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The luminous efficiency of direct solar radiation

M. CHANDRA

Central Building Research Institute, Roorkee

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ABSTRACT. Through the knowledge of luminous efficiency of solar radiation it is possible to derive the values of illumination from the known values of solar radiation. This is important in view of the scarcity of illumination data and easy availability of radiation data. In this paper the author presents the computetd results of luminous efficiency for the direct component of solar radiation over varied solar altitudes and atmospheric turbidity conditions.

This will enable the computation of the externally reflected daylight in buildings which is considerable in tropics. The luminous efficiency of diffuse radiation will be dealt with in a later paper.

1. Introduction

Illumination measurements generally do not figure in the routine observational programmes of climatological elements by meteorological and geological departments. But the data on illumination are extensively needed in the precise solution of many practical problems, *e.g.*, lighting design of building fenestrations. The measurements of solar radiation are carried out practically at all the important meteorological stations. These radiation data can be usefully employed for deriving the required illumination data through the knowledge of luminous efficiency of solar radiation which is simply to be used as a multiplicative factor with the radiation amount. Thus the amount of illumination E available for a given amount of radiation I would be :

$$E = KI \qquad (1)$$

where K is the luminous efficiency. The illumination for a particular place or region for which radiation data is available can thus be easily determined. In the absence of actual measured data, International Commission on Illumination also favours this method of determining illumination data from radiation data for better appraisal of illumination climates of different regions (ICI 1968). In this paper the author presents the computed values of luminous efficiency of direct component of solar radiation for different solar altitudes and turbidity conditions of the atmosphere.

Daylight reaching directly at a point in a building comprises illumination from the point of sky visible from the given point and the sunlight reflected from the sunlit surfaces such as opposite building facades and other surfaces in front of a window. In tropics the contribution of reflected sunlight being considerable (Narasimhan *et al.* 1970, Hopkinson and Petherbridge 1953), the prediction of daylight in buildings requires information regarding the incident sunlight on opposite buildings and other reflecting surfaces. Therefore, the data on the luminous efficiency of direct solar radiation will provide useful information about incident sunlight on various reflecting surfaces which can be subsequently utilized for the computation of externally reflected illumination.

The data on luminous efficiency of diffuse radiation which will enable the computation of daylight from visible sky is also being investigated and will form the subject matter of a separate paper.

2. The computation of direct solar radiation and illumination

For theoretical determination of luminous efficiency of direct solar radiation, the values of direct illumination and direct radiation should be first computed for identical conditions. This requires detailed understanding of interaction of the direct solar beam with the atmospheric constituents. The direct solar beam, while traversing through the terrestrial atmosphere, is depleted in intensity due to scattering by the air molecules and aerosols and absorption by ozone, water vapour, carbon dioxide, oxygen and other less important gaseous elements. In the case of air molecules whose radii are much smaller compared to the wavelengths of solar spectrum, *i.e.*, roughly $< 0 \cdot 1\,\lambda$, the attenuation of energy is caused in accordance with the Rayleigh scattering law. But

TABLE 1

The luminous efficiency of direct solar radiation

(K lux/cal/cm^2/min)

β	θ	Precipitable water, w (cm)							
		1 cm		3 cm		5 cm		7 cm	
		Station ht h (m)		Station ht h (m)		Station ht h (m)		Station ht h (m)	
	(°)	0	5000	0	5000	0	5000	0	5000
0·05	5	22·6	31·1	24·1	33·2	25·1	34·5	—	—
	7	33·3	41·6	35·3	44·2	36·7	45·9	37·4	46·7
	10	44·8	51·7	47·4	54·7	48·9	56·4	50·2	57·9
	15	55·8	60·5	58·5	63·5	60·2	65·3	61·5	66·7
	20	61·3	64·6	64·3	67·8	66·1	69·7	67·3	71·0
	30	66·6	68·5	69·5	71·5	71·3	73·3	72·6	74·7
	45	69·3	70·3	72·5	73·5	74·0	75·1	75·2	76·3
	60	70·4	71·0	73·4	74·1	74·9	75·6	76·1	76·8
	75	70·7	71·3	73·7	74·2	75·3	75·8	76·4	77.0
	90	70·9	71·4	73·8	74·3	75·4	75·9	76·5	77·0
0·10	5	11·9	16·7	12·7	17·8	13·2	18·5	—	—
	7	21·2	27·0	22·5	28·7	23·4	29·8	23·7	30·4
	10	33·2	39·0	35·1	41·2	36·2	42·6	37·2	43·7
	15	46·4	51·0	48·7	53·5	50·1	55·1	51·1	56·2
	20	53·9	57·3	56·5	60·1	58·1	61·9	59·2	63·0
	30	61·4	63·5	64·1	66·3	65·8	68·0	67·0	69·3
	45	65·8	67·0	68·8	70·1	70·3	71·5	71·4	72·7
	60	67·6	68·4	70·5	71·3	71·9	72·8	73·1	74·0
	75	68·3	68·9	71·1	71·8	72·7	73·3	73·7	74·4
	90	68·5	69·1	71·3	71·9	72·9	73·5	74·0	74·6
0·20	5	2·9	4·1	3·1	4·4	3·2	4·6	—	—
	7	7·8	10·1	8·3	10·7	8·6	11·1	8·8	11·3
	10	17·0	20·3	18·0	21·5	18·6	22·2	19·0	22·8
	15	30·7	34·3	32·2	36·1	33·2	37·1	33·9	37·9
	20	40·3	43·6	42·3	45·7	43·5	47·0	44·3	47·9
	30	51·4	53·6	53·6	56·0	55·0	57·4	56·0	58·5
	45	58·7	60·2	61·4	63·0	62·7	64·3	63·7	65·3
	60	61·9	63·0	64·6	65·7	65·9	67·0	67·0	68·1
	75	63·2	64·1	65·8	66·7	67·3	68·2	68·3	69·2
	90	63·7	64·5	66·2	67·1	67·7	68·6	68·7	69·6
0·30	5	0·5	0·8	0·6	0·9	0·6	0·9	—	—
	7	2·6	3·3	2·8	3·6	2·9	3·7	2·9	3·8
	10	8·1	9·8	8·6	10·4	8·9	10·7	9·1	11·0
	15	19·4	21·9	20·4	23·0	21·0	23·6	21·4	24·1
	20	29·2	31·8	30·7	33·4	31·5	34·3	32·1	35·0
	30	42·1	44·3	44·0	46·3	45·1	47·5	46·0	48·3
	45	51·8	53·4	54·2	55·8	55·3	57·0	56·2	57·9
	60	56·2	57·4	58·7	59·9	59·9	61·1	60·8	62·1
	75	58·1	59·1	60·5	61·6	61·8	62·9	62·7	63·8
	90	58·8	59·7	61·1	62·1	62·5	63·5	63·4	64·4

β — Angström's turbidity coefficient, θ — Solar altitude (Degrees), w — Precipitable water (cm), h — Station altitude (metres) in the case of aerosols, the large solid and liquid particles suspended in the atmosphere, the particle radii are much larger ranging from about $0 \cdot 4\mu$ to about $10 \cdot 0\mu$. The scattering of solar beam by such particles is governed by the more complicated theory of scattering of electromagnetic radiation propounded by Mie (1908). The use of this theory is hampered due to lack of authentic information on the density and size distribution of aerosols and vertical extent of their distribution in the terrestrial atmosphere as also the complicated nature of the theory itself. Thus in practical computations Angström's analytical formula (Angström 1964) may be used for calculating the atmospheric extinction of solar radiation by aerosols.

Unlike scattering which is a continuous function of wavelength, the atmospheric absorption of solar radiation is selective in nature. Ozone absorbs almost all solar radiation in the ultraviolet region below about $0 \cdot 30\mu$. In the visible region of the solar spectrum also there is a weak ozone absorption. The absorption due to precipitable water, carbon dioxide and oxygen are more important and are particularly confined to near infrared region of the solar spectrum.

Taking into consideration the latest information on extraterrestrial spectral irradiance (Thekaekara 1973) and scattering and absorption coefficients of atmospheric constituents which significantly attenuate the spectral solar irradiance (Penndorf 1957, Gast 1960 and Yamamoto 1962), the author had recently made computations of direct solar radiation and illumination normal to sun rays on the earth's surface for different solar altitudes and combinations of atmospheric turbidity conditions. These values compare well with the experimentally measured values. The final equations for these quantities are :

$$I_N(\theta, h, \beta, w, z) = \int_{0 \cdot 20}^{9.0} I_{0\lambda}\, \tau_{a_\lambda}^{m_h(\theta)} \,. \left(\tau_{\beta\lambda} \,.\, \tau_{w\lambda} \,.\, \tau_{z\lambda}\right)^{m_r(\theta)} d\lambda \qquad (2)$$

and

$$E_N(\theta, h, \beta, z) = K_{\max} \int_{0.38}^{0.78} I_{0\lambda}\, V(\lambda)\, \tau_{a\lambda}^{m_h(\theta)} \,. \left(\tau_{\beta\lambda} \,.\, \tau_{z\lambda}\right)^{m_r(\theta)} d\lambda \qquad (3)$$

where $I_N(\theta, h, \beta, w, z)$ and $E_N(\theta, h, \beta, z)$ are direct solar radiation and illumination normal to sun rays on the earth's surface and are functions of solar altitude θ, station height above mean sea level h, and other parameters like Angström's turbidity coefficient β, precipitable water w and ozone content z, which affect the overall transmissivity of the atmosphere; $I_{0\lambda}$ is the extra-terrestrial spectral irradiance at the wavelength λ; $\tau_{a\lambda}$, $\tau_{\beta\lambda}$, $\tau_{w\lambda}$ and $\tau_{z\lambda}$ are the atmospheric transmissivities for the zenith sun for air molecules, aerosols, precipitable water etc and ozone respectively; $m_r(\theta)$ and $m_h(\theta) = m_r(\theta)\, p_h/p_0$ are the relative and absolute airmasses, p_h and p_0 being air pressures at station heights h and 0 metres above mean sea level; $V(\lambda)$ is the relative spectral luminosity function for human eye for photopic vision and K_{max} is a constant of multiplication for $V(\lambda)$ for obtaining absolute values of spectral luminosity function. The value of $K_{\max}$ is 680 lumens/watt or 475 K lux cal/cm^2/min (List 1958). The computations of spectral transmissivities etc and the numerical integration of equations (2) and (3) were carried out with the help of a computer.

3. The luminous efficiency of direct solar radiation

The luminous efficiency of direct solar radiation may be defined as the amount of solar illumination available for unit amount of solar radiation and may be expressed in the units of either lumens/watt or K lux/cal/cm^2/min. From the values of computed direct solar radiation and illumination as described in previous section, it is possible to calculate the luminous efficiency of direct solar radiation $K_D(\theta, h, \beta, w, z)$ from the formula :

$$K_D(\theta, h, \beta, w, z) = \frac{E_N(\theta, h, \beta, z)}{I_N(\theta, h, \beta, w, z)} \qquad (4)$$

The computations were carried out for the solar altitudes of 5, 7, 10, 20, 30, 45, 60, 75 and 90 degrees; Angström's turbidity coefficients of $0 \cdot 05$, $0 \cdot 10$, $0 \cdot 20$ and $0 \cdot 30$; precipitable water of 1, 3, 5 and 7 centimetres; station altitudes of 0 (m.s.l.) and 5000 metres (Fig. 1). Only average value of the ozone content of the atmosphere ($z = 0 \cdot 34$ cm) was considered because variation in the amount of ozone was found to have negligibly small influence on the direct solar radiation and illumination and hence on the luminous efficiency.

4. Results and discussion

The values of luminous efficiency of direct solar radiation for different solar altitudes and different atmospheric conditions are given in Table 1. As can be seen from this table, for solar altitudes below about 30 degrees the variation in the values of luminous efficiency is very rapid and above it the variation is slow attaining almost near constancy above 60 degrees. Quite obviously this sort of variation in luminous efficiency is due to corresponding rapid changes in airmass with solar altitudes. Coming to the influence of Angström's turbidity coefficient, with its increasing values, the luminous efficiency values decrease. But with increasing precipitable water the luminous efficiency values are found to increase. The increase in luminous efficiency with increasing precipitable water is due to water vapour absorption in the infrared region and the consequent increase in the relative proportion of visible part in the integral radiation. There is also increase in luminous efficiency with increasing station altitudes above mean sea level. This is due to the reduced number of air molecules and aerosols at higher stations and subsequent less attenuation in the visible region where molecular scattering is more prominent. Due to inverse fourth power dependence of Rayleigh scattering coefficient on wavelength, molecular attenuation in the infrared region does not change significantly at higher station altitudes. Here also the higher changes at lower airmass are attributable to rapid changes in airmass at low solar altitudes.

5. Concluding remarks

In view of the scarce availability of illumination data and easy availability of measured solar radiation data, the coversion of the latter into former seems to be an easy and practicable way for determining the illumination climate of different regions. In this direction the knowledge of luminous efficiency of solar radiation is an essential prerequisite. It is expected that the calculational results reported in this paper will be helpful in better understanding the dependence of luminous efficiency of direct solar radiation on the atmospheric turbidity conditions and hence in such practical conversions with a greater degree of reliance.

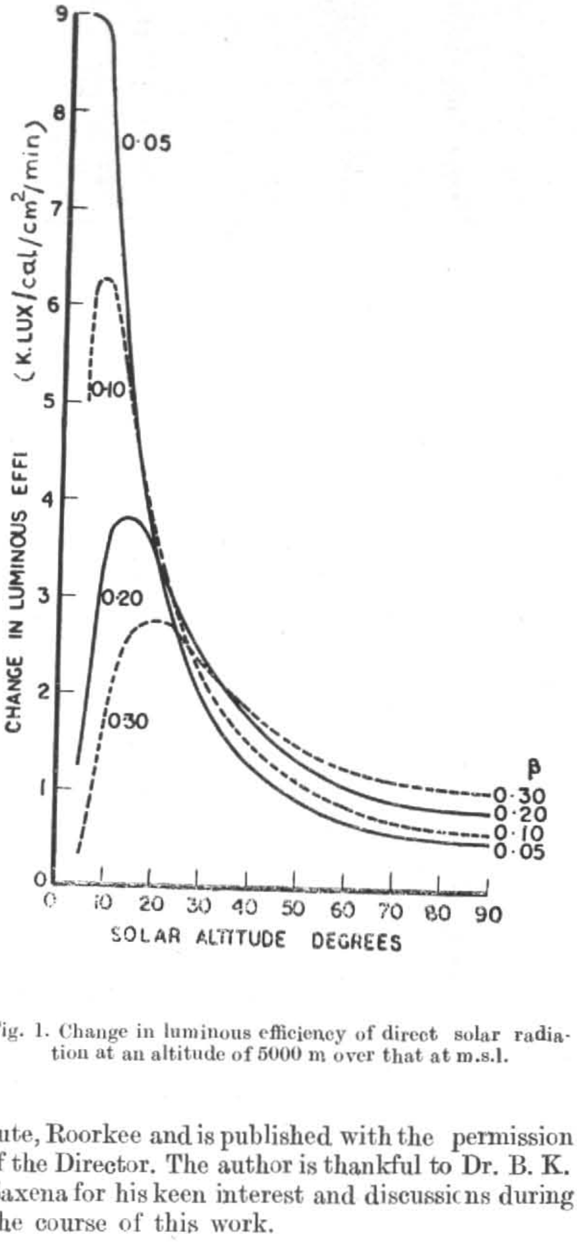

Fig. 1. Change in luminous efficiency of direct solar radiation at an altitude of 5000 m over that at m.s.l.

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REFERENCES

Angström, A.	1964	*Tellus*, **16**, 1, pp. 64-67.
Gast, P. R.	1960	*Handbook of Geoohysics*, U. S. Airforce, New York, Chap. 16, pp. 23-25.
Hopkinson, R. G. and Petherbridge, P.	1953	Proc. Conf. Tropical Arch., p. 63.
ICI	1968	C.I.E. publication No. **14B**, p. 448.
List, R.	1958	*Smithsonian Meteorological Tables*, p. 452.
Mie, G.	1908	*Ann. d. Phys.*, **25**, p. 377.
Narsimhan, V., Saxena, B. K. and Maitreya, V. K.	1970	*BUILD International*, **3**, 9, pp. 251-253.
Penndorf, R.	1957	*J. Opt. Soc. Amer.*, **47**, 2, pp. 176-182.
Thekaekara, M. P.	1973	*Solar Energy*, **14**, pp. 109-127.
Yamamoto, G.	1962	*J. atmos. Sci.*, **19**, p. 182.