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Skylight model and its validation using dome roof of house at New Delhi

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ABSTRACT

The daylight factor model given by Charted Institute of Building Services Engineers (CIBSE) was modified in this paper to incorporate daily time variations with respect to zenith angle (θ_z) and vertical height (h) of working surface to be illuminated above ground surface which was normalized with central height (H) of skylight dome. The modified model contains constant exponents which are determined using linear regression analysis based on the hourly experimental data of the inside and the outside illuminance taken on the typical clear days of each month during the year 2007–2008. The prediction from the modified model is found in good agreement with the experimentally observed inside illuminance data on the basis of values of root mean square percentage error (e) and correlation coefficient (r). The annual average daylight factor values for big and small dome skylight rooms are determined as 2.3% and 4.4% respectively. The estimate of energy saving potential of the skylight rooms for selected climatic locations in India is also presented in this paper. The illuminance data measured for the skylight intergrated room shows that these are suitable for various office buildings in rural and urban areas in India to conserve the electricity demand for lighting during day time.

Keywords: *Skylight, Dome shape roof, Daylight Factor, Illumination, Energy Saving*

Nomenclature

H	*height of the skylight from floor*	m
A_f	*floor area*	m^2
A_g	*total area of glazing*	m^2
A_s	*working surface area*	m^2
A_t	*total area of room-surfaces*	m^2
B_F	*ballast factor or efficiency*	$0 \le B_F \le 1$
C	*correction factor for glazing due to dust, poor maintenance etc*	$0.5 \le C \le 0.9$
DF	*percentage daylight factor*	%
E	*total lighting energy consumption*	Wh/day
h	*vertical height of horizontal surface to be illuminated above ground surface*	m
I_d	*diffuse solar radiation*	W/m^2
I_g	*global solar radiation*	W/m^2
L_i	*illuminance level inside the room on horizontal working surface*	*lux or* $1m/m^2$
L_o	*outside diffuse illuminance on horizontal surface*	*lux or* lm/m^2
m	*constant exponent*	
N	*lighting operation hours*	h/day
n	*constant exponent*	
O_F	*orientation factor for glazing*	$0.97 \le O_F \le 1.55$
P	*total lighting power*	W
R	*average reflectance of all room-surfaces,*	$0 \le R \le 1$

Greek letters

ε	*light source luminous efficacy*	lm/W
ϕ	*total luminous flux*	*lumen or lm*
τ	*transmittance of glazing*	$0 \le \ \le 1$
θ	*vertical angle of visible sky from horizon*	*degree*
θ_z	*zenith angle*	*degree*

1. Introduction

Daylighting is an important issue in modern architecture affecting the functional arrangement of spaces, occupant comfort (visual and thermal), structure and energy use in building [1]. Daylight is considered as the best source of light for good color rendering and its quality closely matches with human visual response. It gives a sense of brightness that can have a significant positive impact on the people. The amount of daylight penetrating a building is mainly through window openings which provides the dual function of not only admitting light for indoor environment but also with a more attractive and pleasing atmosphere. It allows people to maintain visual contact with the outside world. People desire good natural lighting in their living environments [2,3]. The hemispherical skylight at the roof top of a building is shown in Fig.1.

The energy consumption of lighting in buildings is a major contributor to carbon emissions, often estimated as 20–40% of the total building energy consumption as reported by Building Research Establishment (BRE) energy consumption guide [4] and Chartered Institute of Building Services Engineers (CIBSE) [5]. Furthermore, the heat gains produced from artificial and natural lighting have an important influence upon heating and cooling loads reported by Peacock et al. [6]. Using controls for demonstrating the optimized configuration for daylight supplemented electrical lights is well-documented by Greenup et al. [7], Reinhart [8] and Li and Lam [9], with particular interest on the effect of thermal loads reported by Franzetti et al. [10]. However, the more advanced and material-based solutions were reported by Lee et al. [11], Tong et al. [12] and Smith [13] for optimizing daylight. They provide innovative solutions for reducing lighting-energy consumptions.

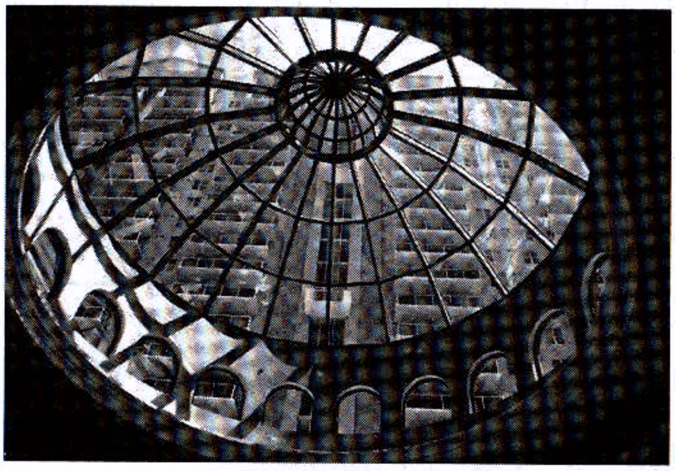

Fig.1. Hemispherical skylight for daylighting

With the project considering a large number of buildings, it is important that the approach should be as efficient as possible with regards to the available time as reported by Reinhart and Fitz [14]. While building-simulation packages and time-series techniques can be used for detailed predictions of lighting use [15]; they can be both time consuming and unnecessary for obtaining first-order estimate. The annual variation in daylight availability in UK can be represented using data reported by CIBSE [16] and Hunt [17,18].

The domestic lighting demand was determined using simple model developed by Stokes et al. [19]. The economics of lighting retrofits for emission reduction was reported by Mahlia et al. [20]. Daylighting is one of the basic components of passive solar building design and its estimation is essential. Laouadi et al. [21] reported that the daylight factor of building depends upon position of light source with respect to the room orientation, the room geometry, the optical characteristics of the room indoor surfaces, any outdoor obstructions and the optical behaviour (transmission, reflection and light scattering) of the fenestration system through which light is admitted into the room space. Daylight coefficient is independent of sky luminance distribution as reported by Tregenza and Waters [22]. Recently, calculating indoor natural illuminance in overcast sky conditions was reported by Rosa et al. [23].

In India and many parts of the world, the availability of measured outside illuminance values are very few. The Indian climate is generally clear with overcast conditions prevailing through the months of June–September, which provides good potential to daylighting in buildings as reported by Joshi et al. [24].

This paper investigates a mathematical model for existing skylight integrated dome shaped mud-house to estimate daylight factor based on the modifications in the model developed by CIBSE [25]. The daylight factor model developed by CIBSE [25] was validated for ground surface illuminance by Chel et al. [2] using experimental data of the existing building. The model developed by CIBSE [25] does not include time variation in a day and vertical height (h) of the work plane above ground surface. Hence, there is need for modification in the model developed by CIBSE [25] to incorporate vertical height (h) normalized with respect to central height (H) of the skylight room and time variations in terms of zenith angle (θ_z). This concept of modeling for skylight is rarely reported in the literature for New Delhi composite climate. The constant exponents in the modified model were determined on the basis of linear regression analysis which is explained in depth in this paper. The values of exponent were determined based on hourly inside and outside illuminance data for typical clear day in each month.

Using the modified model, the daylight factor is determined for three different work planes at different vertical heights (h) from ground surface, i.e. at h = 0 (or ground surface), 0.75 m and 1.5 m above ground surface. The study of work plane at ground level implicates to the students seating on floor and reading and writing in rural village schools in India. The vertical height of 0.75 m implicates to reading on work plane (or table) in modern schools and colleges in India while the 1.5 m vertical height implicates to standing posture of a working person like engineer in the factory (or teacher in school/conference room). The daylight factor values using modified model and experimental data were tabulated and presented in this paper. The energy saving potential of the skylight big and small domes for different selected climatic conditions is reported in this paper.

The annual average artificial lighting energy saving potential and corresponding CO_2 emission mitigation were evaluated for the existing building by Chel et al. [2]. The research pertaining to energy savings due to existing experimental setup of mud-house integrated with an earth to air heat exchanger and embodied energy analysis of building were respectively reported by Chel and Tiwari [26,27]. The existing dome shape building is found to be a promising example of sustainable and low carbon building (or green building) integrated with stand-alone photovoltaic as reported by Chel and Tiwari [28].

2. Pyramid shape skylight over dome roof of Adobe-house at New Delhi

Laouadi and Atif [29] and Chel et al. [2] reported other different skylight shapes for daylighting in buildings (Fig.2). The existing mud-house has vault (or dome shape) roof structure integrated with pyramid shape skylight as shown by the pictorial view in Fig. 3. The inside view of skylight circular aperture is also shown in Fig. 3.

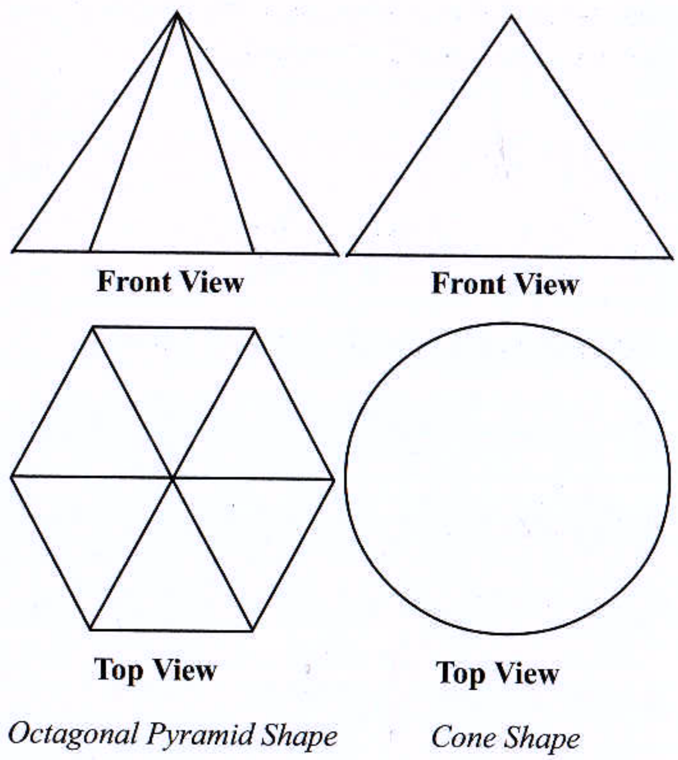

Fig. 2. Octagonal pyramid and cone shaped skylight

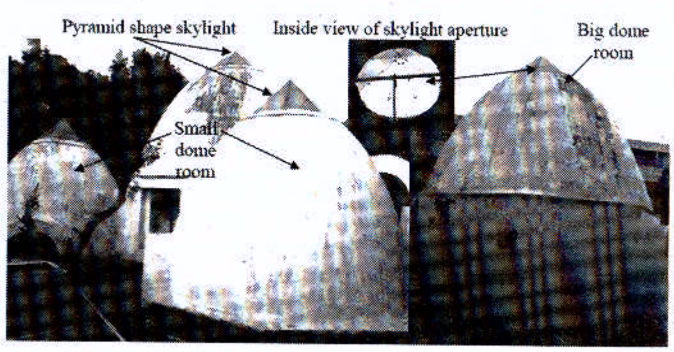

Fig. 3. Skylight over the dome roof of adobe house

3. Percentage daylight factor, DF (%) for the naturally illuminated work plane

The percentage daylight factor, DF (%) is the percentage ratio of inside illuminance, L_i (lux) on the horizontal work plane and outside diffuse illuminance, L_o (lux) on horizontal surface. The daylight factor for skylight integrated dome shape building at ground level is given by Eq.(1) developed by Chartered Institute of Building Services Engineers (CIBSE) [25] and validated by Chel et al. [2, 30]. The various parameters in Eq.(1) are tabulated with their values considered in Table 1. The variation of daylight factor with the time of the day and the normalized vertical height (h) above ground surface with resepect to height of skylight (H) from the ground floor is developed by Chel et al.[30] and expressed in the Eq.(2) as follows:

$$Y' = M'[X'] + C' \quad (1)$$

$$DF = \left[\frac{L_i}{L_o}\right] \times 100 = \left[\frac{\tau \times C \times A_g \times \theta \times O_F}{A_t \times (1-R^2)}\right] \quad (2)$$

Line equation can be easily written as follows:

$$DF = \left[\frac{L_i}{L_o}\right] \times 100 = \left[\frac{\tau \times C \times A_g \times \theta \times O_F}{A_t \times (1-R^2)}\right] \times \left(1+\frac{h}{H}\right)^m (\cos\theta_z)^n \quad (3)$$

This Eq.(3) of line is represented by Eq. (4) as follows:

$$\ln\left[\frac{L_i}{L_o} \times 100\right] = \left[n \times \ln(\cos\theta_z)\right] + \left\{m \times \ln\left(1+\frac{h}{H}\right) + \ln\left[\frac{\tau \times C \times A_g \times \theta \times O_F}{A_t \times (1-R^2)}\right]\right\} \quad (4)$$

On comparing Eqs. (1,4), one gets

$$Y' = \ln\left[\frac{L_i}{L_o} \times 100\right] \quad \text{and} \quad X' = \left[\ln(\cos\theta_z)\right] \quad (5)$$

The values of m and n can determined as follows:

$$\Rightarrow m = \frac{\left\{C' - \ln\left[\frac{\tau \times C \times A_g \times \theta \times O_F}{A_t \times (1-R^2)}\right]\right\}}{\ln\left(1+\frac{h}{H}\right)} \quad (6)$$

Where,

$n = M'$ = slope of line and C' = intercept on Y' axis

The total power of lighting, P (W) can be determined by considering the artificial light source luminous efficacy, ε (lm/W) and efficiency of ballast, B_F (or ballast factor). The total power of artificial electrical lighting required for the measured amount of total luminous flux, Ø (lumen) from the existing skylight in building can be determined mathematically by Eq.(7) using Jenkins and Newborough [31] as follows:

$$P = \left[\frac{Ø}{B_F \times \varepsilon}\right] \quad (7)$$

Where,

$$Ø = [L_i \times A_s] \quad (8)$$

Where, L_i is measured illuminance level (lux or lumen/m^2) inside the skylight building on the horizontal working surface area, A_s (m^2).

Table1 gives all parameterics values. The experimental value of daylight factor is determined based on the measured illuminance data [32].

Table 1. Parameters for daylight factor estimation

No.	Parameter	Value	Parameter	Value
1	Total area of room-surfaces in big dome (A_t, m^2)	80	Total area of room-surfaces in small dome (A_t, m^2)	25
2	Floor area of big dome (A_f, m^2)	26	Floor area of small dome (A_f, m^2)	5
3	Transmittance of glazing (τ)	0.8	Vertical angle of visible sky from horizon (θ, degrees)	90
4	Correction factor for glazing due to poor maintenance/dust ($0.5 \leqslant C \leqslant 0.9$)	0.6	Vertical height of work plane above floor surface (h, m) [0, 0.75 m, 1.5 m]	0, 0.75, 1.5
5	Orientation factor for glazing ($0.97 \leqslant O_F \leqslant 1.55$)	1	Average reflectance of all room-surfaces ($0 \leqslant R \leqslant 1$)	0.3
6	Total area of glazing (A_g, m^2) for big dome	2.6	Total area of glazing (A_g, m^2) for small dome	1.5
7	Ballast factor (B_F)	0.9	Artificial light luminous efficacy (ε, lm/W) (CFL lamp)	40

The total lighting-energy consumption, E (W h/day) can be determined by multiplying total power of lighting, P (W) and required number of hours of operation per day, N (h/day). The total lighting-energy consumption can be expressed mathematically using Eq.(9) as follows:

$$E = [P \times N] \quad (9)$$

4. Results and discussion:

Based on experimental data of inside and outside diffuse illuminance, the daily average experimental values of percentage daylight factor are determined and compared with daily average predicted values of daylight factor using modified model Eq.(2) for each month in Table 2 [30].

The linear regression analysis was carried out as explained in section 3 and the results were plotted for big dome for three heights h= 0, 0.75 m and 1.5 m as follows in Figs.4 [30].

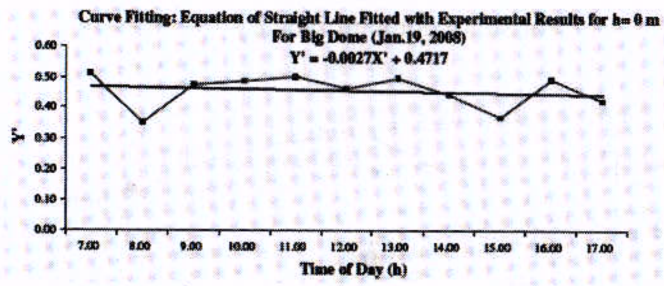

Fig.4 (a). Straight line fit with experimental results of big dome at h=0 m from ground level

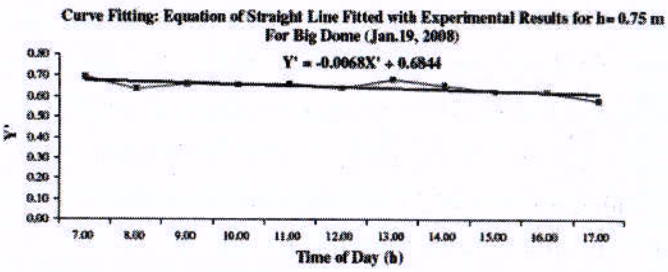

Fig.4(b). Straight line fit with experimental results of big dome at h=0.75 m from ground level

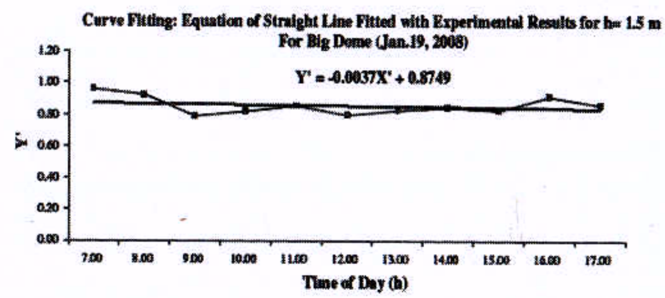

Fig.4(c). Straight line fit with experimental results of big dome at h=1.5 m from ground level

Table 2. Daylight factor using developed skylight model and experimental values

Month	Model/ experimental values	DF-0 B (%)	DF-75 B (%)	DF-150 B (%)	DF-0 S (%)	DF-75 S (%)	DF-150 S (%)
January	Model	1.54	1.99	2.41	2.85	3.23	3.97
	Experimental	1.58	1.90	2.35	2.80	3.37	4.15
February	Model	1.54	1.58	2.20	2.86	2.87	3.34
	Experimental	1.19	1.57	2.08	2.48	3.00	3.52
March	Model	1.51	2.05	2.89	2.86	5.39	6.30
	Experimental	1.52	2.11	2.99	4.02	5.49	7.07
April	Model	1.54	2.55	3.22	2.88	4.54	5.57
	Experimental	1.91	2.55	3.20	3.55	4.56	6.20
May	Model	1.54	2.59	2.97	2.81	4.51	6.30
	Experimental	1.78	2.41	2.91	3.78	4.80	6.07
June	Model	1.53	2.02	2.42	2.84	4.24	6.25
	Experimental	1.61	2.07	2.53	3.00	4.49	6.61
July	Model	1.51	2.09	2.75	2.85	4.50	5.60
	Experimental	1.95	2.40	2.86	3.74	5.14	6.10
August	Model	1.53	2.26	2.82	2.83	4.11	5.39
	Experimental	2.02	2.45	2.92	3.55	4.41	5.46
September	Model	1.50	2.22	2.94	2.81	3.95	5.16
	Experimental	2.03	2.47	2.95	2.69	3.87	5.31
October	Model	1.52	2.27	2.82	2.84	3.87	5.54
	Experimental	1.98	2.43	2.88	3.27	4.24	5.72
November	Model	1.52	1.87	2.37	2.83	3.72	4.58
	Experimental	1.83	2.20	2.59	3.05	4.12	5.30
December	Model	1.52	1.57	1.98	2.82	2.89	4.54
	Experimental	1.18	1.69	2.12	2.22	2.87	3.64

DF- Daylight Factor, h=0/75/150 cm (from ground level), B/S- Big/Small dome roof

The validation of daylight factor (DF) using experimental data of daylight factor for big and small domes at three different heights above floor surface were carried out and given in Table 2. The outside and inside illuminance experimental measured data along with validation is shown in Figs.5 [32].

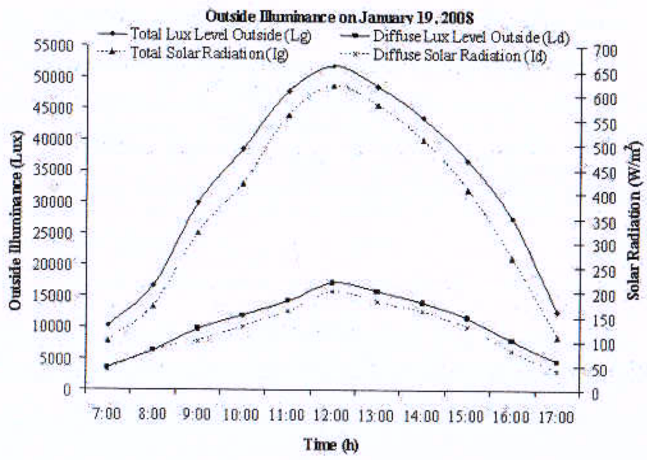

Fig.5(a). Outside illuminance at horizontal surface on January 19, 2008

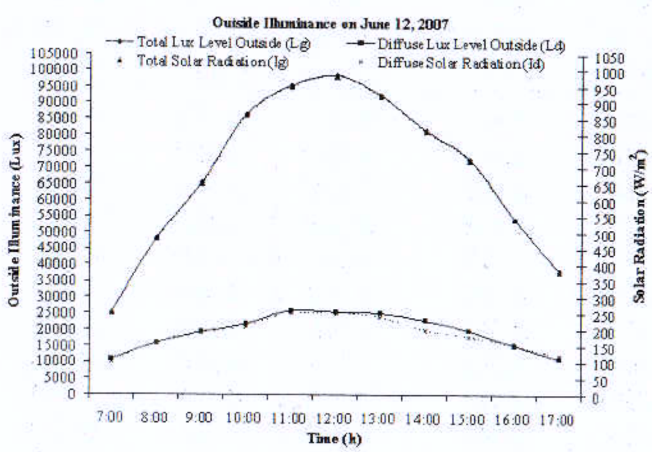

Fig.5(b). Outside illuminance at horizontal surface on June 12, 2007

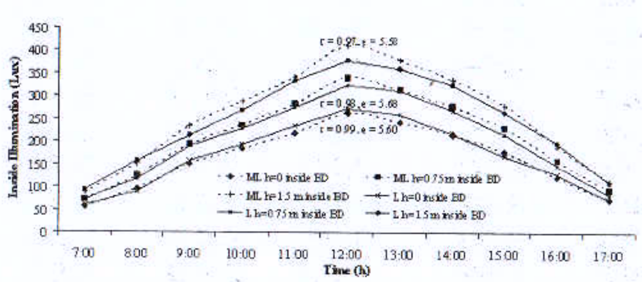

Fig. 5(c). Experimental validation of skylight model for big dome in January 19, 2008

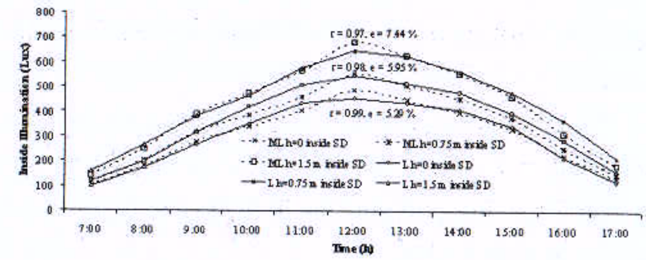

Fig.5(d). Experimental validation of skylight model for small dome in January 19, 2008

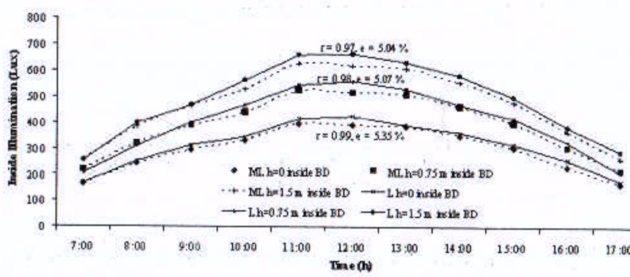

Fig.5(e). Experimental validation of skylight model for big dome in June 12, 2007

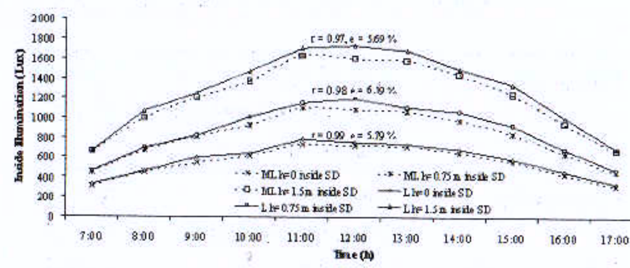

Fig.5(f). Experimental validation of skylight model for small dome in June 12, 2007

The annual average energy saving potential for three heights for big and small domes were determined for selected locations in India and plotted as shown in Fig.6.

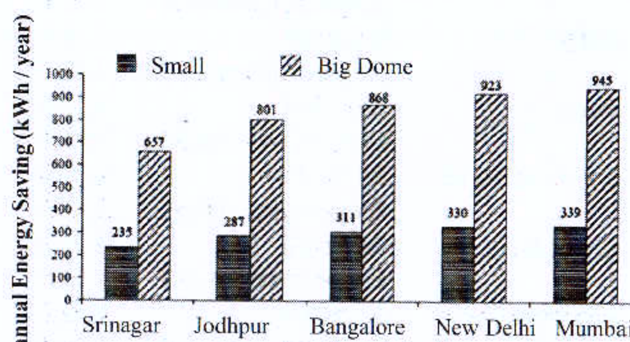

Fig.6. Annual energy saving potential of skylight for big dome room in India

5. Conclusions:

The buildings are rated high if it has daylighting arrangement as per Indian Green Rating for Integrated Habitat Assessment (GRIHA). The key conclusions can be drawn from this investigation as follows:

1. It is found that the root mean square percentage error is in the range of 5–8% for the developed model Eq.(2). Hence, the proposed daylight factor model represented by Eq.(2) can be used to estimate the daylight factor (%) and corresponding inside illuminance at different vertical heights in skylight integrated dome shape roof adobe-house.
2. The illuminance level inside the adobe-house was found sufficient for office work inside the room from 9 am to 5 pm with 100 lux (min.). The small dome room has maximum illuminance value in the range of 450–650 lux (in winter) and 800–1800 lux (in summer) while big dome room with maximum illuminance value (for h = 0–1.5 m) 250–400 (in winter) and 400–900 lux (in summer) in New Delhi (India).
3. The actual annual energy saving potential of the skylight for big and small dome was determined as 474 kWh/year and 818 kWh/year respectively based on the actual number of clear and partially cloudy days. The ammount of CO_2 emission mitigation per year by big and small dome was estimated as 744 kg/year and 1283 kg/year respectively as reported by Chel et al. [30].
4. The experimental daylight factor over the year for big dome room (for h = 0 – 1.5 m) are found in the range of 1.5 – 2.5% (January) and 1.5 – 3.5% (June) while for small dome rooms (for h = 0 – 1.5 m) it varies in the range of 2.5 – 4.5% (January) and 3 – 7.5% (June) based on skylight performance in both winter and summer. The annual average value of percentage daylight factor (for h = 0 – 1.5 m) is determined as 2.3% and 4.4% for big and small dome skylight rooms respectively. Hence, the skylight rooms are suitable for office building, e.g. state government offices in rural and urban areas of India, temple, church, mosque, etc.
5. The vertical height (h) of work plane above floor surface for the skylight room has significant effect on the amount of illuminance. Hence, distance of work plane from skylight is directly proportional to amount of illuminance received on that work plane surface.

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