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Estimation of luminous efficacy of daylight and illuminance for composite climate

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Abstract
This Daylighting is one of the basic components of passive solar building design and its estimation is essential. In India there are a few available data of measured illuminance as in many regions of the world. The Indian climate is generally clear with overcast conditions prevailing through the months of July to September, which provides good potential to daylighting in buildings. Therefore, an analytical model that would encompass the weather conditions of New Delhi was selected. Hourly exterior horizontal and slope daylight availability has been estimated for New Delhi using daylight modeling techniques based on solar radiation data. A model to estimate interior illuminance was investigated and validated using experimental hourly inside illuminance data of an existing skylight integrated vault roof mud house in composite climate of New Delhi. The interior illuminance model was found in good agreement with experimental value of interior illuminance.

Keywords: Global, Diffuse, Efficacy, Irradiance, Illuminance.

1. Introduction

Optimal utilization of daylight can attribute to significant amount of energy savings. Studies do reveal that if daylighting were used for illumination purposes adequately it would reduce the energy consumption in our households. As buildings are architectural elements that are exposed to the sun, prediction of daylight availability in them is required. The availability of daylight for exterior illuminance is a field of study considerably different from the measurement and simulation of solar radiation [1]. Solar radiation is the total incident energy visible and invisible from the sun and daylight is the visible portion of this electromagnetic radiation as perceived by the eye. The task is to isolate this portion from the total energy. Using established models it is possible to predict the Luminous Efficacy and then estimate the monthly mean of hourly exterior illuminance (diffuse, direct and global) on horizontal and for all the four walls (N–S–E–W) of any building in the region.

This paper investigates experimentally the skylight rooms to validate the proposed interior illuminance model which is based on conservation of illuminance. The vertical height considered for the study is 75 cm above floor level which corresponds to working on table by sitting on chair.

The hourly experimental data of illuminance level inside were measured on typical days in each month of the year for small and big dome rooms of the existing skylight building located in New Delhi composite climate. The importance of skylight was presented in this paper by evaluating the artificial lighting energy saving potential and corresponding CO_2 mitigation potential to elaborate the effect of daylighting in climate change mitigation. The carbon credit earning potential of skylight integrated dome shaped roof room was also evaluated. The objective of paper is to introduce the importance of daylighting in building using actual measured data in India especially in New Delhi city and validation of interior illuminance model.

2. Location and climatic conditions

New Delhi is located in Northern part of India, a latitude 28.58^o N and a longitude of 77.02^o E and at an altitude of 216m above M.S.L. The climate of Delhi is a monsoon-influenced humid subtropical climate (Koppen climate classification Cwa) with high variation between summer and winter temperatures and precipitation. Summers start in early April and peak in May, with average temperatures near 32^{o}C (90^{o}F), although occasional heat waves can result in highs close to 45^{o}C (114^{o}F) on some days. The monsoon starts in late June and lasts until mid-September, with about 714 mm (28.1 inches) of rain. The average temperatures are around 29^{o}C (85^{o}F), although they can vary from around 25^{o}C (78^{o}F) on rainy days to 32^{o}C (90^{o}F) during dry spells. The monsoons recede in late September, and the post-monsoon season continues till late October, with average temperatures sliding from 29^{o}C (85F) to 21^{o}C (71^{o}C).
Winter starts in November and peaks in January, with average temperatures around 12-13^{o}C (54-55^{o}F). Although winters are generally mild, Delhi's proximity to the Himalayas results in cold waves that regularly dip temperatures below freezing. Delhi is notorious for its heavy fog during the winter season. In December, reduced visibility leads to disruption of road, air and rail traffic. They end in early February, and are followed by a short spring till the onset of the summer. Extreme temperatures have ranged from −0.6 °C (30.9 °F) to 47 °C (116.6 °F).

3. Estimation of luminous efficacy and horizontal exterior illuminance

Researchers have investigated the relation between solar radiation and daylight and proposed various mathematical models relating the two [2–7]. The model proposed by Perez and others [4] is usually considered to be most accurate and was selected to predict hourly Luminous Efficacy, horizontal and slope illuminance values for the 12 months of a year. The model has been validated by data from different location with a very good agreement [8,9].
According to this model, the global (Kg) and diffuse (K_d) efficacies can be found by the following equation [4]:

$$K_g \; or \; K_d = a_i + b_i W + c_i \cos(z) + d_i \ln(\Delta) \tag{1}$$

where a_i, bi, c_i and d_i are given coefficients (for diffuse or global efficacies), Table 1, corresponding to the sky's clearness (ε), W is the atmospheric precipitable water content; (Δ) is the sky brightness.

The sky clearness (ε) for irradiance is given by

$$\varepsilon = [(I_d + I_n)/I_d + 1.041z^3]/[1 + 1.041z^3] \tag{2}$$

where I_d is the horizontal diffuse irradiance, I_n is the normal incidence direct irradiance; z is the solar zenith angle in radians.

The zenith angle is calculated through

$$\cos z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta \tag{3}$$

where ϕ is the latitude, and δ is the solar declination, which can be expressed as

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \tag{4}$$

where n is the day of the year given for each month in Table 2 [10], ω is the hour angle:

$$\omega = (ST - 12)15^0 \tag{5}$$

where ST is the solar time for our calculations.

$$I_n = I_b / \cos z \tag{6}$$

where I_b is the horizontal beam irradiance.

The sky brightness (Δ) is given by

$$\Delta = I_d m / I_{on} \quad (7)$$

where m is the optical air mass; I_{on} is the extraterrestrial normal incidence irradiance. m was obtained from Kasten's [11] formula, which provides an accuracy of 99.6% for zenith angles up to 89^0.

$$m = [\cos z + 0.15 \times (93.885 - z)^{-1.253}]^{-1} \quad (8)$$

Eq. (8) is applicable to a standard pressure p_0 of 1013.25 mbar at sea level. For other pressures the air mass is corrected by;

$$m' = m(p / 1013.25) \quad (9)$$

where p is the atmospheric pressure in mbar at height h meters above sea level, p was estimated by formula given by Lunde [12],

$$p / p_0 = \exp(-0.0001184h) \quad (10)$$

The atmospheric perceptible water content (cm), is given by Wright et al. [13]:

$$W = \exp(0.07T_d - 0.075) \quad (11)$$

where T_d is the hourly surface dew-point temperature (^{0}C). T_d can be expressed by Magnus-Tetens formulation [14].

For $0^0 C < T < 60^0 C, 0.01 < RH < 1.00, 0^o C < T_d < 50^o C,$

$$T_d = b\alpha / a - \alpha, \quad (12)$$

$$\alpha = aT / b + T + \ln(RH) \quad (13)$$

where a=17.27 and b=237.7^{0}C, T in ^{0}C is the measured temperature and RH is the measured relative humidity.

The extraterrestrial normal incidence irradiance I_{on} can be calculated by

$$I_{on} = 1367[1.0 + 0.033\cos(360n / 365)] \quad (14)$$

The horizontal diffuse illuminance (E_d) and the horizontal global illuminance (E_g) can be estimated by the following:

$$E_d = I_d K_d \quad (15)$$

$$E_g = I_g K_g \quad (16)$$

Thus based on the Eqs. (1)-(16), the luminous efficacy and horizontal diffuse and global illuminance is estimated for New Delhi from the available irradiance data.

4. Estimation of slope exterior illuminance

Direct illuminance on horizontal surface can be calculated from the difference between estimated values of global and diffuse illuminance on a horizontal surface.

The hourly diffuse illuminance, $E_{\beta,d}$ on an inclined surface with a slope β is obtained in the simplified Perez model [4] from the following equation:

$$E_{\beta,d} = E_d[(1-F_1)(1+\cos\beta)/2 + (a_0/a_1)F_1 + F_2\sin\beta] \quad (17)$$

where a_0, a_1 and β are given as;

$$a_0 = \max(0, \cos\theta), \qquad a_1 = \max(0.087, \cos z), \qquad \beta = 90^0 \quad (18)$$

where θ is the incidence angle of the sun on the surface and z the zenith angle. θ can be calculated from the relation:

$$\cos\theta = \sin\phi\sin\delta\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\phi\cos\delta\cos\omega\cos\beta + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (19)$$

where γ is the surface azimuth angle, E_d is the horizontal diffuse illuminance and F_1 and F_2 are coefficients, which respectively express the degree of anisotropy of the circumsolar and the horizon regions. These coefficients show a dependence on the parameters that define the sky conditions:

(a) The zenith angle, z.

(b) The clearness index ε' for illuminance is defined through:

$$\varepsilon' = [(E_d + E_n)/E_d + kz^3]/[1 + kz^3] \quad (20)$$

where E_n is the direct normal illuminance:

$$E_n = E_b/\cos z \quad (21)$$

where E_b is the horizontal beam illuminance.

(c) The sky's brightness Δ' is defined by

$$\Delta' = E_d m/E_o \quad (22)$$

where E_o =133.8 klx is the mean extraterrestrial normal illuminance and m is the optical air mass. The model considers a set of categories for ε' and for each of them F_1 and F_2 are given as;

$$F_1 = F_{11} + F_{12}\Delta + F_{13}z \quad (23)$$

$$F_2 = F_{21} + F_{22}\Delta + F_{23}z \quad (24)$$

In Table 3 coefficients of Perez et al. slope illuminance model are shown. Based on Eqs. (18)–(24) hourly slope diffuse illuminance was estimated. The approach to calculate the global illuminance on a sloping surface is to first estimate the irradiance on a sloping surface and then multiply it by the global luminous efficacy. The hourly global irradiance on an inclined surface I_β with a slope β can be obtained by the following expression given by Liu and Jordon [15]

$$I_\beta = I_b R_b + I_d(1+\cos\beta)/2 + \rho(I_b + I_d)(1-\cos\beta)/2 \quad (25)$$

where $R_b = \cos\theta/\cos z$ and ρ is the reflectivity of the ground taken as 0.2.

The global illuminance on a tilted surface $E_{\beta,g}$ would now be;

$$E_{\beta,g} = I_\beta K_g \quad (26)$$

Table 1. Luminous efficacy coefficients of Perez et al (1990)

S. No.	ε Lower bound	Upper bound	Global efficacy coefficients a_i	bi	c_i	d_i	Diffuse efficacy coefficients a_i	bi	c_i	d_i
1	1	1.065	96.63	-0.47	11.50	-9.16	97.24	-0.46	12.00	-8.91
2	1.065	1.230	107.54	0.79	1.79	-1.19	107.22	1.15	0.59	-3.95
3	1.230	1.500	98.73	0.70	4.40	-6.95	104.97	2.96	-5.53	-8.77
4	1.500	1.950	92.72	0.56	8.36	-8.31	102.39	5.59	-13.95	-13.90
5	1.950	2.800	86.73	0.98	7.10	-10.94	100.71	5.94	-22.75	-23.74
6	2.800	4.500	88.34	1.39	6.06	-7.60	106.42	3.83	-36.15	-28.83
7	4.500	6.200	78.63	1.47	4.93	-11.37	141.88	1.90	-53.24	-14.03
8	6.200	-	99.65	1.86	-4.46	-3.15	152.23	0.35	-45.27	-7.98

Table 2. Average day of each month

Month	Date	Day of the Year
Jan	17	17
Feb	16	47
Mar	16	75
Apr	15	105
May	15	135
Jun	11	162
Jul	17	198
Aug	16	228
Sep	15	258
Oct	15	288
Nov	14	318
Dec	10	344

Table 3. Coefficients of Perez et al. (1990) slope illuminance model

ε’	1-1.065	1.065-1.230	1.230-1.500	1.500-1.950	1.950-2.800	2.800-4.500	4.500-6.200	6.200
F_{11}	0.011	0.429	0.809	1.014	1.282	1.426	1.485	1.170
F_{12}	0.570	0.363	-0.054	-0.252	-0.420	-0.653	-1.214	-0.300
F_{13}	-0.081	-0.307	-0.442	-0.531	-0.689	-0.779	-0.784	-0.615
F_{21}	-0.095	0.050	0.181	0.275	0.380	0.425	0.411	0.518
F_{22}	0.158	0.008	-0.169	-0.350	-0.559	-0.785	-0.629	-1.892
F_{23}	-0.018	-0.065	-0.092	-0.096	-0.114	-0.097	-0.082	-0.055

5. Results and discussion

Tables 4 and 5 show for New Delhi the calculated monthly average of the hourly values of global and diffuse efficacies on a horizontal plane, respectively. Global luminous efficacies in July and August are found to be higher than those of the same hour in other months mainly due to high solar altitude while diffuse luminous efficacy of December month was found to be highest. The annual average efficacy under the sky conditions of the area will be useful for the architects and designers. By knowing the average radiation data, the corresponding average illumination level can be determined using these luminous efficacies.

The estimated yearly average global luminous efficacy is 108.0 lm/W and the yearly average diffuse luminous efficacy is 136.5 lm/W. Diffuse luminous efficacy is higher than the global efficacy in the sky type of the area indicating that diffuse component in daylighting design is more energy efficient.

Table 4. Average global luminous efficacy (lm/W)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8	108	107	108	107	108	110	113	114	112	112	110	109
9	107	107	107	107	108	110	112	113	111	111	109	109
10	107	106	107	107	108	110	110	112	111	109	109	109
11	106	106	106	106	107	109	110	111	110	108	107	108
12	106	106	106	106	106	109	110	111	110	108	107	106
13	106	105	106	105	106	108	110	109	110	107	106	106
14	106	105	106	105	106	108	110	109	110	108	106	106
15	106	106	106	105	106	108	111	110	110	108	106	106
16	105	105	106	105	106	108	111	111	110	108	106	106
17	104	105	106	105	106	109	112	111	110	108	106	104

Table 5. Average diffuse luminous efficacy (lm/W)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8	157	153	149	144	142	142	143	147	148	157	158	160
9	150	145	141	137	135	135	136	140	140	148	152	154
10	144	140	135	131	130	130	129	131	135	139	146	150
11	140	136	131	127	126	126	125	127	131	135	141	145
12	139	135	130	126	125	125	123	126	130	134	138	139
13	139	136	131	127	126	125	124	126	130	134	139	140
14	143	139	135	130	129	128	128	129	133	138	142	144
15	147	144	140	136	134	133	134	135	139	143	147	149
16	153	150	147	142	140	140	141	143	146	150	153	154
17	156	155	153	149	147	148	149	151	153	157	157	155

Figures 1 and 2 show the cumulative frequency distribution of the estimated global luminous efficacy and diffuse luminous efficacy, respectively for typical office hours from 8 am to 5 pm. The global cumulative frequency and the diffuse cumulative frequency drop rapidly from 106 to 114 lm/W and 130 to 160 lm/W respectively indicating that for most of the times of the year the luminous efficacies lie between these two values. From the energy efficiency point of view this is much better than the 16–40 lm/W for incandescent lamps and 50–80 lm/W for fluorescent lamps because there will be less heat penetration to achieve the same lighting levels as compared to electric lighting in buildings. This would also result in less cooling loads and savings in air-conditioning electric consumption.

To estimate the efficacies and illuminances, data of the hourly global and diffuse solar radiation (W/m^2) on a horizontal surface for a period of 11 years (1991–2001) have been used. The data have been obtained from the India Meteorological Department, Pune, India. The data of hourly relative humidity was taken from Mani and Rangrajan [16]. .

The estimated global and diffuse horizontal illuminance data is shown in Tables 6 and 7. The maximum horizontal global illuminance is found in June month because of the higher values of solar radiation and luminous efficacy. The maximum horizontal diffuse illuminance is found in July months because of overcast conditions due to monsoons.

Graphs of illuminance against irradiance were plotted for both global and diffuse components for the location. The graphs Figures 3 and 4 confirm the linear relationship between the irradiance and illuminance.

For daylighting design considerations cumulative frequency distribution curves of illuminance outdoors was plotted to indicate the percentage of working hours in which a given illuminance is exceeded. Figures 5 and 6 show the frequency distribution for estimated outdoor global and diffuse illuminance based on office hours from 08:00 to 18:00 h. Assuming a daylight factor of 3% and the indoor design illuminance of 500 lx, the required outdoor illuminance should be 15,000 lx. From Figure 5 it can be seen that 90% of the time in a year the outdoor illuminance would be above 15,000 lx.

Table 6. Average global horizontal illuminance (lx)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8	14311	19339	28743	39529	44012	48183	41512	38046	31200	18889	13305	10128
9	38084	43094	52393	63018	65656	69970	65812	59832	55880	40440	34479	29918
10	59210	63219	71602	81856	83551	87864	81116	75384	75633	61604	52700	48160
11	72433	77134	85344	94256	96151	99914	91748	91207	89387	75238	65455	60991
12	77002	83082	91882	99439	101900	103353	96994	96242	95709	82096	70739	65879
13	77441	83544	91919	99483	101043	102255	98620	88369	94022	81147	69972	65389
14	69384	76830	84801	92515	94123	95387	90513	83936	85593	73763	62424	58688
15	52868	61647	70395	78658	80750	82740	83254	72209	72169	58536	48323	45185
16	32851	41258	51121	59948	61721	66347	63359	52871	53418	39136	29224	26890
17	11093	18678	27870	36777	39455	45644	41650	33952	29821	16403	8884	7142

Table 7. Average diffuse horizontal illuminance (lx)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8	8257	11205	14001	17611	16751	17543	15628	12705	14779	6959	6781	5826
9	12903	15385	17355	19119	18570	20102	19178	13968	17523	10189	9312	8212
10	15459	17618	19234	20908	19912	20366	22100	20408	18974	16644	11265	8999
11	17075	18699	20265	22252	21027	20092	25620	22435	19854	18593	15399	11802
12	17594	19064	19983	22708	21724	20959	26986	23821	19771	19753	19483	19839
13	19055	19684	20140	23058	22230	23147	27318	25351	20866	20687	18918	19802
14	18293	19216	20341	23090	22606	23155	26203	25515	21893	19612	18670	17162
15	16354	17832	19123	22123	22148	23419	23986	23316	20908	17424	16827	15599
16	13773	15241	17064	20764	21597	20018	21035	18361	17968	13994	13423	12136
17	6528	9941	13133	17228	19528	17126	16422	14162	13970	9351	6759	5812

From Figure 6 it can be seen that above 90% of the time in a year there is availability of diffuse illuminance of 15,000 lx, which is significant because diffuse illuminance is glare free.

To accurately estimate daylight in the interiors it is required to estimate daylight availability outdoors at the four walls of a room. Therefore, slope exterior illuminance was estimated for the June average day and January average day for four orientations (N, E, S and W).

Figures 7 and 8 show the monthly average hourly global illuminance and diffuse illuminance, respectively, for June. It is observed from Figure 7 that due to higher solar altitude in June the horizontal surface receives much more global illuminance than vertical surfaces but the diffuse illuminance is about one and a half times of the vertical surfaces. Secondly due to low solar altitudes in the East and West walls the illuminance on East facing surface during morning and the west-facing surface during evening will be excessive which can create lot of glare. Both the global and diffuse illuminance at south wall is close to the illuminance in East wall during mornings and West wall during evenings as can be seen from Figures 7 and 8.

Similarly, monthly average hourly global illuminance and diffuse illuminance, respectively, for January were estimated and then plotted as shown in Figures 9 and 10. Due to lower inclination angles at the southern facade about 440 at noon the global illuminance at the Southern facade is higher than horizontal illuminance. So a southern facade can be benefited by the diffuse illuminance if an overhang cuts the beam component.

From Figures 9 and 10 the differences in illuminance level, which occur with orientation for both global and diffuse, can be seen. Although the North and South surfaces both peak at noon but global and diffuse illuminance for North surface is less than one fifth and one third of South plane, respectively. Although the illuminance on all the surfaces is higher in January than in June but the illuminance at lower solar altitudes is lower in January at the North plane.

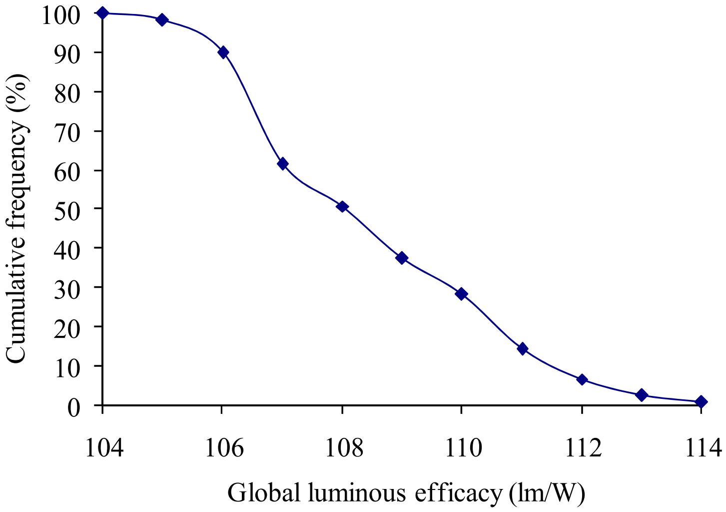

Figure 1. Cumulative frequency distribution for global luminous efficacy

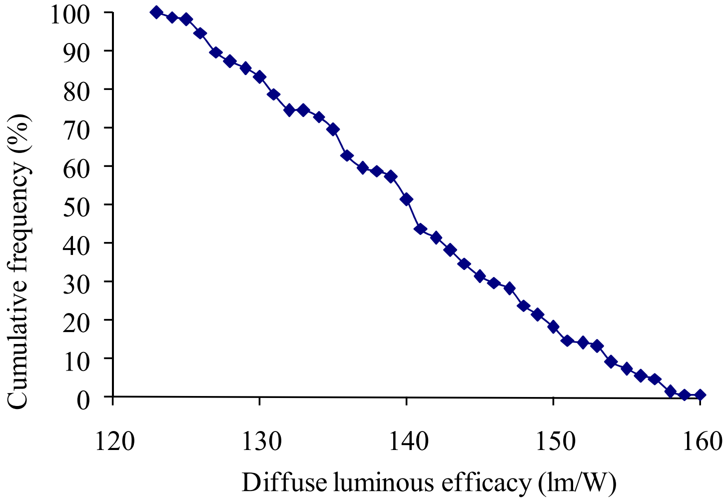

Figure 2. Cumulative frequency distribution for diffuse luminous efficacy

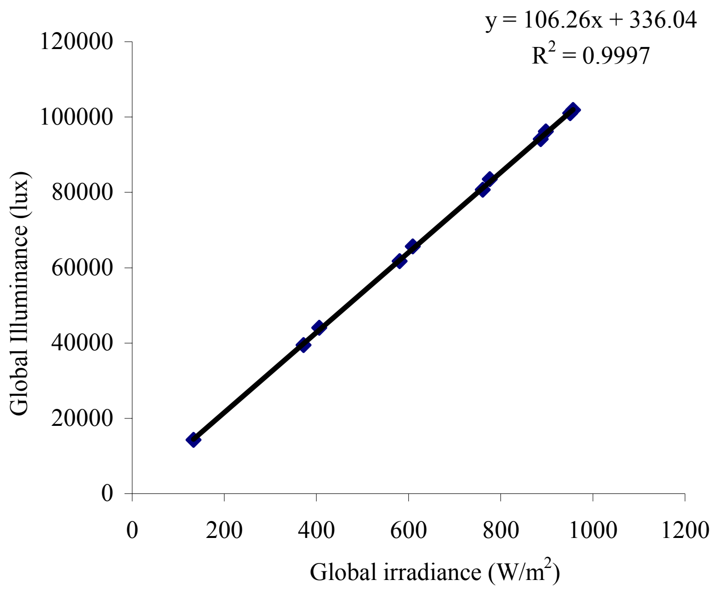

Figure 3. Graph of global illuminance against global irradiance for New Delhi, India

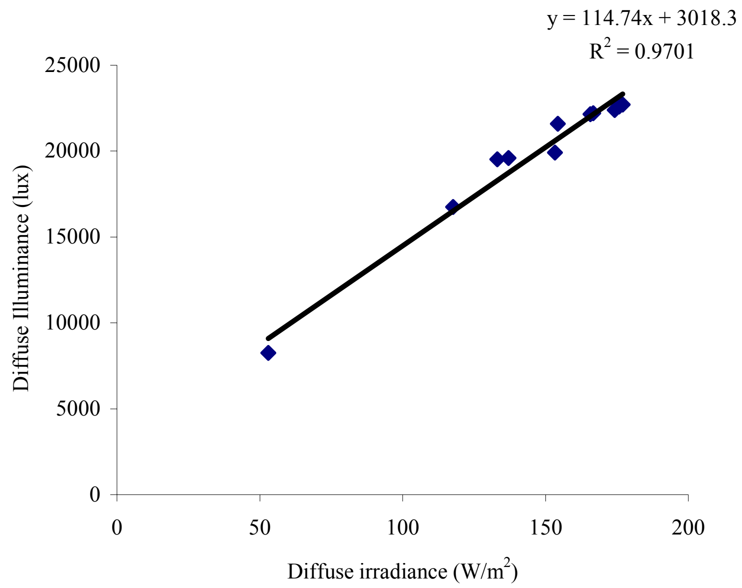

Figure 4. Graph of diffuse illuminance against diffuse irradiance for New Delhi, India

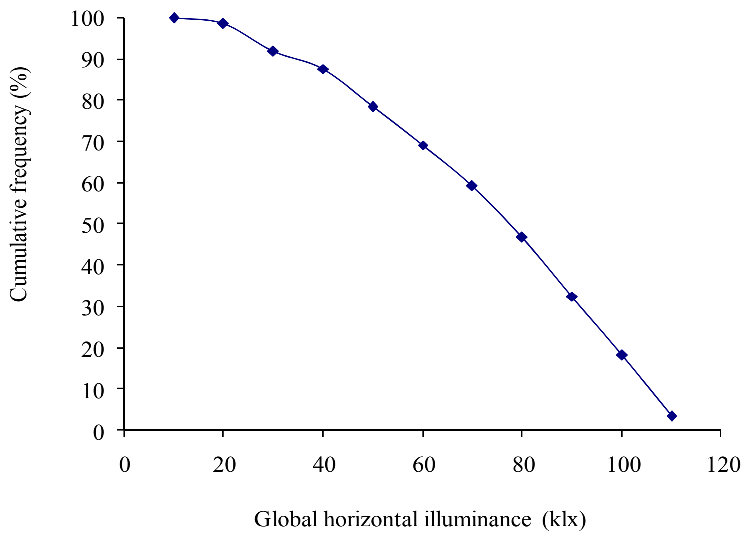

Figure 5. Cumulative frequency distribution for estimated outdoor global illuminance

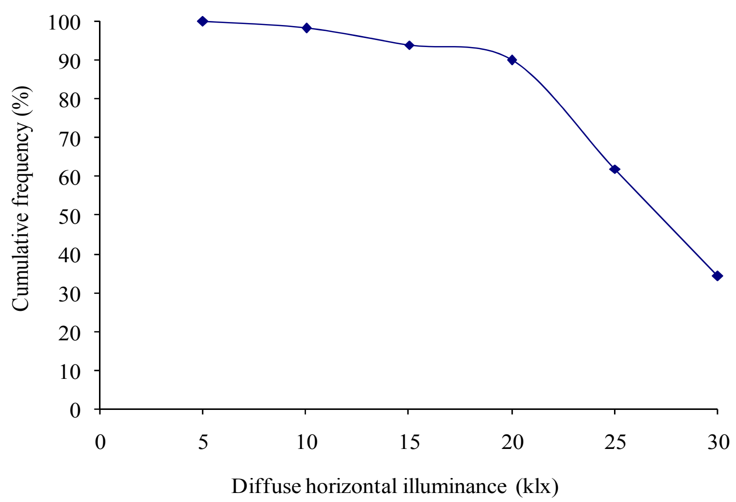

Figure 6. Cumulative frequency distribution for estimated outdoor diffuse illuminance

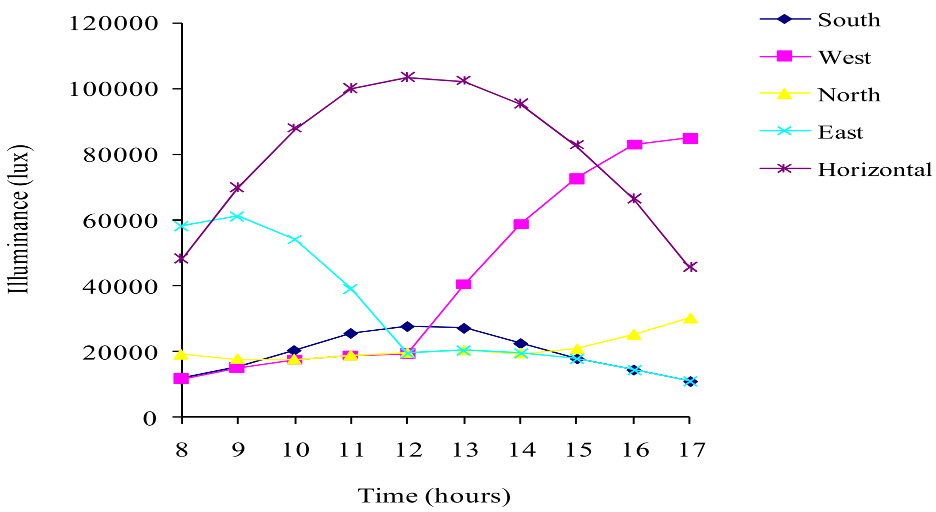

Figure 7. Average global illuminance for horizontal and four vertical surfaces in June

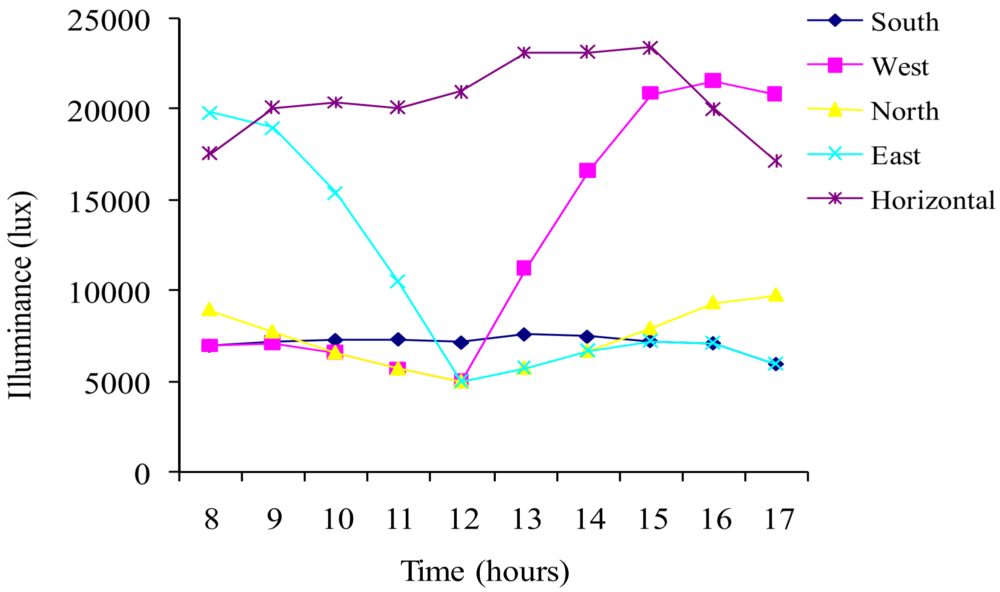

Figure 8. Average diffuse illuminance for horizontal and four vertical surfaces in June

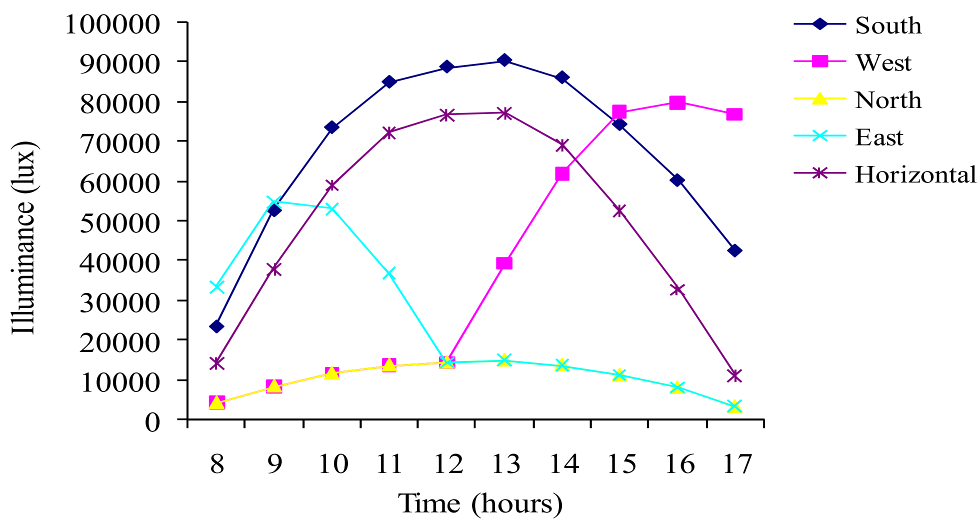

Figure 9. Average global illuminance for horizontal and four vertical surfaces in January

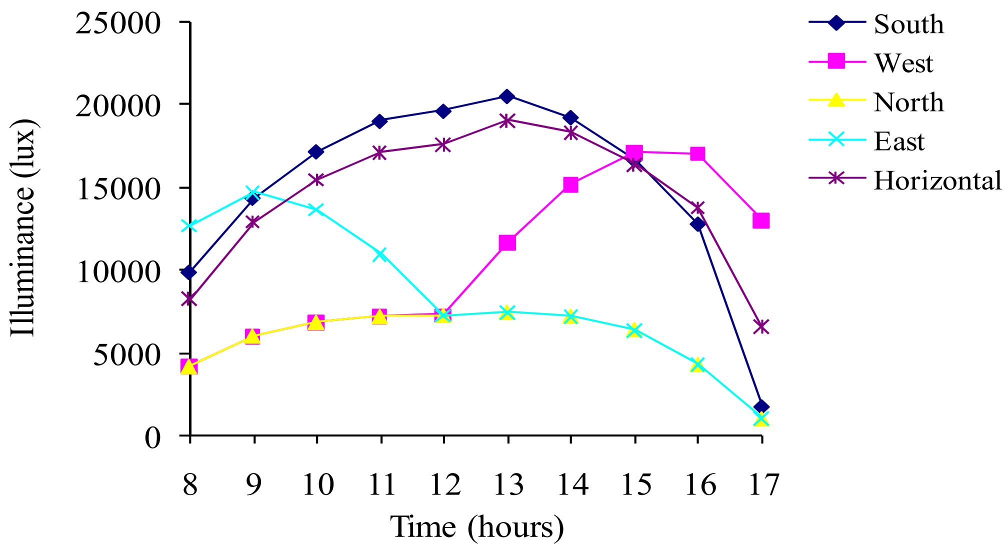

Figure10. Average diffuse illuminance for horizontal and four vertical surfaces in January

6. Average global and diffuse illuminance

For determination of maximum illuminance level the hourly illuminance data for the horizontal surface and the four vertical surfaces were used. Tables 8 and 9 present the average illuminance on horizontal and four vertical surfaces. For the months of November, December, January and February the peak average illuminance occurs on the Southern facade because of low solar inclination on the South facade during these months and for the other months the peak occurs in the horizontal plane. Because of maximum solar altitude in June, the maximum horizontal illuminance occurs in June. The illuminance on East and west planes is like sinosoidal. For vertical surfaces the highest global illuminance occurs in January for a south-facing surface and the lowest occurs for the North-facing surface in December. The maximum diffuse illuminance occurs in January for a South-facing surface, which is because of composite weather conditions in the region while the minimum occurs for the North facing surfaces during winters since the sun moves to southward direction during this period.

Figure 11 presents the cumulative frequency distributions for the hourly global illuminances for the horizontal and four vertical places based on normal office hour of 08.0–17.0. The effects of inclination can be observed. The horizontal illuminance is around one and a half times of the vertical illuminance. It can be seen that the horizontal surface receives the largest amount of illuminance with a peak value of 103,353 lx in June. The north-facing surface has the lowest illuminance among all the vertical surfaces with the peak value being around 30 klx. The East and West facing surfaces touch their peaks at around 61 klx and 84 klx respectively while the South-facing surface has its peak at 90 klx which is three times than that of North facing surface. It can be pointed out that the North-facing surface receives mainly diffuse component of the total illuminance so no shading device is required to exclude the direct component. It can also be noted that at low illuminance levels of around 15 klx and less, the North and East-facing surfaces show similar trends in illumination. Results obtained are in good agreement with results obtained by other similar study [17].

7. Validation of interior illuminance model using experimental performance of skylight

Figure 12 shows the different types of skylight for daylighting of building as reported by Laouadi and Atif [18]. The existing mud-house has vault (or dome shape) roof structure as shown by the pictorial view of skylight dome in Figure 13 shows the schematic diagram of dome shape skylight rooms. There are three numbers of dome shape roof structure rooms out of which two rooms have identical small dome shape rooms with skylight at central height of about 3 m while the large dome shape room has skylight at central height about 7 m. The wall of the dome shape rooms forms regular octagonal base for the dome roof structure. The eight rectangular walls of the big dome shape room have width 2.32 m and height 2.32 m. The dome was constructed over these eight walls.

The experimental measurements were carried out on hourly basis at working levels (75 cm above ground) inside the room. The skylight building is used as conference room which also provides the computer simulation laboratory for the solar energy scientists.
The illuminance level inside the dome shaped room with skylight was practically found suitable for reading and writing from 7 am to 5 pm (daytime). The illuminance level inside the big dome on typical clear days in months of March and April are shown in Figure 14. The value of predicted interior illuminance was determined using following Equation.

$$A_g \times I_g \times \tau \times \rho \times 100 = L_i \times A_f \qquad (27)$$

where A_g is total area of glazing, τ is transmittance of glazing, ρ is average reflectance of all room-surfaces, L_i is illuminance level inside the room on horizontal working surface (Lux or lm/m^2), and A_f is floor area.

Parametric values considered for evaluation of interior illuminance are given in Table 10. Figure 14 shows the experimental validation of interior illuminance model which was used to determine hourly illuminance value inside the big and small rooms. The validation results show that root mean square percentage error varies in the range of 4.5 – 9.66% while the correlation coefficient varies in the range of 0.9 -0.99. The statistical error represented in Figure 14 are within the acceptable limits and hence the proposed model estimation of interior illuminance can be used for estimation of interior illuminance based on the experimental results conducted in the existing building in New Delhi (India). Figure 15 shows the hourly variation of predicted interior illuminance based on Eq (27).

Table 8. Average global illuminance for New Delhi (lux)

Period	South	West	North	East	Horizontal
Jan	67822	38850	10361	24387	50468
Feb	57686	43605	11798	25244	56782
Mar	45614	43919	13514	27940	65607
Apr	32569	43756	15895	30955	74548
May	22369	40676	17879	30707	76836
Jun	19294	42159	20717	31426	80166
Jul	20665	41367	19806	30462	75458
Aug	25817	38412	15833	29551	69205
Sep	39884	42399	14337	28778	68283
Oct	48940	37405	11366	24637	54725
Nov	56404	34217	9618	22374	45550
Dec	64042	40737	8740	20928	41837

Table 9. Average diffuse illuminance for New Delhi (lux)

Period	South	West	North	East	Horizontal
Jan	15031	10526	5760	8555	14529
Feb	15017	11380	6229	9520	16388
Mar	13391	12174	6593	10304	18064
Apr	10806	12926	6662	10744	20886
May	8007	12585	6899	10195	20609
Jun	7084	12226	7311	10208	20593
Jul	7567	12505	6952	10204	22448
Aug	9476	12401	6507	9768	20004
Sep	12324	12427	6598	10336	18651
Oct	13679	11108	6084	8640	15321
Nov	14149	9898	5510	7726	13684
Dec	15005	9407	5653	7775	12519

Table 10. Parametric values considered for evaluation of interior illuminance

No.	Parameter	Value
1	Floor area of room under big dome (A_f, m^2)	26
2	Floor area of room under small dome (A_f, m^2)	5
3	Total area of glazing (A_g, m^2) for big dome	2.6
4	Total area of glazing (A_g, m^2) for small dome	1.5
5	Transmittance of glazing (τ)	0.5
6	Average reflectance (ρ) of all room surfaces	0.4

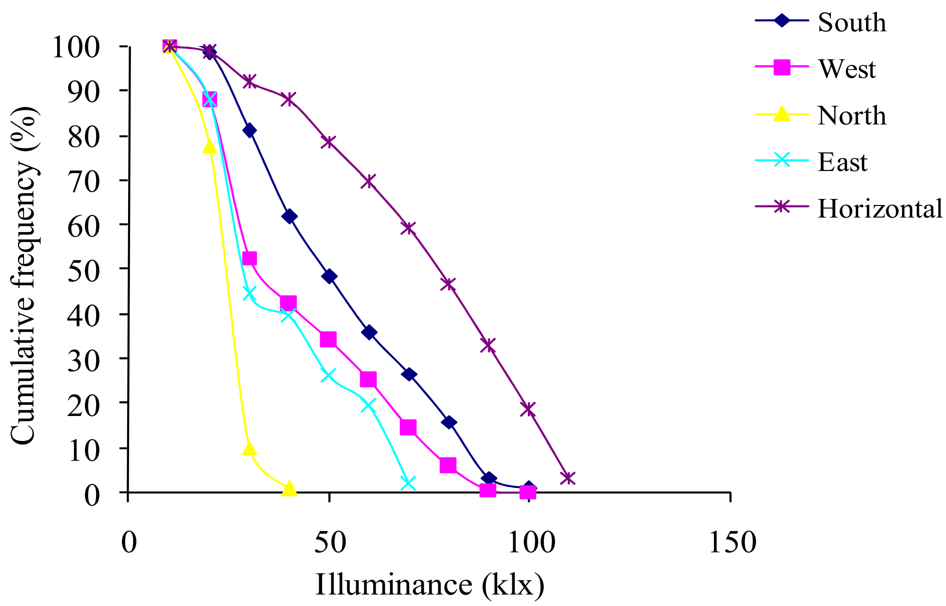

Figure 11. Cumulative frequency distribution for the hourly global illuminances for the horizontal and four vertical places

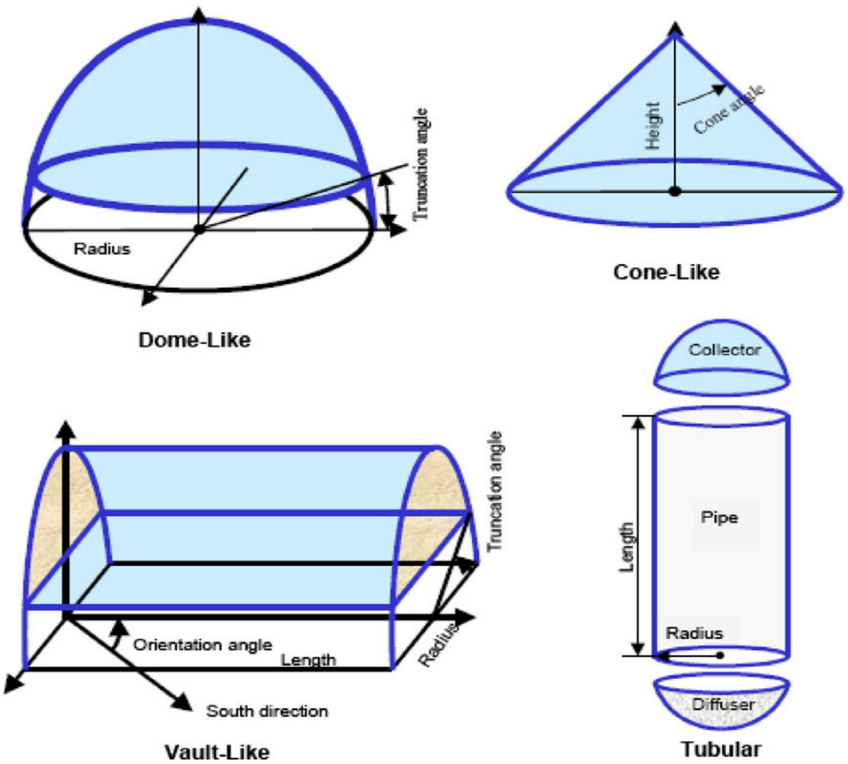

Figure 12. Types of skylight for daylighting in buildings (Laouadi and Atif [18])

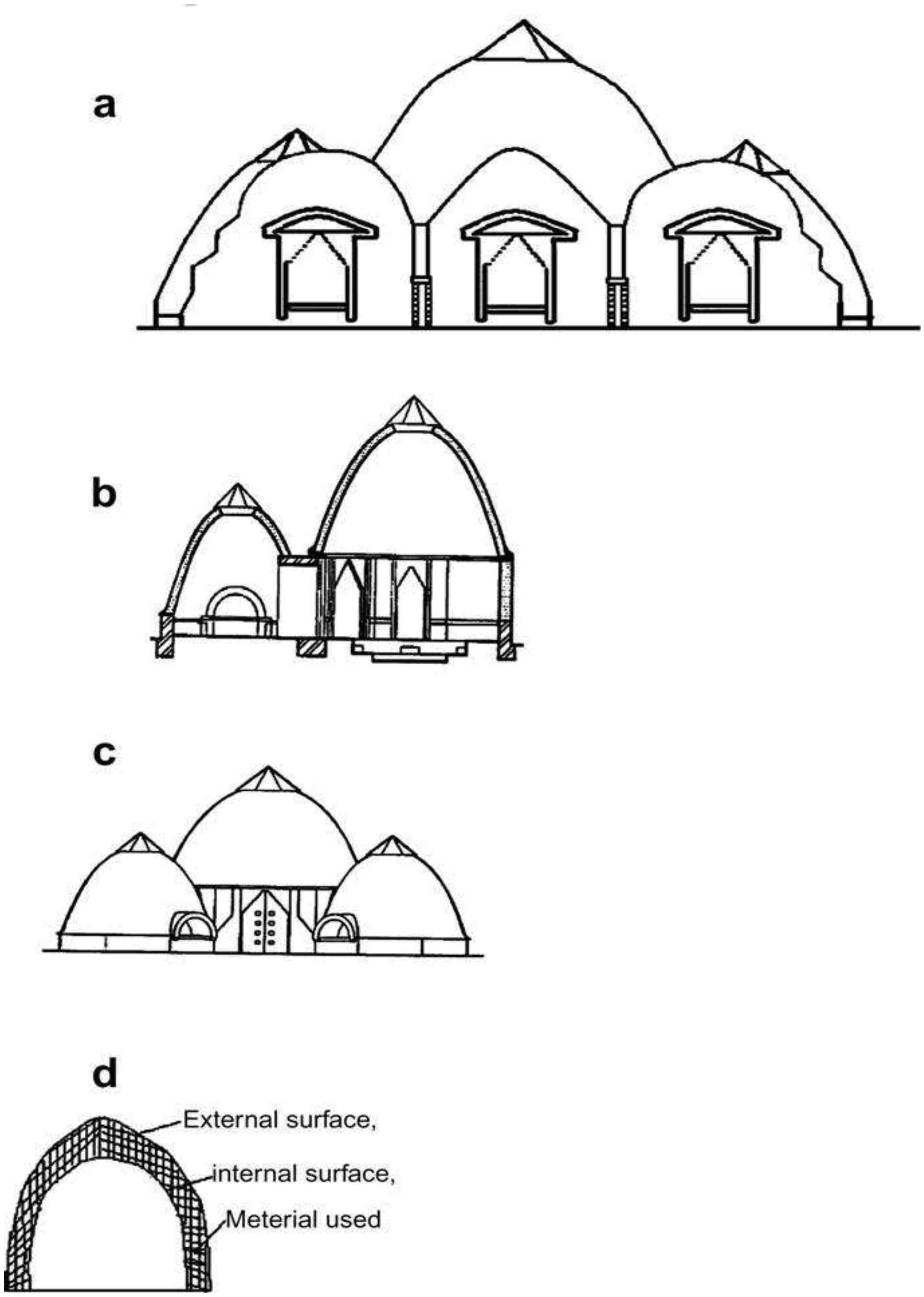

Figure 13. Adobe house (a) front view (b) side view (c) rear view (d) schematic diagram for material calculation

8. Mitigation of CO_2 emission

The mitigation of CO_2 emission from the energy saving potential and corresponding amount of carbon credit potential of the skylight for big and small dome room was estimated to promote daylighting issue in buildings. The CO_2 emission intensity at coal thermal power plant in India was estimated as 1.568 kg/kW h of electrical energy generated as reported by Watt et al [19]. The mitigation of CO_2 emission from the actual amount of lighting energy saving potential due to skylight can be determined using the relation reported by Watt et al [19] as follows:

$$\text{Mitigation of } CO_2 \text{ emissions} = \text{Energy saving (kWh/year)} \times 1.568 \text{ (kg of } CO_2\text{/kWh)} \quad (28)$$

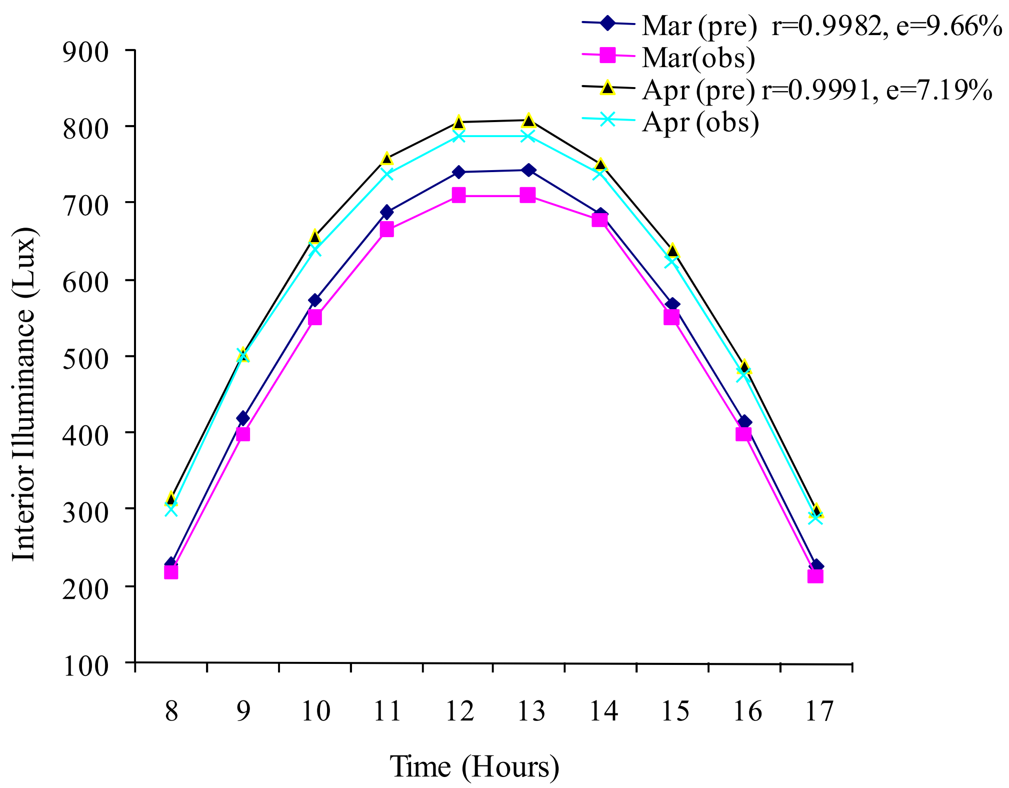

Figure 14. Hourly variation of predicted and observed interior illuminance

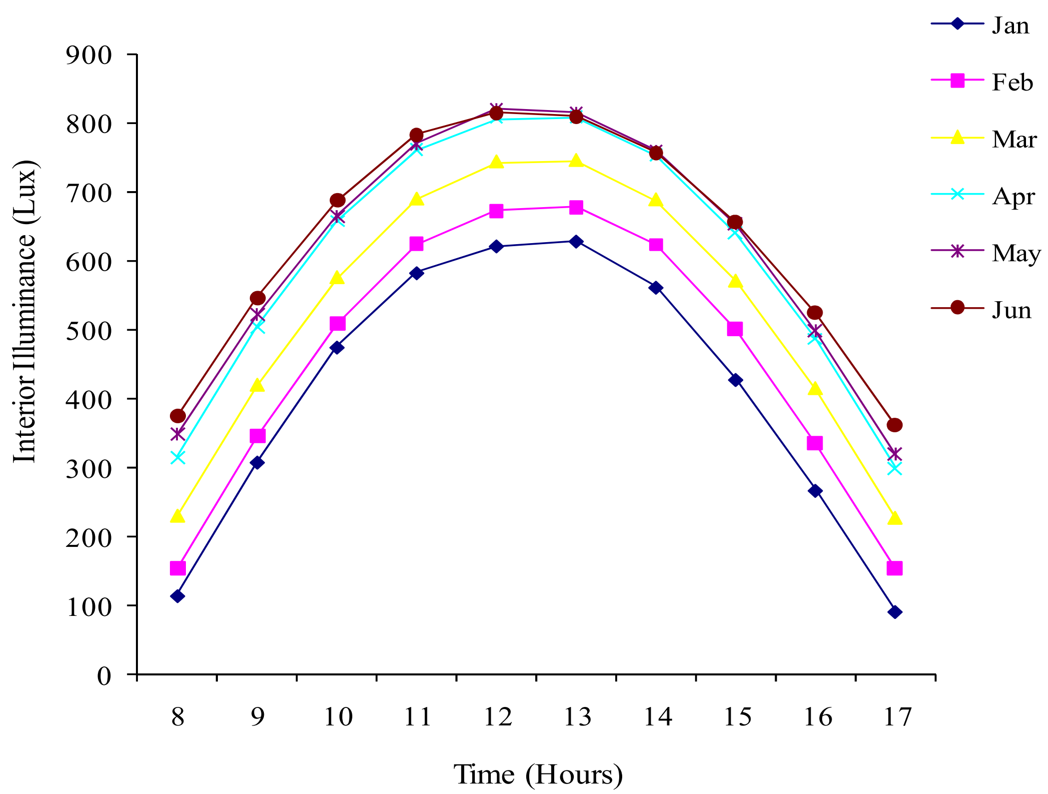

Figure 15. (a) Hourly variation of interior illuminance from January to June months

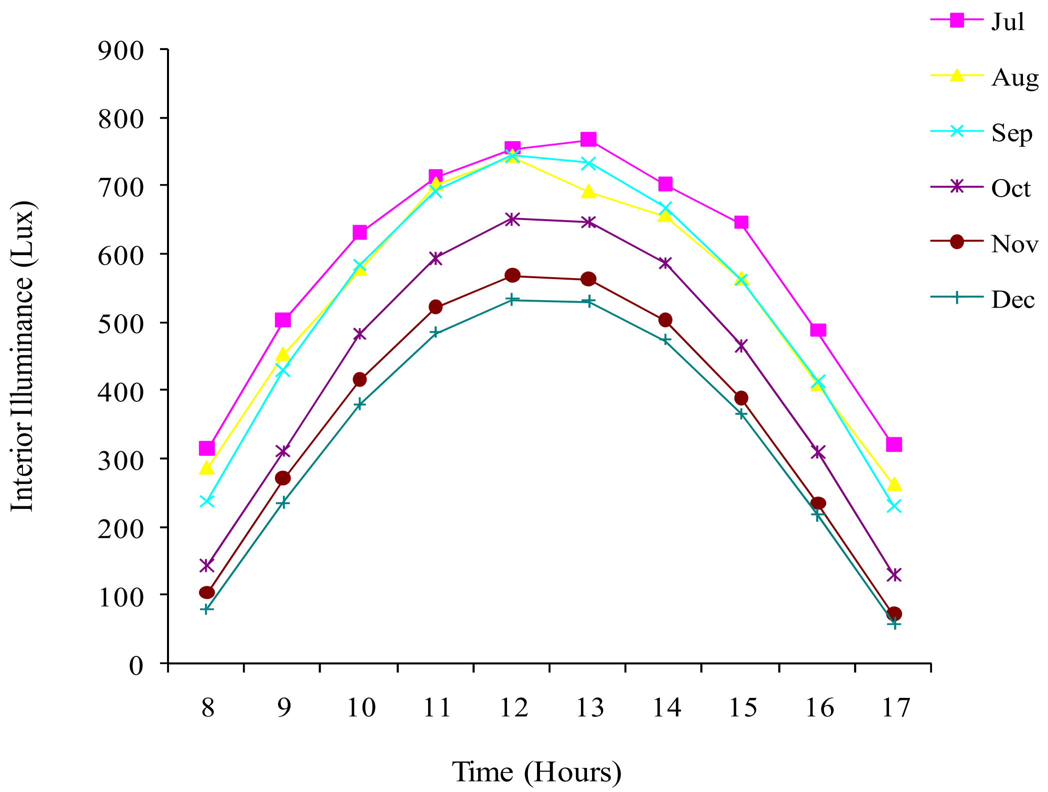

Figure 15. (b) Hourly variation of interior illuminance from July to December months

9. Carbon credit earned from mitigation of CO_2 emission

The carbon credit earned from the mitigation of CO_2 emissions (in tons/year) can be determined using the relation as follows [19, 20]:

$$\text{Carbon credit earned} = \text{Mitigation of } CO_2 \text{ emissions (tons/year)} \times 21 \text{ (Euro/ton of } CO_2\text{)} \quad (29)$$

The factor considered in Eq. (29) is 21 Euro (€)/metric tons of CO_2 mitigation in Asia (especially in India) [19] represents the monetary value of one carbon credit earned due to mitigation of 1 metric ton of CO_2 emissions due to skylight for natural daylighting inside the room.

10. Conclusion

This study was a step towards predicting the illuminance in buildings in India. It is evident that the South wall has the highest daylight availability during winter, which is desirable from it during these months. So buildings oriented South can not only be benefited by daylight but also by warmth during this period in the area. It is also evident that the global luminous efficacy can lie at 108.0 lm/W in the area and the diffuse luminous efficacy can lie between 136.5 lm/W, which is close to established values. The maximum horizontal illuminance of 70,000 lx is exceeded in the area for most of the months touching the maximum of 103,353 lx in June. This approach is particularly useful for estimating the illuminance of different daylighting schemes during the conceptual design stage. The north-facing wall mainly receives the diffuse component of illuminance values while the horizontal and other vertical surfaces receive certain amount of direct component. The information of percentage of working period in which a given illuminance is exceeded is valuable in designing the building for specific interior illumination.

The interior illuminance model to determine inside illuminance of the skylight building was found in good agreement with experimental results of skylight building at working level of interest (75 cm above floor level) for both small and big dome rooms. Also, the methodology to calculate energy saving potential of daylighting showed that tremendous amount of energy can be conserved from skylight integrated buildings if adopted in both rural and urban areas of India. The skylights were found to provide diffuse light and not the direct light based on the experimental observations. The direct light provides undesirable glare and heating effect inside the room. Hence, daylight are often termed as cool light to provide illumination for the given task of human being such as reading, writing, drawing, etc.

The emission reduction and carbon credit potential were discussed to signify daylighting as one of the environment friendly sustainable approach for buildings. The Indian government had planned to adopt green rating for integrated habitat assessment (GRIHA) for all new buildings. This will be made mandatory for the commercial buildings which consume 100 kW of power or more in 1 h [21]. The daylighting is one of the important building codes defined by GRIHA for building rating system in India. With the advent of this rating system, day-lighting in buildings will be made mandatory for commercial complexes to reduce lighting-energy-consumption of buildings. The integration of artificial lights with natural light is desirable for effective utilization of daylighting in buildings.

Appendix

Horizontal irradiance for New Delhi, W/m^2

Solar Radiation	Month ▶ Time ▼	January	February	March	April	May	June	July	August	September	October	November	December
Global	8am	132.99	180.29	266.77	368.14	406.31	436.67	367.36	333.59	277.96	168.75	121.46	93.12
	9am	355.56	403.58	488.94	588.48	608.84	637.22	587.04	528.54	501.3	364.58	316.04	275.27
	10am	554.69	594.44	671.21	767.81	776.26	802.22	737.27	674.49	682.04	565.28	485.35	443.25
	11am	680.73	729.39	804.33	888.32	897.98	915	831.71	820.2	809.07	694.45	609.97	565.87
	12pm	726.74	786.02	866.93	941.01	956.82	951.67	881.48	868.18	869.07	761.8	664.01	621.83
	1pm	733.85	792.03	869.28	944.12	950.51	946.11	896.53	807.83	855.19	756.25	657.45	618.39
	2pm	656.08	728.58	803.15	878.68	886.62	882.78	820.6	766.67	779.81	686.11	587.37	553.31
	3pm	500	584.23	665.33	746.9	761.37	765.56	753.24	658.08	656.48	543.75	454.17	426.19
	4pm	311.46	391.22	483.01	568.3	580.81	611.67	569.68	477.78	483.89	362.5	274.62	253.97
	5pm	106.42	178.23	264.1	348.61	372.48	420	373.15	305.81	270.19	152.08	84.09	68.78
Diffuse	8am	52.6	73.3	94.23	122.47	117.68	123.89	109.03	86.62	100	44.44	42.8	36.37
	9am	86.28	105.82	123.02	139.54	137.12	149.44	141.44	100	124.81	68.75	61.36	53.31
	10am	107.29	126.08	142.2	159.4	153.28	157.22	171.07	155.3	140.93	119.45	77.15	60.19
	11am	121.53	137.36	154.11	174.84	166.67	158.89	205.09	176.26	151.67	137.5	109.6	81.61
	12pm	126.39	141.31	153.21	180.39	174.24	167.78	218.75	189.65	152.41	147.92	141.67	142.46
	1pm	136.63	145.07	153.21	181.78	177.02	185	219.68	201.26	160	154.17	136.36	141.27
	2pm	128.3	138.35	151.12	177.45	175.76	180.56	204.86	197.48	164.26	142.36	131.82	119.18
	3pm	110.94	123.84	136.54	163.24	165.66	176.11	179.63	172.72	150.74	121.53	114.77	105.03
	4pm	90.28	101.52	116.35	146.08	154.29	142.78	149.54	128.28	123.15	93.06	88.01	78.84
	5pm	41.84	63.98	85.74	115.36	133.08	116.11	110.42	93.69	91.3	59.72	43.05	37.43

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