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Measurement & Analysis of Solar Radiation & Illumination for Clear Sky Conditions

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Simultaneous measurements of solar radiation and illumination carried out over a period of nearly three years at Roorkee for clear sky conditions have been analyzed and a set of empirical expressions are obtained for the direct and diffuse components of solar radiation and illumination. Different expressions, in sine functions of solar altitude, are given for three different ranges of atmospheric turbidity specified in terms of Linke's new turbidity factor. These expressions are useful for the calculation of thermal radiation and illumination quantities for practical problems, e.g. in the design of buildings. The values of luminous efficiency for the two components of solar radiation determined from these measurements are also given. A knowledge of luminous efficiency can enable the conversion of relatively abundant solar radiation data in to illumination data which are scarce.

1. Introduction

An important requirement for the design of the thermal and visual environments in buildings is the knowledge of climatological factors which influence the internal environment. Of these, thermal and visual components of radiation from the sun and the sky are of particular significance. Simple methods for the calculation of solar radiation and illumination intensities are, therefore, needed to solve the problems related to functional efficiency of buildings. If the radiation and illumination quantities are expressed as functions of solar altitude and atmospheric turbidity, these quantities, on any plane of inclination, can be easily assessed with reasonable accuracy for any plane, season and time. In this direction, empirically established relationships can play an important role. In the past, several workers have attempted to evolve computational methods for these quantities.[1-5] However, these methods are generally applicable for certain places or regions only and accordingly have their own limitations. Interrelationships between different components of solar radiation have also been attempted to facilitate the use of solar radiation data in localities where estimates of long term average total radiation are available.[6,7] The present study deals with simultaneous measurements of solar radiation and illuminations (on a horizontal surface) for clear (cloudless) sky conditions covering wide range of atmospheric turbidity. Based on these measurements, polynomial expressions in sine functions of solar altitude for the direct and diffuse components of both the solar radiation and illumination have been established separately for three distinct ranges of atmospheric turbidity specified in terms of Linke's new turbidity factor.[8-10]

Often, long term solar radiation data collected and processed by meteorological departments are readily available in suitable form. But similar illumination records are not available as they do not figure in the routine observational programmes of climatological elements. In view of this, attempts have been made to derive natural illumination intensities from solar radiation data. In the absence of measured data on illumination, the International Commission on Illumination (CIE) also favours this method. Based on this approach, the illumination climate in USSR has been classified into five luminous climatic zones.[11] For such conversions, a knowledge of values of luminous efficiency of solar radiation to a certain degree of accuracy is essential. Some workers have reported the values of luminous efficiency for certain European cities.[5,12-15] In the tropics, practically no attempt was made to determine it except for some approximate and indicative results.[16] In view of the demand for illumination data, the luminous efficiency of both the direct and diffuse solar radiation derived from above measurements are presented in this paper.

2. Atmospheric Attenuation of Solar Radiation

Solar radiation incident on a unit surface normal to sun's rays outside the earth's atmosphere, for mean sun-earth distance, is known as the solar constant.

Its most recent and accepted value, as given by Thekaekara,[17] is 1353 W/m^2 or 1·94 cal cm^{-2} min^{-1}. The solar light constant calculated by the present author from Thakaekara's extra-terrestrial spectral irradiance comes out to be 127·1 klux.

While passing through the earth's atmosphere, the direct solar beam interacts with the atmospheric constituents like air molecules, aerosols, water vapour, ozone, etc. Thus the incoming solar energy is partly scattered, partly absorbed, and partly transmitted as direct component. On the earth's surface, the proportion of the direct and diffuse components depends on the angular height of the sun above the horizon and concentration of the atmospheric elements, i.e. turbidity conditions.[18] Therefore, both the direct and diffuse components of solar radiation and illumination available on the earth's surface should be expressible as functions of solar altitude and atmospheric turbidity.

3. Spectral Luminosity and Luminous Efficiency of Solar Radiation

On the earth's surface, the spectral composition of solar radiation may vary from about 0·30 μ in the ultraviolet region to about 3·0 μ in the infrared region. The human eye can perceive energy in the wavelength region from about 0·38 to 0·78 μ only. The relative sensitivity of normal-light adopted human eye is different at different wavelengths in this region and is represented by relative spectral luminosity function $V(\lambda)$. The variation of $V(\lambda)$ for photopic vision (Ref. 19) is shown in Fig. 1. Its absolute values are obtained by multiplying $V(\lambda)$ with a constant factor $K_{\max}$ ($=680$ lumens/W$\approx$ 475 klux/cal cm^{-2} min^{-1}). Thus the luminous efficiency of solar radiation can be mathematically represented by the expression

$$K=\frac{K_{\max}\int_{0\cdot38}^{0\cdot78} V(\lambda)\, I_\lambda\, d\lambda}{\int_0^\infty I_\lambda\, d\lambda}=\frac{E}{I} \qquad \ldots(1)$$

where I_λ is the spectral solar energy and E and I are the simultaneously available integral illumination and radiation, respectively.

4. Measurement of Solar Radiation and Illumination

Instantaneous spot measurements were carried out simultaneously for global and diffuse solar radiation and illumination on a horizontal surface. The experimental arrangement is shown in Fig. 2. A Moll-Gorczynski Pyranometer called solarimeter[20] and a selenium photocell were mounted side by side on an adjustable tilt table which was held in the horizontal position for the measurements presented here. Measurements were carried out on the terrace of the Physics Laboratory of the Central Building Research Institute, Roorkee, so as to provide unobstructed view of the whole sky vault to the sensing elements

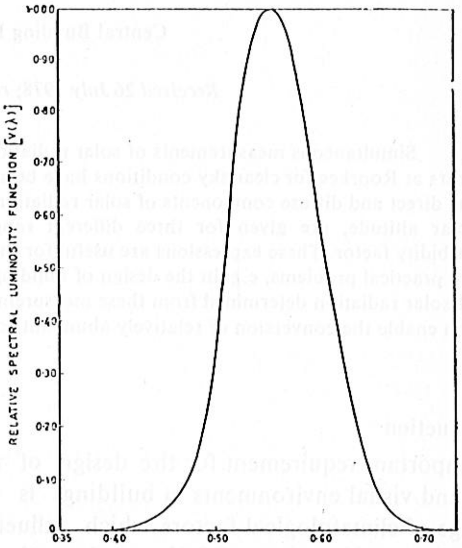

Fig. 1—Relative spectral luminosity function at different wavelengths in the visible region

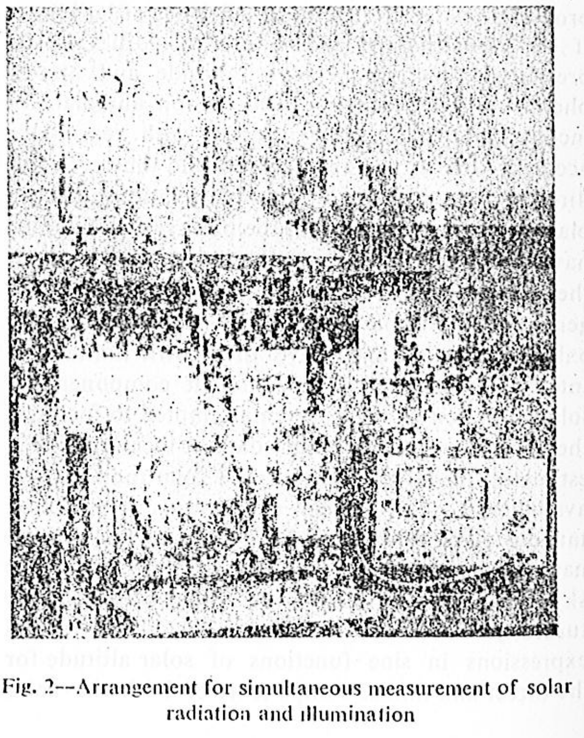

Fig. 2—Arrangement for simultaneous measurement of solar radiation and illumination

of solarimeter and photocell. Nearby was a building subtending an angle of approximately 1 degree from the measuring spot. This will have practically no effect on the accuracy of measured values. The diffuse solar radiation and illumination were obtained by shading the sensitive elements by means of a blackened circular disc of appropriate diameter. The outputs of the solarimeter and photocell were recorded by means of suitable meters.

5. Results and Discussion

The radiation and illumination values measured at different solar elevations were divided into three different ranges of atmospheric turbidity specified in terms of Linke's new turbidity factor T. This has the advantage of representing atmospheric turbidity conditions with a single meteorological parameter. It is defined as the ratio of total extinction coefficient (σ_m) of the actual atmosphere for direct solar beam to that of a standard atmosphere (σ_s) consisting of pure air molecules and 1 cm of precipitable water.[10] Thus

$$T=\frac{\sigma_m}{\sigma_s}=\frac{\log\,(I_0/I_m)}{\log\,(I_0/I_s)}$$

or

$$T=\frac{\log I_0-\log I_m}{\log I_0-\log I_s} \qquad \dots(2)$$

where I_0 is the solar constant; I_m is the measured direct solar radiation and I_s that for the standard atmosphere for the same solar elevation as I_m, both at normal incidence. For determination of T, I_m was measured with a Linke and Fuessner actinometer[21] and values of I_s were calculated from more recent available data.[22,23] The three ranges of atmospheric turbidity, namely, $2{\cdot}0 < T < 3{\cdot}0$, $3{\cdot}0 < T < 4{\cdot}0$ and $4{\cdot}0 < T < 5{\cdot}0$ (denoted by T_1, T_2 and T_3) into which the data were broadly divided, may be roughly considered as the representatives of low, average and high turbidity conditions, respectively.

5.1 Direct and Diffuse Solar Radiation

Fig. 3 shows the plot of direct solar radiation (D_H) on a horizontal surface against solar altitude (θ) for the three turbidity ranges mentioned earlier. The direct component was obtained by subtracting the diffuse component from the global radiation. These data were used for determining the empirical relations for direct radiation intensity on a horizontal surface. As discussed by Spencer,[24] the form of the expression for a horizontal surface was assumed to be polynomial in sine function of solar altitude having no constant and linear terms, i.e.

$$D_H = a_2 \sin^2\theta + a_3 \sin^3\theta + a_4 \sin^4\theta + \dots \qquad \dots(3)$$

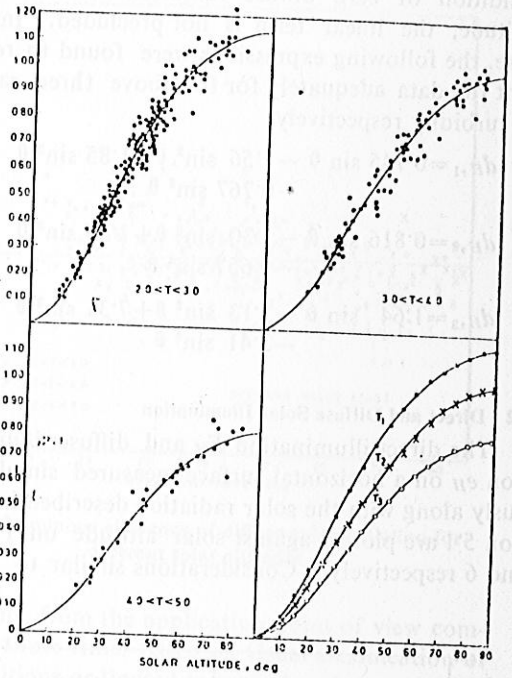

Fig. 3—Variation of direct solar radiation on a horizontal surface with solar altitude for different turbidity conditions

From this it is easy to derive an expression for the radiation intensity normal to sun's rays which is often more convenient for calculating direct solar radiation on inclined planes. In the above polynomial expression [Eq. (3)], constants a_2, a_3, a_4,...etc. (regression coefficients) were evaluated by fitting the data in the expression and applying the least squares criterion for obtaining normal equations which were solved by the matrix inversion method. Polynomials containing different number of terms were tried. Keeping in view the reasonable accuracy, etc. the following expressions were finally chosen.

For $2{\cdot}0 < T < 3{\cdot}0$

$$D_{H,1}=3{\cdot}27 \sin^2\theta-3{\cdot}17 \sin^3\theta+1{\cdot}03 \sin^4\theta \qquad \dots(4)$$

For $3{\cdot}0 < T < 4{\cdot}0$

$$D_{H,2}=2{\cdot}58 \sin^2\theta-2{\cdot}68 \sin^3\theta+1{\cdot}10 \sin^4\theta \qquad \dots(5)$$

and for $4{\cdot}0 < T < 5{\cdot}0$

$$D_{H,3}=1{\cdot}64 \sin^2\theta-1{\cdot}10 \sin^3\theta+2{\cdot}64 \sin^4\theta \qquad \dots(6)$$

Here the radiation values are in cal cm^{-2} min^{-1}. The corresponding expressions for direct solar radiation normal to sun's rays are found by dividing the right hand side of Eqs. (4), (5) and (6) by the cosine of solar angle of incidence, i.e. $\cos(90-\theta)=\sin\theta$.

In the case of diffuse solar radiation on a horizontal surface, d_H is plotted against solar altitude as in Fig. 4. Though there should not be a constant term in the power series expression to satisfy the condition of zero diffuse radiation at zero solar altitude, the linear term is not precluded. In this case, the following expressions were found to represent the data adequately for the above three ranges of turbidity respectively.

$$d_{H,1}=0{\cdot}745 \sin\theta - 1{\cdot}56 \sin^2\theta + 1{\cdot}85 \sin^3\theta - 0{\cdot}767 \sin^4\theta \quad \ldots(7)$$

$$d_{H,2}=0{\cdot}816 \sin\theta - 1{\cdot}30 \sin^2\theta + 1{\cdot}45 \sin^3\theta - 0{\cdot}657 \sin^4\theta \quad \ldots(8)$$

$$d_{H,3}=1{\cdot}64 \sin\theta - 5{\cdot}13 \sin^2\theta + 7{\cdot}31 \sin^3\theta - 3{\cdot}41 \sin^4\theta \quad \ldots(9)$$

5.2 Direct and Diffuse Solar Illumination

The direct illumination E_H and diffuse illumination e_H on a horizontal surface measured simultaneously along with the solar radiation described in Section 5·1 are plotted against solar altitude on Figs. 5 and 6 respectively. Considerations similar to those of solar radiation led to the following expressions for the two components of solar illumination.

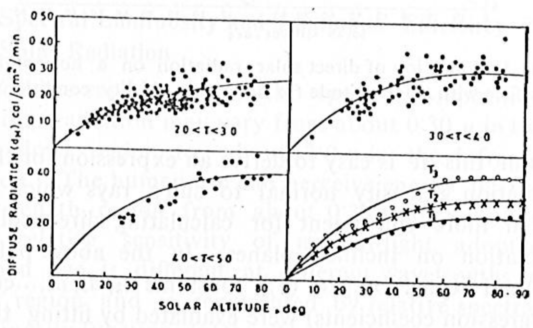

Fig. 4—Variation of diffuse solar radiation on a horizontal surface with solar altitude for different turbidity conditions

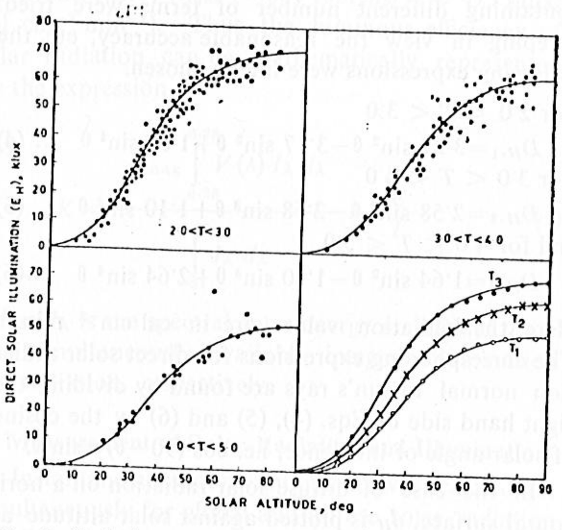

Fig. 5—Variation of direct solar illumination on a horizontal surface with solar altitude for different turbidity conditiosn

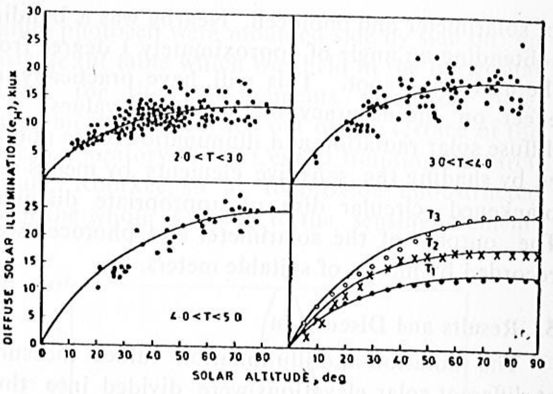

Fig. 6—Variation of diffuse solar illumination on a horizontal surface with solar altitude for different turbidity conditions

For direct solar illumination

$$E_{H,1}=109{\cdot}2 \sin^2\theta - 110{\cdot}6 \sin^3\theta + 557{\cdot}3 \sin^4\theta - 536{\cdot}4 \sin^5\theta \quad \ldots(10)$$

$$E_{H,2}=116{\cdot}1 \sin^2\theta - 414{\cdot}8 \sin^3\theta + 1414{\cdot}6 \sin^4\theta - 1745{\cdot}3 \sin^5\theta + 692{\cdot}6 \sin^6\theta \quad \ldots(11)$$

$$E_{H,3}=5{\cdot}0 \sin^2\theta + 193{\cdot}8 \sin^3\theta - 148{\cdot}6 \sin^4\theta \quad \ldots(12)$$

For diffuse solar illumination

$$e_{H,1}=37{\cdot}7 \sin\theta - 51{\cdot}6 \sin^2\theta + 39{\cdot}4 \sin^3\theta - 12{\cdot}3 \sin^4\theta \quad \ldots(13)$$

$$e_{H,2}=24{\cdot}2 \sin\theta + 30{\cdot}9 \sin^2\theta - 64{\cdot}9 \sin^3\theta + 27{\cdot}5 \sin^4\theta \quad \ldots(14)$$

$$e_{H,3}=58{\cdot}2 \sin\theta - 114{\cdot}8 \sin^2\theta + 153{\cdot}2 \sin^3\theta - 71{\cdot}7 \sin^4\theta \quad \ldots(15)$$

The values of illumination calculated from these expressions are in the units of klux. The expressions for direct solar illumination at normal incidence are obtained by simply reducing the power of sin θ by unity in each term of the Eqs. (10), (11) and (12).

5.3 Determination of Luminous Efficiency

From the simultaneously measured radiation and illumination quantities, the computations for the luminous efficiency of direct radiation (K_D) and of diffuse radiation (K_d), were made from the formulae,

$$K_D = E_H/D_H \quad \ldots(16)$$

and

$$K_d = e_H/d_H \quad \ldots(17)$$

These values are plotted in Figs. 7 and 8 respectively. Lot of scatter is observed in the luminous efficiency values. Bartineva and Polakova[13] have also reported large scatters. Although the luminous efficiency

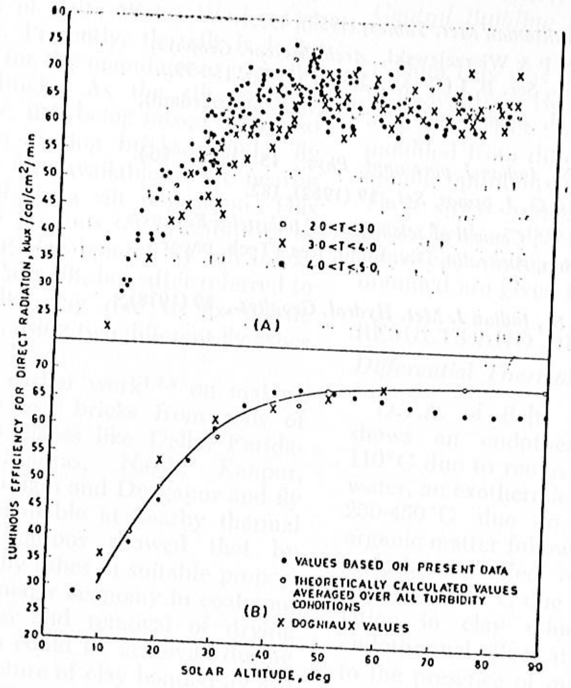

Fig. 7—Luminous efficiency for direct solar radiation for different solar altitudes

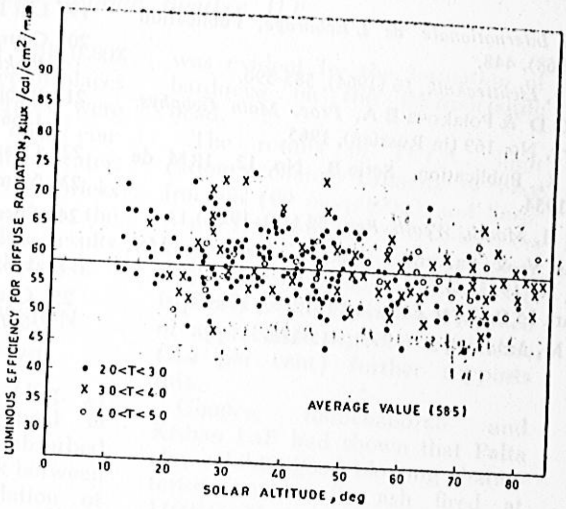

Fig. 8—Luminous efficiency of diffuse solar radiation for different solar altitudes

depends on turbidity factor, more data will be required for categorizing it in different turbidity ranges. However, average values may be used for most practical purposes. In the case of luminous efficiency for direct component, a least square polynomial in sin θ as given below was obtained

$$K_D = 32{\cdot}2 - 87{\cdot}7 \sin\theta + 644{\cdot}8 \sin^2\theta - 905{\cdot}8 \sin^3\theta + 308{\cdot}7 \sin^4\theta \quad . \ (18)$$

The values calculated from this expression are plotted in Fig. 7(B). In this figure the values reported by Dogniaux[14] and those calculated by the author[25] averaged over all conditions of the atmosphere, are also plotted. The solid curve may finally be considered for practical use.

In the case of luminous efficiency for diffuse radiation, there does not seem to be any significant variation with solar altitude as shown on Fig. 8. An average value of 58·5 klux/cal cm^{-2} min^{-1} is good enough for practical use under all conditions in the tropics.

6. Conclusion

Empirical relations have been obtained for direct and diffuse components of both solar radiation and illumination for different turbidity ranges under tropical clear sky conditions. These formulae have wider scope from the application point of view compared to those either based on visual classification of sky conditions or limited to typical regions.

The values of luminous efficiency given in this paper may be considered as the representative values for tropical conditions for the conversion of solar radiation data into natural illumination.

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