.0	24.5	692,643.11	19,185.71
March	10.0	896.5	918.5	22.0	770,380.38	18,905.04
April	19.5	896.0	918.5	22.5	745,113.60	18,711.00
May	26.0	896.0	942.4	46.4	769,950.72	39,872.45
Jun	30.0	865.0	924.0	59.0	719,334.00	49,064.40
Jul	24.0	835.5	871.0	35.5	717,961.86	30,505.86
Aug	21.0	795.5	819.9	24.4	683,589.06	20,967.41
Sept	11.5	837.5	846.9	9.4	696,465.00	7,817.04
Oct	19.5	883.0	904.5	21.5	758,779.56	18,475.38
Nov	27.0	884.5	938.5	54.0	735,550.20	44,906.40
Dec	30.0	865.5	928.5	63.0	743,741.46	54,137.16
Total	269.5	10,400	10,838.2	438.2	8,772,953.81	370,669.77

The analysis from Table 1 indicated that when a flat surface was located at the predicted optimum angle of inclination for each month of the year, an average annual increment of 4.23% solar radiation intensity was achieved, when compared with the yearly average solar radiation intensity harnessed by a flat plate collector on horizontal position and under the same condition. This percentage increase amounted to annual average solar energy gain of 370,670 MJ/m^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 22.5°.

4 Conclusions

The optimum angle of inclination for maximum collection of solar energy radiation intensity varies with each month of the year. Zaria optimum angles of inclination at which solar panels can be mounted to harness maximum collection of solar energy radiation intensity for each month of the year were identified. It was found that solar flat collector can be fixed permanently in Zaria at 22.5°. When the average annual solar energy radiation intensity obtained at the optimum angle of inclination was compared with that from the horizontal zero degree position, 4.23% average yearly increase in solar energy radiation intensity was achieved. Also an average annual solar energy gain of 370,670 MJ/m^2, over the horizontal position, was achieved, when the flat plate was inclined at optimum angle for harnessing maximum solar radiation intensity.

Recommendation

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.

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