Mean Global Radiation Captured by Inclined Collectors at Various Surface Azimuth Angles in Nigeria

M. T. Oladiran

Department of Mechanical Engineering, Botswana Polytechnic, Private Bag 0061, Gaborone, Botswana

ABSTRACT

The use of solar energy is well established for low-grade thermal applications such as water heating and purification. In many of the solar systems, the collector surface located in the Northern Hemisphere faces the true south direction. However, there are occasions in which the radiation received by the collector at various orientations is desirable, such as a collector incorporated with a tracking system. The data for such situations are not available for several solar farms in Nigeria. Consequently, in this study, the average global radiation on flat surfaces was determined for three zones in Nigeria. The total insolation was obtained while the surface azimuth angle was varied between 0° and 75° at 15° intervals. The results are presented for three inclinations of the collector surface, namely L – 10, L, and L + 10 degrees respectively.

NOTATION

H	Monthly radiation (MJ/m^2)
L	Latitude (degrees)
n	Number of days beginning from 1 January as 1
R	Collector tilt factor
R_b	Tilt factor for beam radiation
R_g	Tilt factor for ground-reflected radiation
R_s	Sky view correction factor
t_{sr}	Minimum between local or apparent sunrise hour-angle

β Collector inclination (degrees)
δ Solar declination (degrees)
ρ Ground albedo
ψ Azimuth angle (degrees)
Ω Local sunrise hour-angle
Ω' Apparent sunrise hour-angle

Suffices

1 Extraterrestrial
2 Terrestrial
b Beam value on horizontal surface
at Annual total value
bt Beam value on tilted surface
d Diffuse
g Ground reflected
s Sky reflected
t Total value on an inclined surface

INTRODUCTION

Solar energy is appealing for several applications because it is a non-combustion power system, so that its environmental pollution is limited. It is also a renewable resource and its availability is thus assured. In order to design solar devices and systems, the terrestrial radiation data are required for the particular location. Extensive study has been carried out for predicting the total solar radiation on a horizontal plane at various inclination.[1-6] Because of the diurnal variation of solar thermal density, some applications employ a tracking device to ensure that the maximum energy is captured by the collector. Such solar equipment needs the values of diffuse and beam components of the total radiation for proper design and evaluation.

In several countries, one principal limitation to the utilization of solar energy is the non-availability of reliable radiation data. Measurements of insolation are often restricted to those incident on horizontal planes, and this is certainly, the case for the Nigerian environment. In these circumstances, empirical equations were employed to predict the solar radiation for some locations.[7-11] For example, Fagbenle[10] developed solar radiation isolines for Nigeria by employing various mathematical models together with the sunshine hours recorded by the Meteorological Services Department. Oladiran[11] used the Ångström-type model to analyse agro-meteorological measurements from 16 locations and noticed the significant effect of latitude on radiation in Nigeria. Thus, he proposed that the country should be composed of three solar zones based on latitude.

Data on measured radiation for inclined planes at different orientations are often scarce for Nigeria. However, in a recent work, Oladiran[12] studied the effect of inclination on total radiation. He suggested that the collector surface should be tilted between $L - 10$ and $L + 10$ degrees depending on the season. However, for an all year solar application, it was found that an angle of tilt equal to the latitude produced optimum thermal benefit.

The main objective in the present investigation was to obtain the insolation for flat surfaces with inclinations of $L - 10$, L, and $L + 10$ degrees while tilting the surface from 0° to 75° at 15° intervals. First, a characteristic location was chosen for each of the individual zones: Maiduguri ($L = 11{\cdot}85°$), Ilorin ($L = 8{\cdot}48°$) and Lagos ($L = 6{\cdot}33°$) for the northern, the middle and the southern zones, respectively. The total radiation falling on oriented surfaces in each zone was calculated and was considered to be representative of all positions in the zone.

THEORETICAL MODELS

The mean total solar flux (H_t) collected by tilted planes is the sum of the direct radiation (H_{bt}), the diffuse sky component (H_s), and the ground reflected radiation (H_g). Thus,

$$H_t = H_{bt} + H_s + H_g \tag{1}$$

The direct beam radiation incident on an inclined surface is given by:

$$H_{bt} = R_b H_b \tag{2}$$

where

$$H_b = H_2 - H_d \tag{3}$$

The average monthly solar flux on a horizontal surface (H_2) was obtained using the Ångström-type model because the values of both the extraterrestrial radiation (H_1) and the sunshine hours were readily obtainable.[12]

Several correlations are available for computing the diffuse component and the following equation proposed by Collares-Pereira and Rabl[13] was employed in this study:

$$\begin{aligned} H_d = H_2\{0{\cdot}775 + 0{\cdot}00653(\Omega - 90) \\ - [0{\cdot}505 + 0{\cdot}000455\,(\Omega - 90)] \cos (115\; H_2/H_1 - 103)\} \end{aligned} \tag{4}$$

Also

$$R_b = \frac{\cos(L-\beta)\cos\delta\sin t_{sr} + t_{sr}\sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin\Omega + \Omega\sin L\sin\delta} \quad (5)$$

The value of t_{sr} in eqn (5) is the smaller of either the local or apparent sunrise hour angle, i.e.

$$t_{sr} = \min[|\Omega'|, |\Omega|]$$

where the local sunrise hour angle, Ω is

$$\Omega = \cos^{-1}(-\tan L \tan\delta) \quad (6)$$

and

$$\delta = 23{\cdot}45 \sin[360(284 + n)/365] \quad (7)$$

The apparent sunrise hour angle for an inclined surface, which faces due south is given by:

$$\Omega' = \cos^{-1}[-\tan(L-\beta)\tan\delta] \quad (8)$$

Equation (5) was proposed by Liu and Jordan[14] for collectors which are oriented directly towards the equator. However, Klein[15] modified eqn (5) so that it can be employed for surfaces with different orientations from either the true south or north. Thus, in this study, the following equation was employed to estimate R_b while varying the azimuth angle.

$$\mathrm{R_b} = \begin{bmatrix} (\cos\beta\sin\delta\sin L)\frac{\pi}{180}(\Omega' - \Omega) \\ -(\sin\delta\cos L\sin\beta\cos\psi)\frac{\pi}{180}(\Omega' - \Omega) \\ +(\cos L\cos\delta\cos\beta)(\sin\Omega' - \sin\Omega) \\ +(\cos\delta\cos\psi\sin L\sin\beta)(\sin\Omega' - \sin\Omega) \\ -(\cos\delta\sin\beta\sin\psi)(\cos\Omega' - \cos\Omega) \end{bmatrix} \div [2(\cos L\cos\delta\sin t_{sr} + \tfrac{\pi}{180} t_{sr}\sin L\sin\delta] \quad (9)$$

For $\psi > 0$,

$$\Omega = -\min\left[t_{sr}, \arccos\left(\frac{AB - \sqrt{(A^2 - B^2 + 1)}}{A^2 + 1}\right)\right] \quad (10)$$

$$\Omega' = \min\left[t_{sr}, \arccos\left(\frac{AB + \sqrt{(A^2 - B^2 + 1)}}{A^2 + 1}\right)\right]$$

where

$$A = \frac{\cos L}{\sin\psi\tan\beta} + \frac{\sin L}{\tan\psi}$$

and

$$B = \tan\delta\left(\frac{\cos L}{\tan\psi} - \frac{\sin L}{\sin\psi\tan\beta}\right)$$

The sky diffuse and the ground reflected radiation components can, respectively, be expressed as:

$$H_s = R_s H_d \tag{11a}$$

and

$$H_g = \rho R_g H_2 \text{d} \tag{11b}$$

R_s is the sky-view correction factor and assuming the sky diffuse solar radiation to be isotropic, we have:

$$R_s = (1 + \cos\beta)/2 \tag{12}$$

R_g, the tilt factor for ground reflected radiation, is:

$$R_g = (1 - \cos\beta)/2 \tag{13}$$

and ρ, the albedo of 0·26 for green-grass surfaces was assumed for the three zones in this study.

The mean monthly total radiation orientation factor, R, was defined as:

$$\text{R} = H_t/H_2 \tag{14}$$

Substituting eqns (6), (7) and (9) into equation (10), we have

$$\text{R} = (H_b/H_2)R_b + (H_d/H_2)R_s + \rho R_g \tag{15}$$

Computer programs were written to solve eqns (1)–(15) for three collector inclinations and six surface azimuth angles. A simplified version of the computer flow chart is depicted in Fig. 1.

RESULTS AND DISCUSSION

The main input parameters for the execution of the program were the latitude, solar constant, sunshine hours, month of the year, ground albedo and constants in the Ångström-type equation. The daily solar declination and sunrise hour angle were calculated and then used to determine both the mean monthly extraterrestrial radiation and global radiation on a horizontal plane. Two sub-routines were incorporated in the program for the variation of the collector inclination and the surface azimuth angle so that the radiation components were computed iteratively. For each run of the program, a data file was created and it contained the total insolation, orientation factors and other radiation data, which were used in the graphic presentation. The surface azimuth angle was varied from 0° to 75°, an orientation of 0° coincides with the situation

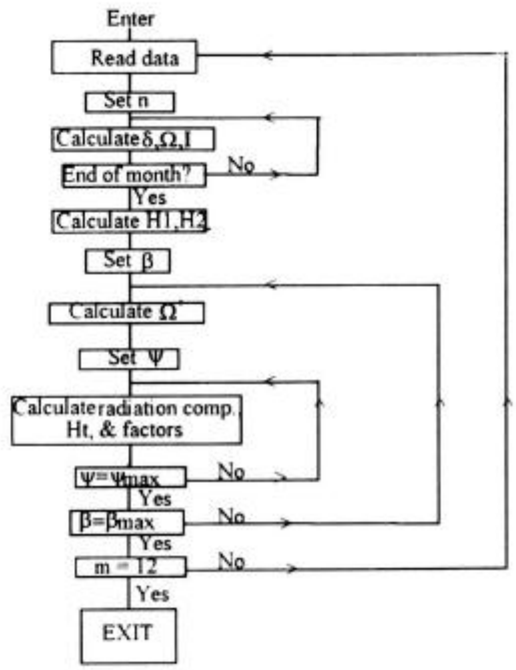

Fig. 1. Flowchart.

when the collector surface faces the south direction directly and the positive value is in the westerly direction.

The mean monthly total radiation is high in the three zones for all the inclinations and orientations so that solar energy is attractive for various applications, including heating, cooling and power production. The maximum radiations are 33·14, 23·4 and 18·01 MJ/m^2 day for zones 3, 2 and 1, respectively. The corresponding lowest values are 21·07, 13·58, and 10·33 MJ/m^2 day, respectively. The maximum values occurred at an inclination of $L + 10$ degrees between November and December while the minimum values occurred in July at the same inclination. Both the largest and smallest values were obtained with an orientation of 0°.

It is pertinent to mention that Nigeria lies between a latitude of 4° and 14° north of the equator and experiences two main seasons, namely the rainy season and the dry season. These occur, respectively, from March to September and from October to February. The rainy season is usually characterized by heavy cloudiness and much suspended water vapour in the atmosphere. The dry season is associated with minimal cloudiness and high ambient temperatures. Thus, the occurrence of the maximum and minimum values of the total radiation during the dry and rainy seasons respectively is in agreement with local geographical conditions.

TABLE 1
Mean monthly radiation for zone 3 (MJ/m^2)

Azimuth	*Inclination*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
0	L − 10	22·50	26·58	28·00	28·20	28·07	26·99	23·81	26·09	23·45	26·31	28·26	25·80
	L	24·21	27·69	27·93	27·09	26·28	25·17	22·66	22·71	23·96	28·06	31·07	28·49
	L + 10	25·35	28·14	27·22	25·40	23·99	22·88	21·07	21·83	23·93	29·15	33·14	30·49
15	L − 10	22·49	26·57	28·00	28·20	28·07	26·99	23·81	23·09	23·45	26·30	28·24	25·78
	L	24·12	27·63	27·94	27·14	26·36	25·25	22·71	22·73	23·93	27·97	30·94	28·36
	L + 10	25·20	28·04	27·26	25·53	24·17	23·06	21·18	21·90	23·89	28·99	32·90	30·27
30	L − 10	22·45	26·54	27·99	28·22	28·10	27·02	23·83	23·09	23·43	26·26	28·18	25·72
	L	23·89	27·47	27·94	27·28	26·58	25·47	22·85	22·77	23·86	27·73	30·56	28·00
	L + 10	24·79	27·80	27·33	25·86	24·65	23·54	21·50	22·03	23·79	28·58	32·22	29·61
45	L − 10	22·39	26·50	27·99	28·24	28·15	27·07	23·86	23·10	23·41	26·19	28·08	25·63
	L	23·54	27·24	27·92	27·46	26·89	25·79	23·05	22·82	23·74	27·37	29·98	27·45
	L + 10	24·20	27·44	27·38	26·28	25·31	24·20	21·93	22·18	23·63	27·98	31·23	28·67
60	L − 10	22·31	26·44	27·97	28·27	28·20	27·13	23·89	23·10	23·38	26·11	27·96	25·51
	L	23·08	26·92	27·89	27·67	27·27	26·18	23·28	22·87	23·57	26·90	29·25	26·75
	L + 10	23·45	26·96	27·40	26·73	26·04	24·95	22·39	22·32	23·40	27·22	30·00	27·49
75	L − 10	22·22	26·37	27·96	28·30	28·26	27·19	23·93	23·10	23·34	26·02	27·81	25·38
	L	22·55	26·53	27·82	27·89	27·68	26·60	23·52	22·90	23·36	26·34	28·40	25·94
	L + 10	22·56	26·34	27·33	27·15	26·78	25·71	22·85	22·42	23·08	26·30	28·57	26·12

In all cases, the total radiations on the plane are highest for sites in zone 3 (Table 1). This zone lies mainly in the Sahara desert and experiences severe weather conditions including high temperatures most of the year. It is apparent from Table 1 that during the rainy season the insolation is maximum when the inclination is equal ($L - 10$) degrees. However, during the dry season the insolation reaches the peak value when the surface is tilted at $(L + 10)^\circ$. March and September are transitional months and optimal results appear insensitive to slope. This observation agrees with the data from previous studies.[12]

In Table 1, the orientation of the collector seems beneficial during the rainy season especially for an inclination of $L + 10$ degrees. The monthly average total radiations (Ht) for inclination of $L + 10$ degrees are shown in Figs 2–4 for zones 1–3, respectively. The pattern of the figures is fairly similar for the three zones. For all orientations, the insolation generally decreases from March, reaching the minimum value between July and August and then increases until the maximum value is attained in November or December. Between April and July, solar radiation increases gradually as the azimuth angle increases from 0° to 75°. The percentage gain varies from a peak value of about 12%, in zone 3, to about 7% in zone 1. Similarly, the minimum gain varies from 2 to 4% from zones 1 to 3, respectively. However, in the dry season, the collector facing the equator directly

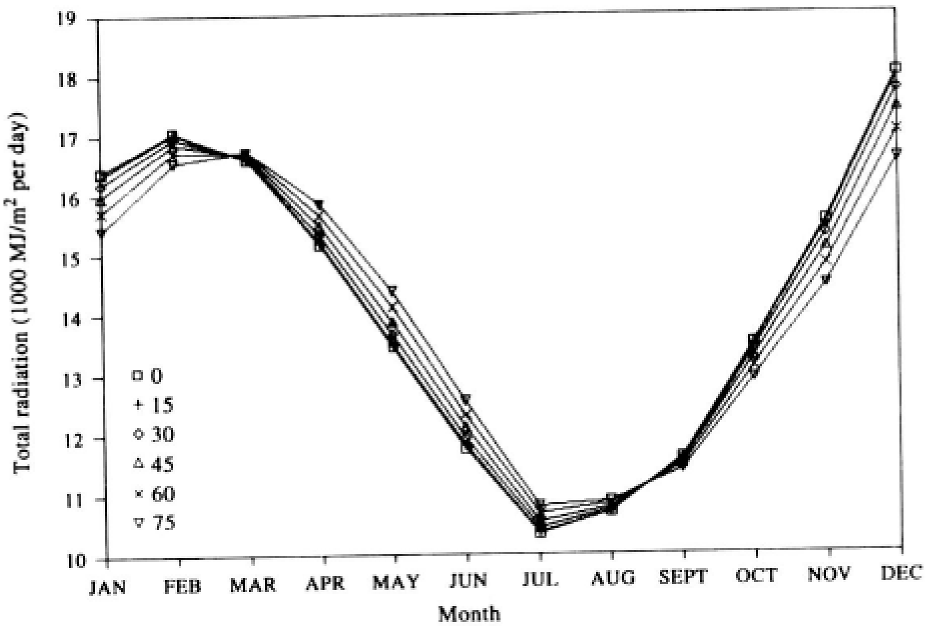

Fig. 2. Variation of mean monthly radiation for zone 1 (inclination = $L + 10$).

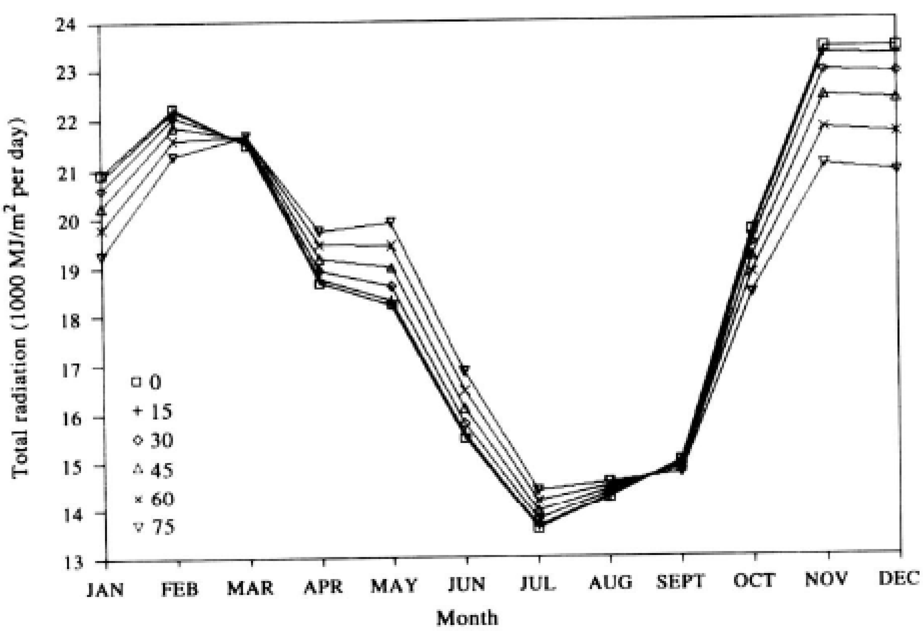

Fig. 3. Variation of mean monthly radiation for zone 2 (inclination = $L + 10$).

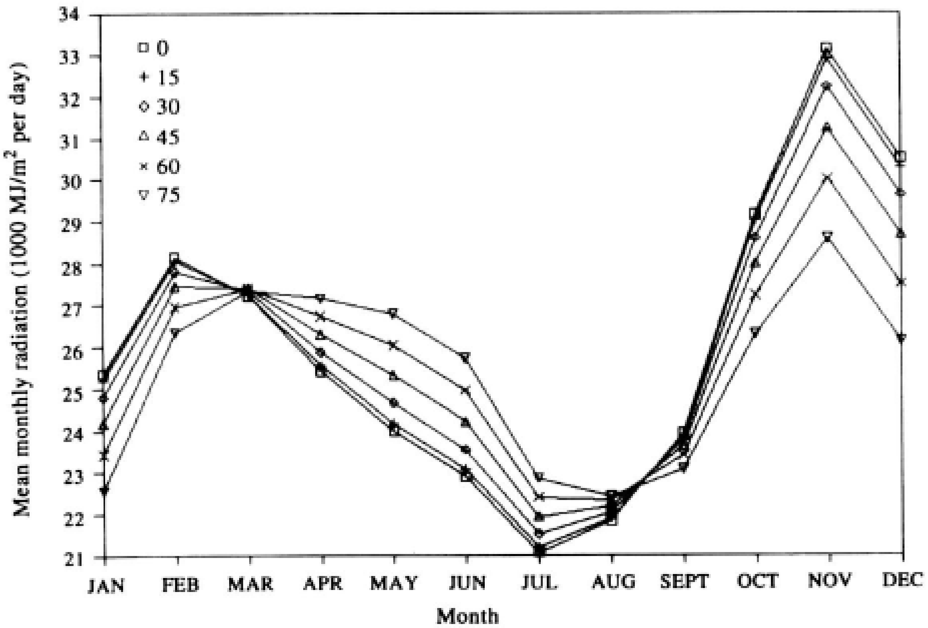

Fig. 4. Variation of mean monthly radiation for zone 3 (inclination = L + 10).

harnesses the maximum radiation, so orientation is not advantageous during this period. Studies have not been previously carried out for the present conditions, so direct comparisons were not made. However, in a similar study Gopinathan[1] observed that during the summer season in Lesotho, the optimal tilt for maximum radiation for all azimuth angles was L–15 degrees. Figures 5–7, respectively, show the variations of the monthly orientation factors for zones 1–3 for a collector inclination of L + 10 degrees.

Figures 8–10 present the total annual radiation for various collector orientations for zones 1–3, respectively. The maximum total yearly radiation varies from about 173 MJ/m^2 day in zone 1 to about 320 MJ/m^2 day in zone 3. Thus, the application of solar devices should be more attractive as the latitude increases. For a collector inclination of L and L + 10 degrees, the total annual radiation diminishes as the azimuth angle increases. This result compares favourably with those of Gopinathan:[1] his collector orientations were L and L + 15 degrees. He suggested that the variations may be due to changes in the local climatic-conditions. However, the reduction in radiation seems negligible (less than 4%) for azimuth angles less than or equal to 30°. This observation corroborates the data obtained by Dufie and Beckman[16] who showed that the change in the yearly radiation is insignificant for orientations varying between 20 and

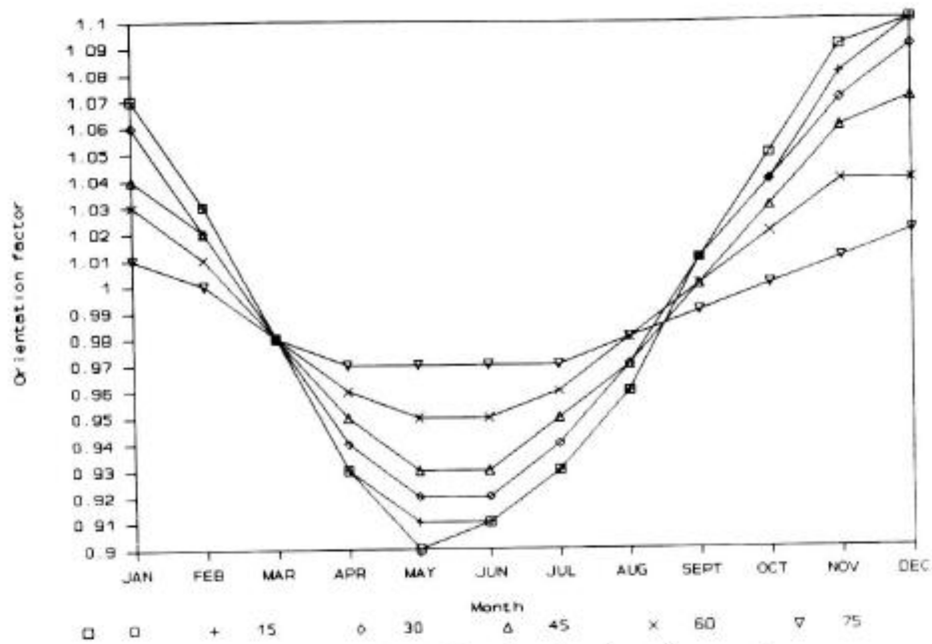

Fig. 5. Variation of monthly orientation factor for zone 1.

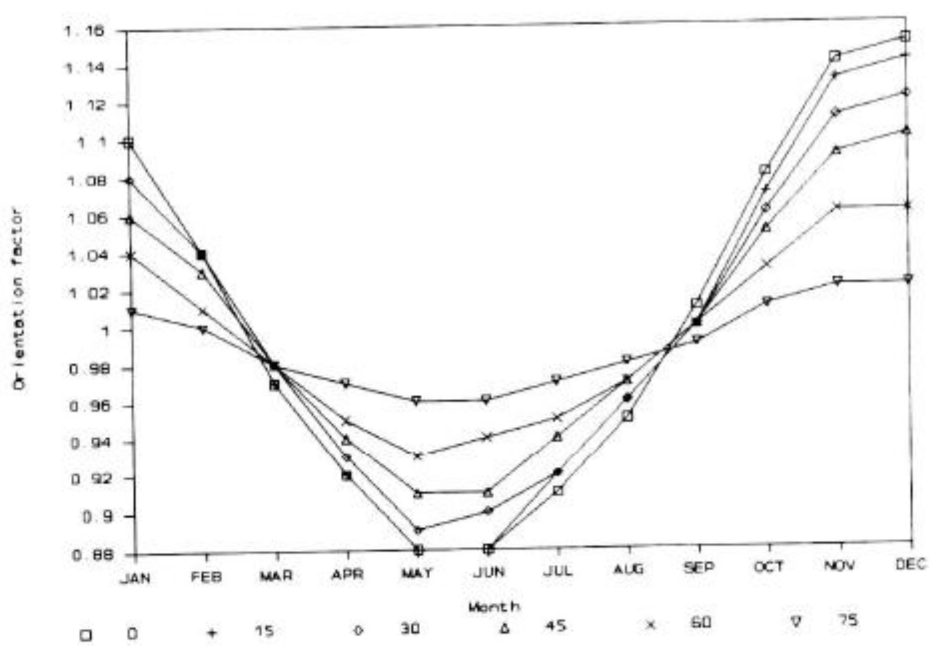

Fig. 6. Variation of monthly orientation factor for zone 2.

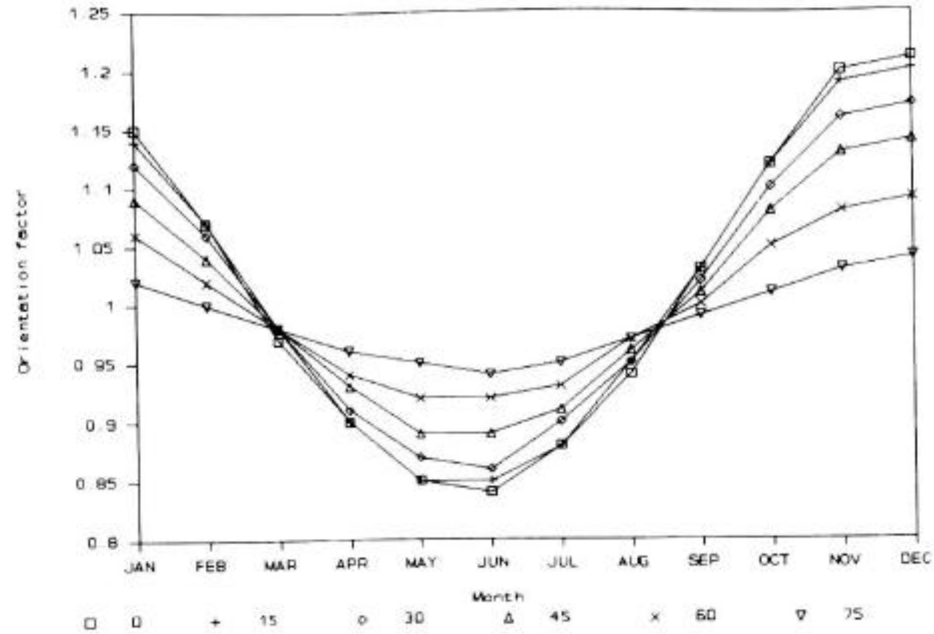

Fig. 7. Variation of monthly orientation factor for zone 3.

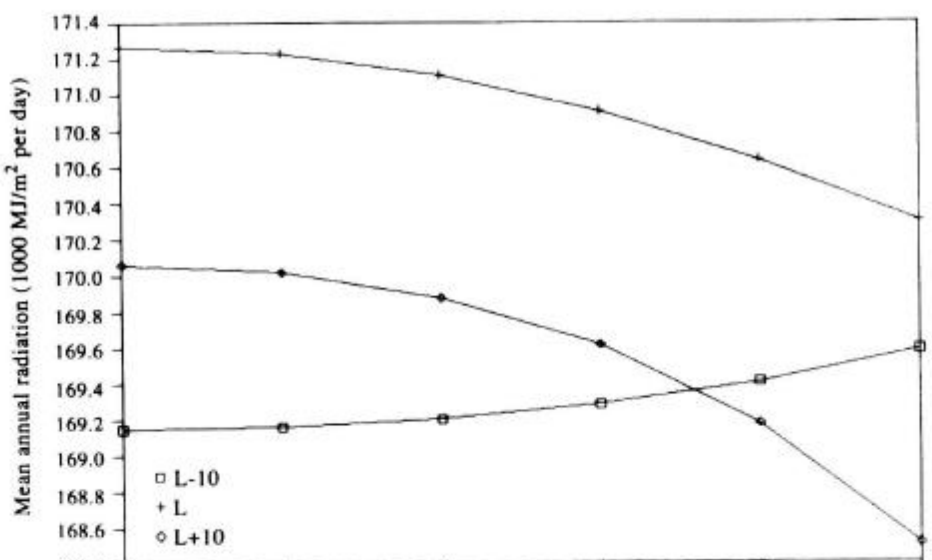

Fig. 8. The effect of azimuth angle on mean annual radiation for zone 1.

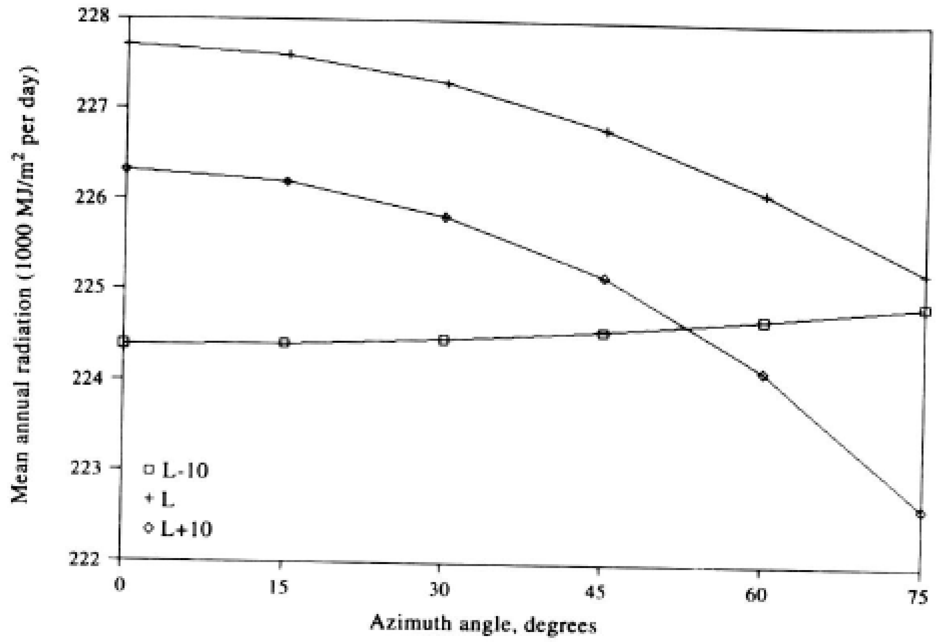

Fig. 9. The effect of azimuth angle on mean annual radiation for zone 2.

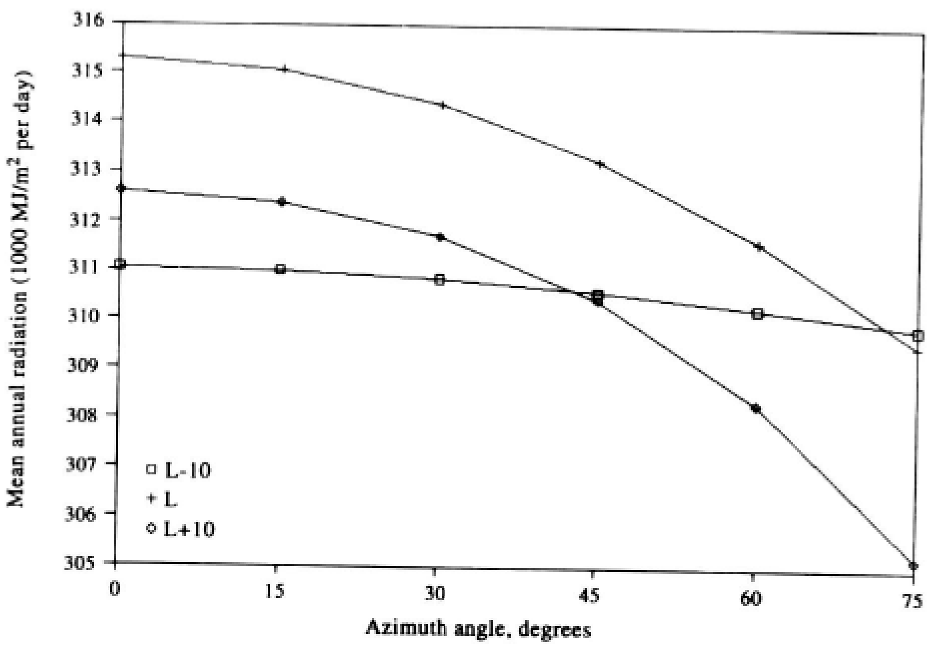

Fig. 10. The effect of azimuth angle on mean annual radiation for zone 3.

30°. Moreover, the reduction in the annual solar radiation in this study increases rapidly for higher azimuth angles, especially for inclinations of $L + 10$ degrees. For an inclination of $L - 10$ degrees, there seems to be an increase in the total annual mean radiation with the azimuth angle. Finally, for all azimuth angles, an inclination of L degrees produces the best all-year-round performance.

CONCLUSIONS

The terrestrial radiation incident on oriented surfaces was determined for three zones in Nigeria. The results show that insolation is dependent on local conditions. For example, insolation on plane surfaces is significantly reduced as the latitude is decreased.

The maximum benefit for orientation of the collector surface varies from about 2 to 12% depending on both the geographical location and time of year. The total annual radiation appears to be unaffected by tilting the surface for azimuth angles between 0° and 30°; for larger azimuth angles, rapid changes occurred in the radiation collected. It seems that for optimal all-year performance of solar systems, the collector surface should be fixed at an inclination of L degrees for all azimuth angles.

ACKNOWLEDGMENT

The use of the facilities at the Computer Centre of Botswana Polytechnic is gratefully acknowledged.

REFERENCES

1. Gopinathan, K. K., Solar radiation on variously oriented sloping surfaces. *Solar Energy*, **47** (1991) 173–9.
2. Lavagnini, A. & Jibril, Z., Monthly maps of daily diffuse solar irradiance for Italy. *Renewable Energy*, **1** (1991) 779–89.
3. Manes, A. & Ianetz, A., Solar irradiance on non-horizontal surfaces at the east-Mediterranean coastal plain of Israel. *Solar Energy*, **31** (1983) 3–19.
4. Khogali, A., Solar radiation over Sudan — comparison of measured and predicted data. *Solar Energy*, **31** (1983) 45–53.
5. Liu, B. H. Y. & Jordan, R. C., The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy*, **4** (1960) 1–19.
6. Page, J. K., The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for

latitudes 40°N–40°S. *Proceedings of UN conference New Sources of Energy*, **4**, (1961) 378–84.
7. Ezekwe, C. I. & Ezeilo, C. C. O., Measured solar radiation in a Nigerian environment compared with predicted data. *Solar Energy*, **26** (1981) 181–6.
8. Bamiro, O. A., Empirical relations for the determination of solar radiation in Ibadan, Nigeria. *Solar Energy*, **31** (1983) 85–94
9. Ideriah, F. J. K. & Suleiman, S. O., Sky conditions at Ibadan during 1975–1980. *Solar Energy*, **43** (1989) 325–30.
10. Fagbenle, R. L., A comparative study of some simple models for global solar irradiation in Ibadan, Nigeria. *International Journal of Energy Research*, **16** (1992) 583–95.
11. Oladiran, M. T., Utilization of solar energy in Nigeria. In *Multiphase transport and particulate phenomena*, Vol 2, ed. Veziroglu, T. N. pp 615–29. Hemisphere, New York, 1990.
12. Oladiran, M. T., Total solar radiation received at various collector inclinations. *Applied Energy*, **48** (1994) 149–61.
13. Collares-Pereira, M. & Rabl, A., The average distribution of solar radiation — correlations between diffuse and hemispherical and between daily and hourly insolation values. *Solar Energy*, **22** (1979) 155–64.
14. Liu, B. Y. H. & Jordan, R. C., (Eds) Availability of solar energy for flat plate solar heat collectors. In *Applications of Solar Energy for Heating & Cooling of Buildings*. ASHRAE, Atlanta, 1977.
15. Klien, S. A., Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, **19** (1977) 325–9.
16. Duffie, J. A. & Beckman, W. A., *Solar Engineering of Thermal Processes*. Wiley, New York, 1980.