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Model development and evaluation of global and diffuse luminous efficacy for humid sub-tropical region

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ABSTRACT

Daylight has a significant role for energy conservation in buildings. Luminous efficacy models have been applied by many researchers to estimate the illuminance level from available irradiance data. In the present study, the characteristics of global (K_g) and diffuse (K_d) luminous efficacies are reported based on measured data for the humid sub-tropical region of New Delhi, India. Four existing efficacy models have been compared based on the measured irradiance and illuminance data. Statistical analysis indicates that the existing models performed poorly for the selected location. The performance of the models was significantly improved when the optimized coefficients were adopted using the measured data. Global and diffuse efficacy under clear, intermediate, overcast and all sky conditions, using existing and developed efficacy models were computed and compared. A good agreement has been exhibited for variation of efficacies with the measured values for different sky conditions from cloud to clear skies. Variation of global and diffuse efficacy for sky (clear, intermediate and overcast) w.r.t. solar altitude angle and sky clearness index has been presented. Finally, mean monthly global (L_g) and diffuse (L_d) illuminance were also estimated using the original and optimized version of efficacy models to provide impression of deviation of the models.

1. Introduction

Lighting plays an important role for energy conservation in buildings. The Bureau of Energy Efficiency (BEE) accounts lighting to be 28% of the total electric energy usage in buildings in India [1]. Daylighting is an important passive method of building design in reducing energy consumption in lightings. An intelligent utilization of daylight can significantly reduce the use of artificial lighting and the respective electrical demand. Therefore, it is useful to estimate its availability before integrating it in building design.

Luminous efficacy (lm/W) is the parameter used to calculate the illuminance from solar irradiance. It is defined as the ratio of solar illuminance (in units of lux) to solar irradiance (in units of W/m^2) on the same surface [2]. The calculation of luminous efficacy requires its relation with solar angles, which is presented in Appendix I. Solar illuminance data for most of the Indian locations are not available. So, the luminous efficacy approach can be used to generate solar illuminance from solar irradiance data. Another reason to evaluate luminous efficacies is that, simulation based daylight analysis requires information regarding outdoor conditions. Irradiance data used for computational simulation is available in the form of weather data of the location. The weather data consists of horizontal global, diffuse solar irradiance, ambient temperature and relative humidity values which can be applied for the estimation of horizontal and vertical daylight illuminance using a suitable daylight illuminance distribution model [3,4].

Various studies have been conducted for the validation and development of efficacy models. Littlefair [5] measured the solar global and diffuse radiation during one year 1984–85 for a location near London, UK. A relation between luminous efficacy (both direct and global) and solar altitude angle was established for clear to overcast sky. Sunshine probability was used as an indicator of sky clearance. Perez et al. [3] developed and validated several efficacy models for the calculation of daylight illuminance (global, beam and diffuse). Models were formulated to estimate illuminance (global, diffuse) as a function of solar irradiance and sky condition parameters. The Perez model was used by Colaco et al. [6] to develop computer simulation tool (*Daylight*), which computes the

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daylight availability for Bangalore.

Chandra [7] derived a luminous efficacy model from the measured values of solar irradiance and illumination for Roorkee. The values of luminous efficacy were plotted against solar altitude angle and under varied turbidity conditions. Muneer and Kinghorn [8] developed two models for both global and diffuse efficacy expressed in terms of the sky clearness index (k_t). They compared efficacy models including average-value, Perez, Joule models with their proposed models.

Ruiz et al. [9] assessed the Muneer model using data obtained at Madrid and proposed different models for global efficacy for all sky types as a function of the sky clearness index and sun altitude. Patil et al. [10,11] validated several efficacy models for horizontal as well as vertical planes using measured data for New Delhi. The study was further extended for the computation of daylight on horizontal and vertical surfaces for different Indian locations in different climates.

The efficacy of solar irradiance varies with sky conditions. Studies on the evaluation of luminous efficacy have been conducted for different locations [12–15]. The dependency of luminous efficacies on the local conditions has been reported. The detailed study on the determination of luminous efficacy for various sky conditions for the sub-tropical region, especially for the Indian subcontinent has not been carried out so far. Therefore, in the present work luminous efficacies for different sky conditions using existing and developed models against the measured data has been computed and compared. This study aims to explore the characteristics of sub-tropical daylight efficacies.

2. Location and climatic conditions

New Delhi, latitude 28.58 °N and longitude of 77.2 °E, is located in the Northern part of India, at an altitude of 216 m above mean sea level. The climate of New Delhi is a monsoon influenced sub-tropical composite type of climate with remarkable variation between summer and winter temperatures. The average temperature of the summer months is 32 °C, with a maximum temperature of 45 °C on some days. In winters, the average temperatures range around 12–13 °C. The intensity of solar radiation is high during summers with diffuse radiation adding a small amount to the total. In monsoons, the intensity is low with mainly diffuse radiation due to an overcast sky. The sky is clear during winter [16].

3. Methodology

In this study, two sets of irradiance data have been used. To assess the efficacy models, a set of measured data for irradiance and illuminance over the period of six months (from January to June month) in a year was established. The mean hourly data has aggregated from measured irradiance and illuminance values on horizontal surfaces during daytime. The measurements taken covers a variety of sky conditions, from clear, to intermediate, to overcast and includes all seasonal effects. Measurements involving very low sun altitudes (less than 5°) and very low irradiance values (less than 50 W/m^2) were excluded from the calculations. To compute monthly global and diffuse illuminance of a year using original and optimized models, the annual irradiance data for New Delhi given by Mani and Rangrajan [17] was used. Their average data are based on measurements from a period of 15 years.

The experimental set-up was mounted on the roof of workshop block of the Centre for Energy Studies, IIT Delhi. A standard precision pyranometer has been used for the irradiance measurement, which was manufactured and calibrated by Eppley Laboratory Inc., USA. The illuminance meter (Li 210-SA) used to measure illuminance was supplied by LI-COR Inc., USA. The experimental set-up is shown in Fig. 1 and the ambient temperature and relative humidity (RH) has been measured using mini-datalogger supplied by Testo.

The technical specifications of applied pyranometer and illuminance meter are mentioned in Tables 1 and 2 respectively.

4. Development and assessment of efficacy models

In this section, existing luminous efficacy models are evaluated against measured data of the selected location. Due to dependency of luminous efficacy on local conditions, an additional set of models are formulated with optimized coefficients based on data collected using regression analysis. Two models are also developed and proposed in the study: one for the global efficacy (K_g) and another for the diffuse efficacy (K_d). Each model was then analysed statistically.

The accuracy of the models was determined using three statistical indicators: relative error (*RE*), relative mean bias difference (*rMBD*) and root mean square difference (*rRMSD*). The denotation of *rMBD* and *rRMSD* is different in nature. The value of *rRMSD* is always positive, while *rMBD* can be positive or negative. A positive *rMBD* exhibits the model tendency to overestimate, while negative shows tendency to underestimate. These statistical indicators are defined as follows [18]:

$$RE_i(\%) = \frac{(C_i - M_i)}{M_i} \times 100 \tag{1}$$

$$rMBD(\%) = \frac{\sum_{i=1}^{n} \frac{(C_i - M_i)}{M_i}}{n} \times 100 \tag{2}$$

$$rRMSD(\%) = \sqrt{\frac{\sum_{i=1}^{n} \left[\frac{(C_i - M_i)}{M_i}\right]^2}{n}} \times 100 \tag{3}$$

In above equations, M_i is the measured illuminance, C_i is the derived illuminance from efficacy models and n is the total number of pairs of irradiance and illuminance values.

4.1. Global efficacy models

Four existing luminous efficacy models were selected for assessment namely: Littlefair, Muneer and Kinghorn, Perez and Ruiz model. The selection of the models was based on their previous testified performance.

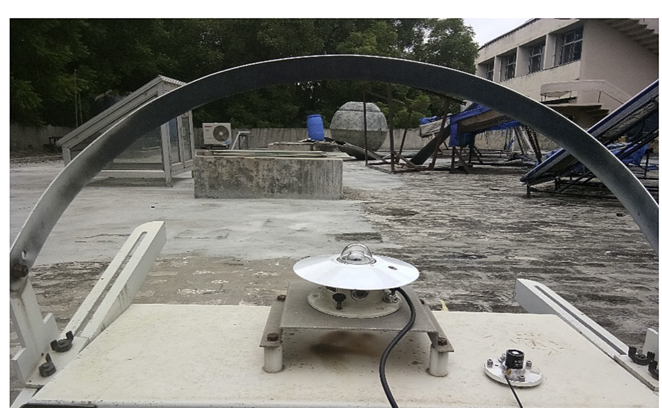

Fig. 1. Applied pyranometer and illuminance meter.