551.521.1 : 551.506

Design data for direct Solar Utilization devices
Part II — Solar Radiation data

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(*Received 7 May 1968*)

ABSTRACT. This paper reports the computed values of conversion factor for obtaining the values of mean monthly daily total solar radiation received on tilted surfaces from the available records on horizontal surfaces for four widely separated Indian cities. The angles of tilt selected are normally used for flat plate collectors during various seasons of the year. Measured values of the ratio of diffused to total solar radiation have been used for Delhi and Poona, and computed values for Calcutta and Madras. Liu and Jordan's formulae based on the assumption of an isotropic sky have been employed.

1. Introduction

The availability of data regarding solar radiation at any place is an essential pre-requisite for deciding the techno-economic feasibility of solar utilization and subsequent design of the equipment. The India Meteorological Department publishes the solar radiation data in *Monthly Radiation Bulletins*, in the form of daily and sometimes hourly values of total solar radiation intensity on a horizontal plane. In most of the cases, only actual sunshine hours are recorded and only in very few cases, the values of diffused radiation on horizontal plane are given. For the deisgn and feasibility studies on flat plate collectors, however, it is essential to know the total incident solar radiation including the diffuse one, when the collector is inclined at an optimum angle (Garg and Gupta 1967) corresponding to the critical season of use. For this purpose, it is convenient to know the conversion factors for tilted surfaces for a single representative day of each month. Liu and Jordan (1967) have tabulated these conversion factors only for direct radiation and Page (1961) has assumed an empirical relation for the ratio of diffused to total radiation to get such values for total radiation for various latitudes. Van Straaten (1961) has computed the actual value of radiation received by tilted surfaces for cities of South Africa and Morse (1958) for the cities in Australia. No such data for tilted surfaces, relevant to the tilts used for solar devices, seems to be available in literature so far for Indian cities. This paper seeks to report such data for four principal Indian cities, characteristic of the respective latitudes and climates: Delhi, Poona, Calcutta and Madras.

2. Computation procedure

As reported by Ward (*see* Ref.), the hourly conversion factor for direct radiation for a tilted surface with any general orientation with reference to normal radiation intensity in terms of celestial co-ordinates is given by the equation—

$$I_{th} / I_{NH} = \cos \theta_t$$

I_{th} = Direct hourly solar radiation intensity on tilted surface.

where I_{NH} = Normal and hourly beam radiation intensity

$$\cos \theta_t = (\cos \beta \sin L - \sin \beta \cos L \cos \phi) \sin \delta + (\cos \beta \cos L + \sin \beta \sin L \cos \phi) \times \cos \delta \cos \omega + \sin \beta \sin \phi \cos \delta \sin \omega \quad (1)$$

and β = Tilt with respect to horizontal

L = Latitude

ϕ = Azimuth angle with respect to south direction

δ = Solar declination in the relevant data

ω = Solar hour angle at the particular hour with respect to solar noon.

Further, for the radiation on horizontal surface, the angle of incidence is deduced from the following expression obtained by purely geometrical considerations—

$$\frac{I_{Hh}}{I_{Nh}} = \cos \theta_H$$

I_{Hh} = Direct hourly solar radiation intensity on horizontal surface

where $\cos \theta_H = \cos L \cos \delta \cos \omega + \sin L \sin \delta \quad (2)$

Hence, $$\frac{I_{th}}{I_{Hh}} = \frac{\cos \theta_t}{\cos \theta_H} = R_{DH} \quad (3)$$

where R_{DH} = Hourly conversion factor for direct radiation.

Assuming the isotropy of sky radiation [though it is not so and is always more from the sky near the sun and so a surface facing the sun will receive more diffuse radiation (Heywood 1966)] the hourly conversion factor for diffused radiation R_{dh} is given by—

$$R_{dh} = \frac{(1 + \cos \beta)}{2} \qquad (4)$$

The hourly total radiation conversion factor (R_{Th}) can now be obtained from R_{DH}, R_{dh} and the hourly ratio D/H of diffused total solar radiation intensity—

$$R_{Th} = (1 - D/H)\, R_D + (D/H)\, R_d$$

$$= \frac{H_{th}}{H_{Hh}} \qquad (5)$$

where H_{th} = Total hourly solar radiation on tilted surface and H_{Hh} = Total hourly solar radiation on horizontal surface.

The celestial co-ordinates have been used to reduce the input data to the computer as the solar declination is assumed to be constant for a day and is easily available from the *Nautical Almanac* (*see* Ref). The hour angle ω (in radians) is easily calculated within the programme by the equation—

$$\omega = 0{\cdot}01745 \times 15 \times [\, 12 - EN - 0{\cdot}0666\,(L^* - 82{\cdot}5) - \text{I.S.T.}] \qquad (6)$$

where L^* = Longitude of the place, and

EN = Equation of time (Heywood 1966).

For getting the daily value of conversion factor, we obtain the value—

$$R_T = \frac{\Sigma\,(H_{th})^+}{\Sigma\,(H_{Hh})} = \frac{H_T}{H},$$

where the summation is for all hours when H_{th} is positive.

3. Results and Discussions

Using the hourly total and diffused values of solar radiation intensity for Delhi and Poona, as reported by Mani and Chacko (1963) and the hourly total values at Calcutta and Madras (Mani *et al.* 1962) along with the computed values of D/H obtained by using the curves reported by Garg and Gupta (*see* Ref.) the hourly conversion factors have been obtained for total direct and diffused radiation and the daily conversion factor for total solar radiation. The tilts considered were Lat. $\pm$ 15 deg. and 0·9 times the latitude for orientation due South. The other azimuths with respect to South orientation were for the tilt corresponding to 0·9 times the latitude for Delhi and Madras only and had the values 15°, 30° and 45°. A digital computer, IBM 1620, was employed to determine the value of average daily conversion factors for each month of the year.

Figs. 1–4 show the month by month variation of the daily conversion factor for the various tilts and the cities considered and for an orientation due South. It can be easily seen that from March to October, the tilt (Lat. —15°) gives the maximum conversion factor which is almost equal to unity throughout the period. For winter season, the tilt (Lat. + 15°) gives the maximum conversion factor and these occur fortunately in the coldest months of December and January when the daily solar radiation has the least value (Gupta *et al.* 1967). The miximum value, however, varies with the latitude and is fortunately higher with higher latitudes, the range being from 1·15 for Madras to 1·45 for Delhi. The curves for the tilt (= 0·9 latitude) are in the middle of these hours.

The effects of varying the orientation from South are shown in Figs. 5 and 6 for the lowest and highest latitude corresponding to Madras and Delhi and for a tilt=0·9 times the latitude. It can be seen that except for November and December in Delhi a deviation upto 45° from South towards West is not only permissible but is beneficial. For November and December, there is a reduction upto 5 per cent upto a deviation of 30° and upto 10 per cent upto a deviation of 45° West.

4. Summary and conclusions

(i) Conversion factors for obtaining incident solar radiation on tilted flat plate collectors have been obtained and reported for Delhi, Calcutta, Poona and Madras.

(ii) A shift of upto 30° towards West from average orientation due South has been found to slightly increase the incident radiation on tilted collectors when working round the year.

5. Acknowledgement

The authors are grateful to Shri N. K. D. Choudhury, Head of the Physics Division, for his guidance and constant encouragement. The work reported here forms a part of the research programme of Central Building Research Institute, Roorkee and is published with the permission of the Director.

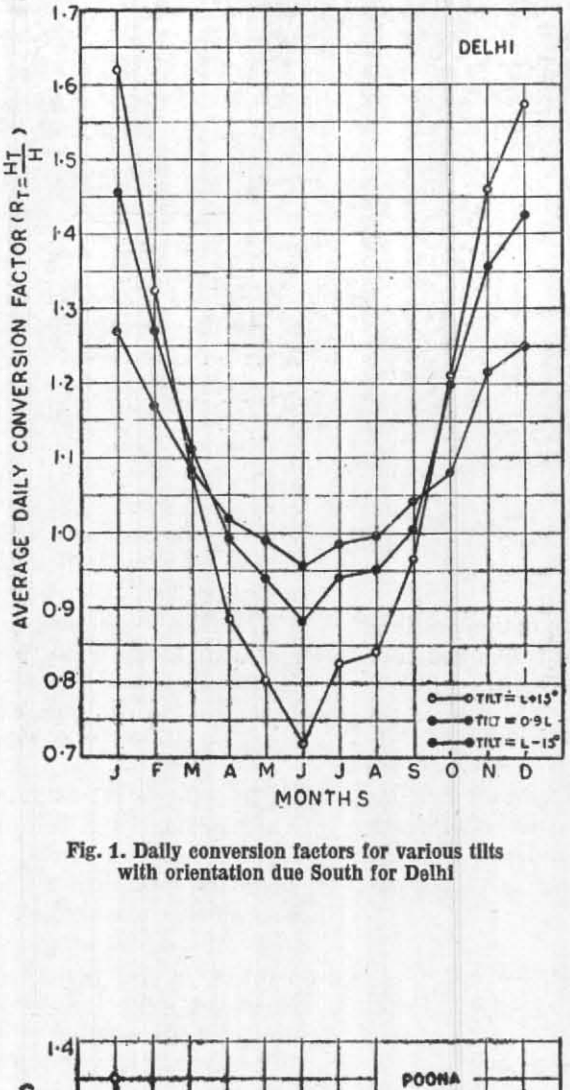

Fig. 1. Daily conversion factors for various tilts with orientation due South for Delhi

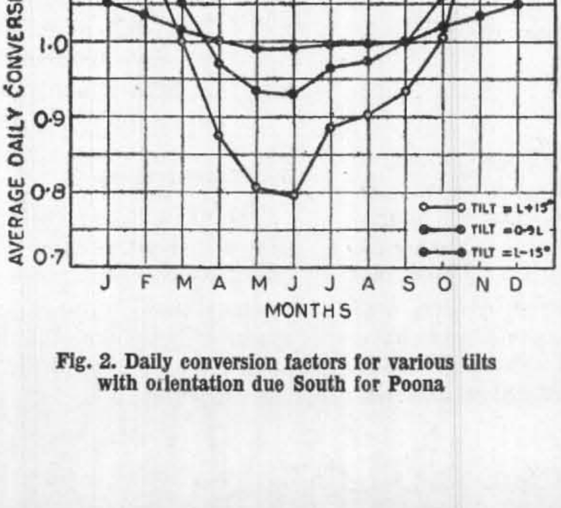

Fig. 2. Daily conversion factors for various tilts with orientation due South for Poona

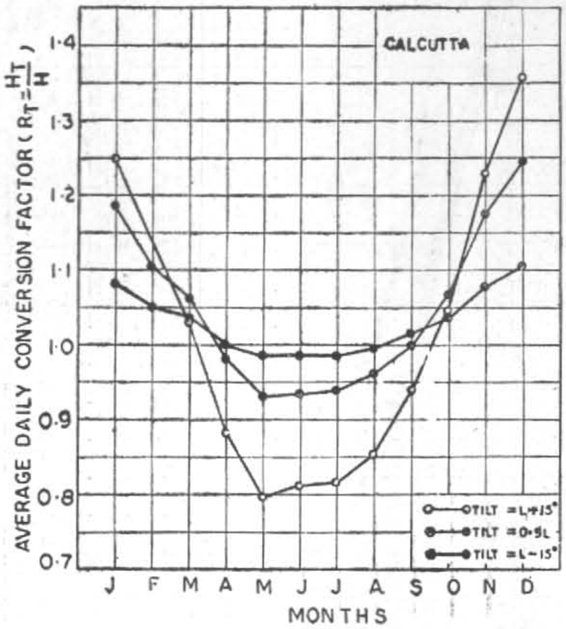

Fig. 3. Daily conversion factors for various tilts with orientation due South for Calcutta

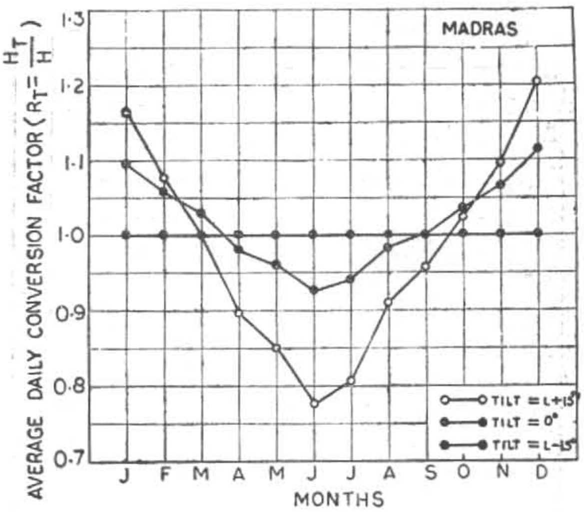

Fig. 4. Daily conversion factors for various tilts with orientation due South for Madras

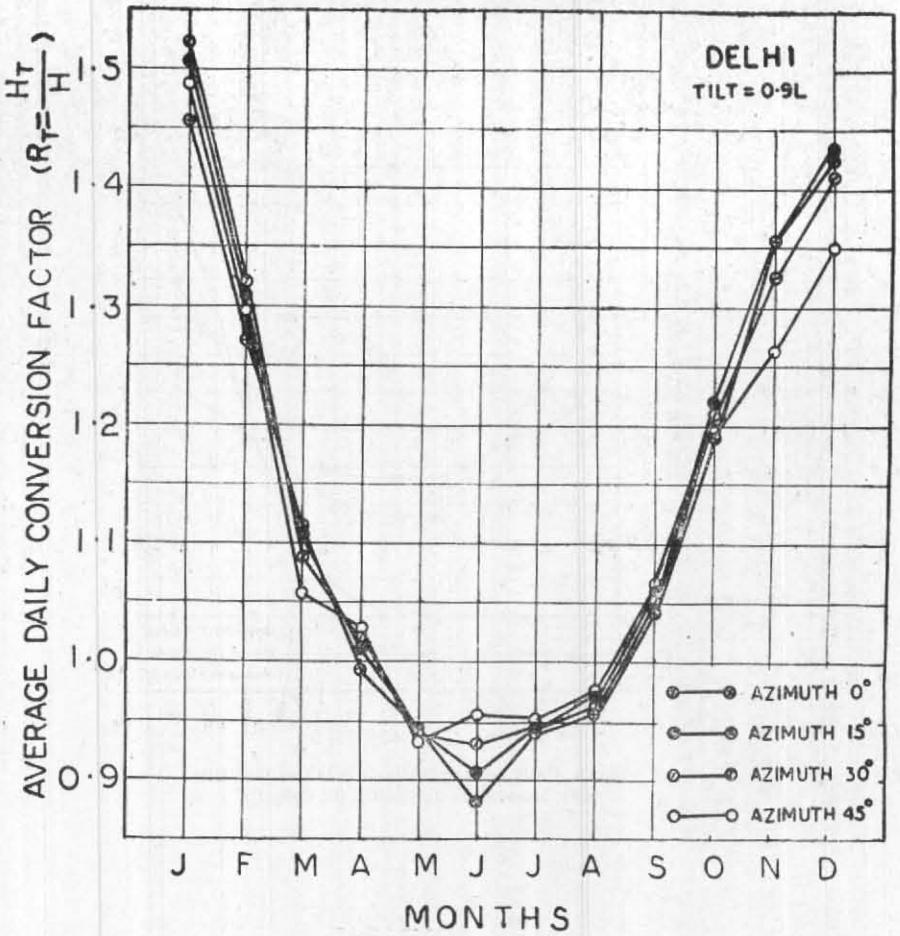

Fig. 5. Daily conversion factors for various azimuths for Delhi

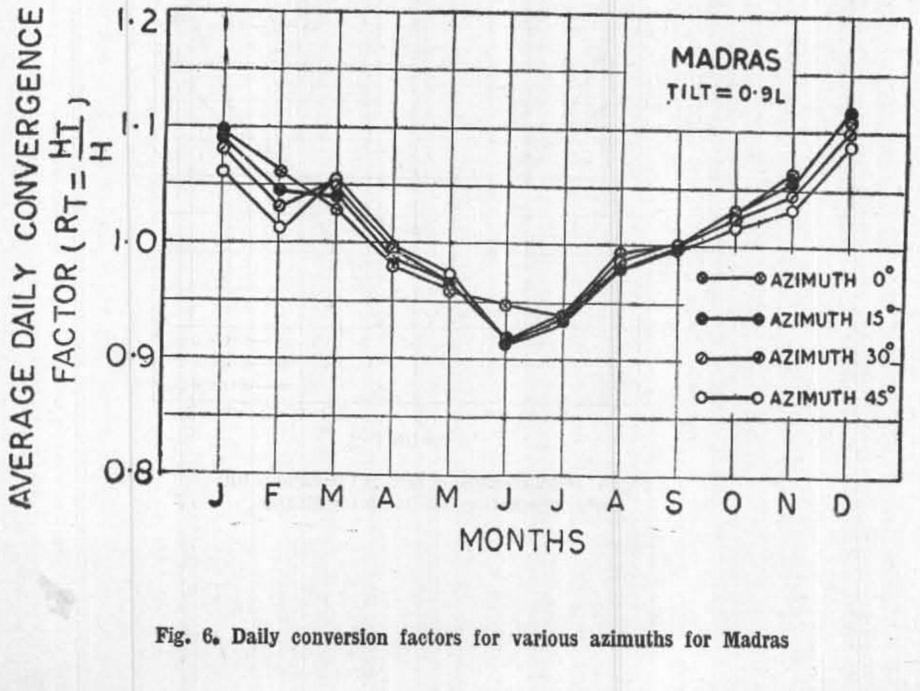

Fig. 6. Daily conversion factors for various azimuths for Madras

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