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Measurement of global solar radiation on inclined surfaces of any orientation under overcast sky condition

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ABSTRACT. In this paper some observations of total solar radiation on sloped surfaces of different inclinations made at Roorkee under overcast sky conditions are presented along with the measuring technique. The observations indicate that the assumption of isotropy of the sky radiation under overcast sky conditions with altrostratus type of clouds is not justified. It is shown that the total radiation received by a surface of any inclination varies considerably with the orientation with respect to the sun for a given solar altitude. The ratio of total solar radiation on an inclined plane of any azimuthal orientation with respect to the sun, to that on a horizontal plane is found to be fairly independent of solar altitude. It is also observed that the albedo of the ground with green grass varies from 20 to 24 per cent.

1. Introduction

The increased use of flat plate collector for utilization of solar energy for water heating and airconditioning the space has led to the necessity of measuring solar radiations on inclined surfaces under different sky conditions. Measurement of direct and diffuse radiation on sloped surfaces of any orientation under overcast, average and clear days have not been so far attempted in the tropics.

The India Meteorological Department publishes the measured solar radiation data, in their monthly radiation bulletins, in the form of daily totals and some times hourly values of total solar radiation intensity on a horizontal plane for a few stations. For most of the engineering problems such as the utilization of solar energy and for environmental control, the solar radiation data for sloped and vertical surfaces for various orientations for clear, average and overcast sky conditions are needed. Such measured data is practically nonexistent in this country. For the purpose of assessing design solar heat loads on buildings usually the solar radiation for clear days is used. However, for the design of solar energy utilization devices, total solar radiation other than on clear days should also be given the weightage. It has been reported by Desikan, Iyer and Rahalkar (1968) that at Delhi (near to Roorkee) the diffuse radiation on a horizontal surface varies from 19 per cent (November) to 26 per cent (June) of the total solar radiation on clear days and from 24 per cent (November) to 59 per cent (July) if all days are taken into account. It indicates that in tropical regions diffuse radiation forms a high percentage of the total radiation and thus plays an important role.

The total radiation received on any day, by an inclined plane is dependent on the cloudiness, the atmospheric turbidity and the albedo of the ground. Unfortunately in tropics not much measured data is available on cloudiness per cent. If such data based on measurements spread over long periods are available, the estimation of total solar radiation on a horizontal surface can be made to a fair degree of accuracy. However, in case of vertical and inclined surfaces, knowledge of the distribution of diffuse radiation over the sky vault is also necessary.

Various assumptions are made for the computation of total solar radiation on inclined surfaces for a cloudless sky. In the formula proposed by Morse and Czarnecki (1958) it is assumed that the diffuse radiation is largely concentrated around the sun and treated as directional radiation. Whereas Liu and Jordan (1961) have assumed the diffuse radiation as uniformly distributed over the whole sky, which implies that radiation flux on a vertical surface will be one-half of that on a horizontal surface. Norris (1966) in Australia has shown, based on actual measurements of solar radiation made on an inclined surface (60 degrees to the horizontal) facing north, that errors upto 22 per cent and 30 per cent result by using the formula suggested by Liu and Jordan and Morse and Czarnecki respectively; still higher errors were found under cloudy sky conditions. Kondratyev and Manolva (1960) suggest that for an overcast sky an azimuthal isotropy

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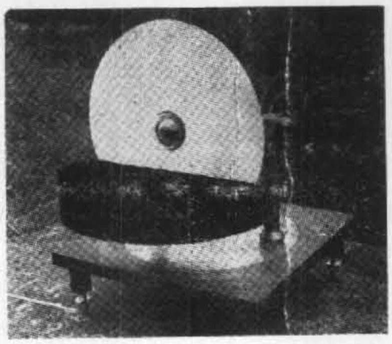

Fig. 1

can be assumed, while Moon and Spencer (1942), Robinson (1966), Heywood (1970) and Parmelee (1954) consider that as in the case of clear sky conditions, the anisotropy of the sky radiation should be taken into account. It should also be noted that the ground reflected component cannot be neglected, in the computation of total solar radiation on vertical and inclined surfaces. For this purpose, the albedo of the ground under different sky conditions is to be known. The results of some experimental work done in this context are discussed in this paper.

2. Experimental procedure

Total and diffuse solar radiation on a horizontal surface are being continuously recorded at the Institute's observatory for several years. Moll-Gorczyinski solarimeters and Cambridge recorders are used for this purpose. The diffuse solar radiation is measured by using a suitable shield over the thermopile which cuts-off direct solar rays throughout the day. The shield is a circular flat ring 5 cm wide and 35 cm in diameter and can be clamped at any point along two parallel bars, inclined to the horizontal at angle equal to the latitude of the place. Errors due to the shade ring (HMSO 1956) are taken into account and diffuse part is corrected accordingly.

A Kipp solarimeter is mounted on a universal stand, which enabled it to be tilted at any angle in the vertical plane between the horizontal and vertical positions and rotated to any azimuthal orientation in the horizontal plane. A detachable semi-circular screen as designed by the Division of Building Research, Australia, painted with lamp-black is also used to prevent the reflected ground radiation reaching the instrument. By keeping the screen horizontal irrespective of the inclination of the solarimeter, the radiation reflected from the ground can be excluded. The e.m.f. output of the solarimeter was observed with a sensitive D.C. Microvoltmeter which can read to 1.0 microvolt. The solarimeter with the universal mount and the ground reflection screen is shown in Fig. 1.

3. Measurement of albedo of the ground

It is known that an inclined surface receives direct solar radiation, diffuse solar radiation and also the radiations reflected from the ground. Measured data on the ground reflected radiation for sloping surfaces of different inclinations is not usually available. However, it can be obtained from the measurement made with and without the ground reflection screen and the total solar radiation on a horizontal surface. From these observations the albedo of the ground could be computed as shown below:

The total radiation (I_{TR}) received by an inclined surface as given by Garg (1972) is

$$I_{TR} = D_T + d_T + I_H R \sin^2(\beta/2) \tag{1}$$

where,

D_T = direct solar radiation on inclined surface,

d_T = diffuse solar radiation on inclined surface,

I_H = total solar radiation on horizontal surface,

R = albedo of the ground, and

β = tilt of plane from horizontal.

When a screen is used to cut-off the ground reflected part, Eq. (1) reduces to

$$I_T = D_T + d_T \tag{2}$$

From equations (1) and (2) we get the albedo of the ground, as

$$R = \frac{I_{TR} - I_T}{I_H \sin^2(\beta/2)} \tag{3}$$

TABLE 1

Ratio of total solar radiation on various inclined surfaces to total solar radiation on horizontal surface (I_T / I_H) for different solar altitudes and azimuth angles under overcast sky conditions for Roorkee

Tilt of plane from horizontal (°)	Azimuth of plane relative to sun (°)	Altitude of sun (°) 20°	30°	40°	50°	60°	70°	80°	$^*I_T / I_H = \cos^2(\beta/2)$
	0	1·03	1·02	1·02	1·00	0·99	0·99	0·98	
	45	1·00	0·99	0·99	0·98	0·97	0·96	0·95	
30	90	0·93	0·92	0·92	0·91	0·90	0·90	0·89	0·39
	135	0·86	0·86	0·85	0·85	0·85	0·84	0·84	
	180	0·82	0·81	0·80	0·80	0·79	0·78	0·78	
	0	0·96	0·95	0·95	0·94	0·94	0·93	0·93	
	45	0·90	0·89	0·89	0·89	0·88	0·88	0·87	
45	90	0·85	0·84	0·84	0·83	0·83	0·82	0·82	0·85
	135	0·79	0·78	0·78	0·77	0·77	0·76	0·75	
	180	0·71	0·70	0·70	0·70	0·69	0·68	0·68	
	0	0·87	0·86	0·85	0·85	0·84	0·83	0·83	
	45	0·77	0·76	0·75	0·75	0·74	0·73	0·72	
60	90	0·64	0·63	0·62	0·62	0·61	0·61	0·60	0·75
	135	0·58	0·57	0·56	0·56	0·55	0·54	0·53	
	180	0·53	0·52	0·51	0·50	0·49	0·49	0·48	
	0	0·63	0·63	0·62	0·62	0·61	0·61	0·61	
	45	0·57	0·56	0·56	0·55	0·54	0·54	0·53	
90	90	0·49	0·48	0·48	0·48	0·47	0·47	0·46	0·50
	135	0·38	0·37	0·36	0·36	0·36	0·36	0·35	
	180	0·36	0·36	0·35	0·35	0·35	0·34	0·34	

*By Liu and Jordan's formula where the sky is assumed as isotropic.

About 80 observations were made for computing albedo of the ground. The ground surface at which the observations were made was fully covered by green grass. These results indicate that for a ground covered by green grass, the albedo varies from 0·20 to 0·24 around the average value of 0·22.

4. Radiation on inclined surfaces on overcast days

A number of observations of total solar radiation were made on inclined surfaces of different slopes and orientations at Roorkee during several overcast days during 1969 and 1970. It may be mentioned here that these studies were spread over several overcast days and these days were so selected that the sky conditions were similar. The type of cloud cover may be classified as thick altostratus (C_M2) as per World Meteorological Organisation's (WMO) classification. As the sun was not visible, the altitude and the azimuth of the sun at the time of observations were computed. The azimuthal orientation with respect to sun was then obtained from the azimuthal position of the scan and the solar azimuth with respect to the true north.

The data collected has been analysed in terms of the ratios (I_T/I_H) of radiation on inclined (with ground reflection screened) to a horizontal surface for various solar altitudes and azimuthal orientation In this study, azimuthal orientation

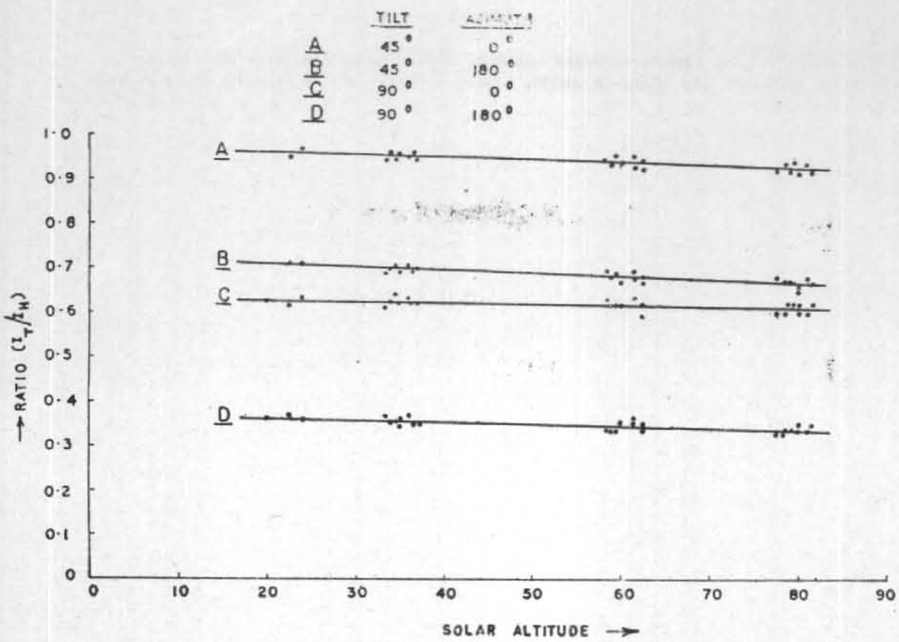
TILT
A 45° 0°
B 45° 180°
C 90° 0°
D 90° 180°
A
B
C
D
→ RATIO (I_T/I_H)
SOLAR ALTITUDE →

Fig. 2

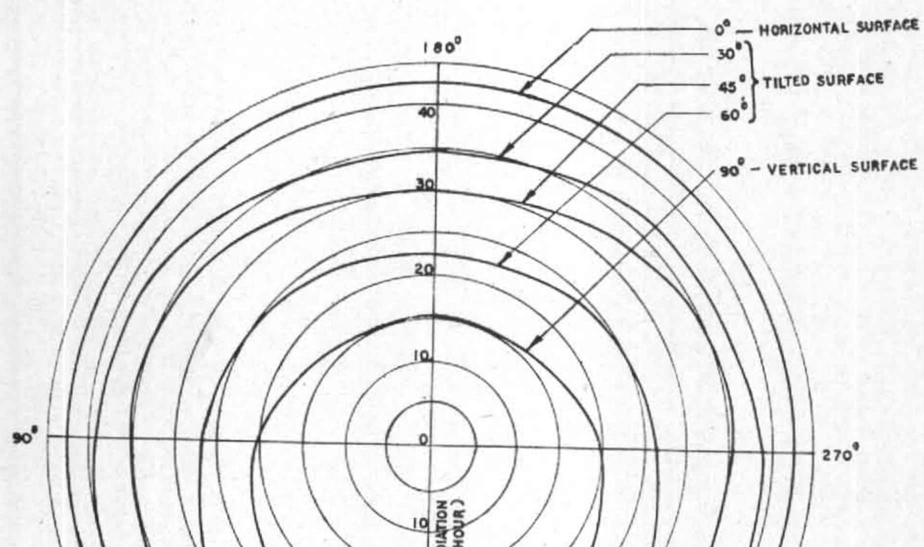
0° — HORIZONTAL SURFACE
30°
45° TILTED SURFACE
60°
90° - VERTICAL SURFACE
180°
90°
270°
0°
TOTAL SOLAR RADIATION (LANGLEY/HOUR)
AZIMUTH

Fig. 3

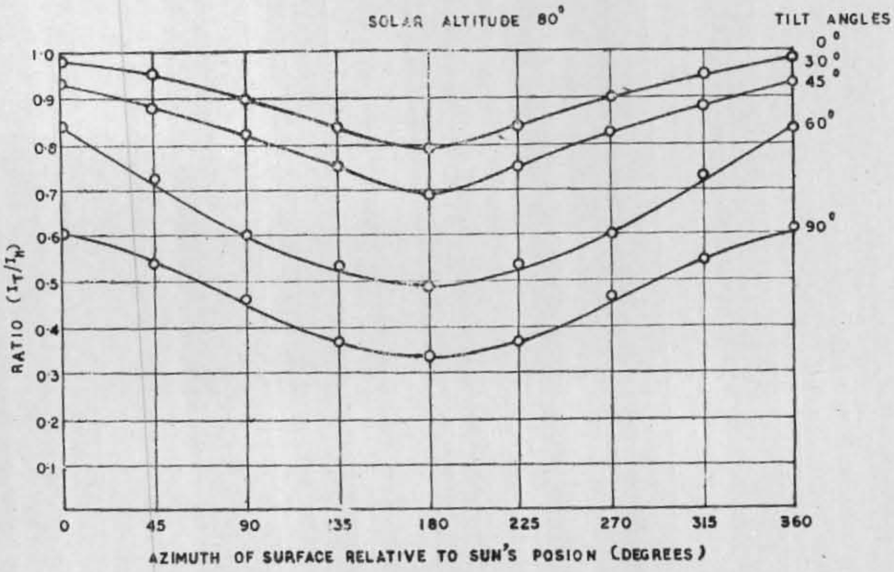

Fig. 4

of the surface is measured with respect to the position of the sun at any time. These observations cover a range of solar altitudes from 20 degrees to 80 degrees. The tilts selected for the study were 30°, 45°, 60° and 90° from the horizontal. The ratios I_T/I_H were plotted against solar altitude for various azimuthal orientations. Fig. 2 illustrates the effect of solar altitude on these ratios for a few typical cases. It can be seen that though the effect of solar altitude on these ratios is very small there appears to be linear variation with solar altitude. The ratios of I_T/I_H for all the solar altitudes from 20° to 80° at interval of 10° for the above four tilts as obtained from these plots are given in Table 1. It can be seen from the table that the ratios vary linearly with the solar altitude, though this variation is small (of the order of 4 to 6 per cent). It may also be noted that for a given solar altitude, these ratios vary considerably with the azimuthal orientation and tilt angles. As much as 20 and 40 per cent fall is found for variation in azimuthal orientation from 0 to 180° in the case of 30° and 90° tilts respectively.

Typical azimuthal variation of total solar radiation for a fixed solar altitude of 30-degree is shown in a polar diagram (Fig. 3) for different tilts. Fig. 4 gives the variation of the ratios (I_T/I_H) for various tilts with the azimuthal orientation for a solar altitude of 80 degrees. This clearly brings out that for overcast sky conditions with altostratus type of clouds anisotropy exists.

5. Conclusions

Though this type of study needs analysis of data based on prolonged periods, the significant conclusions one could draw on these limited observations made under altostratus clouds are :

1. Measurements of solar radiation on inclined surfaces for overcast sky conditions indicate that the usual $\cos^2(\beta/2)$ relation between the intensity of diffuse radiation I_T incident upon a surface titled at β degrees from the horizontal surface, to the intensity of diffuse radiation I_H is not valid.

2. Considerable azimuthal anisotropy exists even in case of overcast sky. For a given solar altitude and tilt of the surface, the one facing the sun receives more diffuse radiation than the one facing just opposite.

3. For a given azimuthal orientation the ratio of total radiation on an inclined surface to that on a horizontal surface is found to be practically constant with solar altitude.

4. It is observed that the albedo of the ground when covered with green grass varies from 0·20 to 0·24.

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