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Monthly luminous efficacy models and illuminance prediction using ground measured and satellite data

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ABSTRACT

This paper presents the derivation of the simple monthly luminous efficacy models to be applicable in daylight design and practice. Illuminance and irradiance data from the CIE IDMP station in Bratislava and climatological data from the Slovak Hydrometeorological Institute as well as data obtained from the satellite representing the climate of Bratislava are used in this study. Three models of luminous efficacy based on statistical analyses are proposed. New models are compared with the Perez model and results are discussed. Finally the study is devoted to predict exterior illuminance using the proposed luminous efficacy models and derived from satellite irradiance data. The advantage of the presented approach is in application of irradiance data regularly measured on the ground and data from satellite images when no measured illuminance is available. After a simple calculation processing the results have shown good accuracy in terms of the RMSE and MBE when comparing the new model with the Perez model as reference.

1. Introduction

In recent years the role of daylight application in buildings and energy effective illumination brought new view in the energy efficient building design. Office spaces spent large amounts of energy for artificial lighting during work hours and during daytime. Artificial light should supplement daylight for conserving the energy demand, not vice versa. In this sense a potential of daylight is in its availability, variability of levels, time of occurrence and interior lighting system performance. In order to estimate possible savings of energy various computer simulation methods have been developed. Generally, these were based on the availability of daylight data in the specific locality (e.g. Littlefair, 1988; Muneer, 2004; Reinhart, 2001). The luminous efficacy concept enables calculation and evaluation of illuminance variability using irradiance data in a locality without access to illuminance measurements.

Simulations or evaluations of daylighting in the interior require information about external daylight conditions in the specific place often represented by cloudiness, sunshine duration and humidity. The parameters of daylight climate are regularly measured at the CIE IDMP stations. More widely and commonly available is irradiance than illuminance. When the luminous efficacy is known, illuminance can be estimated using measured irradiance data for a certain locality (Chung, 1992; Kong and Kim, 2013; Muneer and Angus, 1995; Muneer and Kinghorn, 1997). Respecting CIE S 017/E:2011 definitions the value of luminous efficacy is calculated by the ratio of measured illuminance to irradiance. Atmospheric conditions and sun elevation change during a day continually and affect illuminance and irradiance levels. Human eyes perceive light at the moment of its occurrence, not as average values in a certain time interval. Therefore, the daylight evaluation should be based on instantaneous data reflecting daylight conditions in a short interval (Walkenhorst et al., 2004; Perez et al., 2012; Darula and Fabian, 2012; Fabian and Darula, 2013b, 2013a). Databases with detailed yearly data of daylight parameters are scarcely available over the world. The year 1991 has been declared as the International Daylight Measurement Year by the CIE. Thereafter the CIE IDMP stations equipped by instruments for daylight measurements have been built worldwide and 42 CIE IDMP stations started operation (IDMP-CIE, 2014; IEA-SHCP-17E-2, 1994). The set up and operation of these stations are quite expensive; therefore, appropriate methods for evaluation of daylight parameters are still desirable. As ground measurements are spread, the satellite techniques allow to derive data with high spatial resolution over the globe; these data are appropriate resource of solar irradiance (e.g. Beyer et al., 1996; Janjai et al., 2008). The data obtained at CIE IDMP stations represent climate conditions in a specific

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Nomenclature

Note: This nomenclature is respecting the CIE Vocabulary (2011).

a	number of neglected values per time interval
CI	clearness index
CR	cloud ratio
$Effd$	diffuse luminous efficacy (lm W^{-1})
$Effg$	global luminous efficacy (lm W^{-1})
$Effs$	direct luminous efficacy (lm W^{-1})
$E_{e,d}$	diffuse horizontal irradiance (W m^{-2})
E_{e,d_e}	estimated diffuse irradiance (W m^{-2})
E_{e,d_s}	satellite diffuse irradiance (W m^{-2})
$E_{e,g}$	global horizontal irradiance (W m^{-2})
E_{e,g_e}	estimated global irradiance (W m^{-2})
E_{e,g_s}	satellite global irradiance (W m^{-2})
E_{eo}	extraterrestrial irradiance (W m^{-2})
E_{eoh}	extraterrestrial horizontal irradiance (W m^{-2})
$E_{e,s}$	direct horizontal irradiance (W m^{-2})
E_{e,s_e}	estimated direct irradiance (W m^{-2})
E_{e,s_s}	satellite direct irradiance (W m^{-2})
$E_{v,d}$	diffuse horizontal illuminance (lx)
$E_{v,g}$	global horizontal illuminance (lx)
$E_{v,ge}$	east vertical illuminance (lx)
$E_{v,gs}$	south vertical illuminance (lx)
$E_{v,gn}$	north vertical illuminance (lx)
$E_{v,gw}$	west vertical illuminance (lx)
$E_{v,s}$	direct horizontal illuminance (lx)
I	incident normal direct irradiance (W m^{-2})
k	constant 1.041
L_{vz}	zenith luminance (cd m^{-2})
LST	Local Standard Time (h)
MBE	Mean Bias Error (lm W^{-1})
m	optical air mass (–)
$RMSE$	Root Mean Square Error (lm W^{-1})
T_{dew}	surface dew point temperature (°C)
TST	true solar time (h)
T_L	Linke turbidity factor (–)
T_v	luminous turbidity factor (–)
W	precipitation (mm)
Z	solar zenith angle (deg)
φ	geographical latitude (deg)
γ_s	solar altitude (deg)
Δ	sky brightness (–)
ε	sky clearness (–)
э	eccentricity of the Earth's orbit (–)
δ	solar declination (deg)

locality and cannot be evaluated for a large area but they can be used for verification and testing of calculation techniques and developed satellite algorithms.

2. Luminous efficacy

The earth's atmosphere consists mainly of nitrogen, oxygen, carbon dioxide and inert gases, water vapour, dust and ice crystals. The quantity of solar radiation and daylight at the earth's surface depends on the atmospheric composition in a specific locality and solar altitude γ_s, which is related to the length of the direct sunbeam propagating through the atmosphere.

The luminous efficacy is a variable that allows to predict illuminance at places where daylight illuminance is not measured and only irradiance data are available. Daylight illuminance data in a certain locality offers the specific exterior conditions for the prediction of illuminance levels in a room, e.g. during a year, for calculation of energy savings using daylight and more effective daylight performance applying simulation programs. Three types of luminous efficacies, global *Effg*, diffuse *Effd* and direct *Effs* can be recognised:

$$Effg = \frac{E_{v,g}}{E_{e,g}} \tag{1}$$

$$Effd = \frac{E_{v,d}}{E_{e,d}} \tag{2}$$

$$Effs = \frac{E_{v,s}}{E_{e,s}} \tag{3}$$

Luminous efficacy significantly depends on the solar altitude during sunny situations. Direct sunlight luminous efficacy increases in accordance with the solar altitude with a higher increment in the lower values and a lower increment in higher values. Global and diffuse luminous efficacies are rather independent from solar altitude while values of diffuse luminous efficacy are higher than values of global luminous ones (Kittler et al., 2012; Navvab et al., 1986). During overcast situations is valid $E_{v,g} = E_{v,d}$ and $E_{eg} = E_{e,d}$ because of absence of the direct component and therefore the luminous efficacy $Effg = Effd$.

In the past many models of luminous efficacy were proposed by several authors (e.g. Chung, 1992; Littlefair, 1988; Muneer and Angus, 1995; Perez et al., 1990; Robledo and Soler, 2001); however, their description is based on local climate conditions and varies significantly from region to region. The luminous efficacy is often derived from three basic parameter groups. The first group takes into account only the solar altitude γ_s, i.e. one variable, the second group uses several meteorological variables and the third group applies only constant values of such parameters.

The first approach allows estimation of global and diffuse luminous efficacies on the base of a polynomial fit of γ_s. Many authors tried to find relation between luminous efficacy and another variables like humidity, sky brightness Δ, sky clearness ε, cloud ratio etc. As was mentioned above illuminance measurements are rather rare; therefore, models of luminous efficacy are often included into simulation programs to calculate illuminance. One of the most precise model proposed by Perez et al. (1990) is applied for example in Radiance program or other simulation packages.

2.1. Description of the Littlefair model

A simple model for estimation of the luminous efficacy was proposed by Littlefair (1988). It was derived from yearly data measured in Garston, England, applying polynomial fit based only on γ_s. Measurements of both global and diffuse illuminances and irradiances on the horizontal plane and on four vertical surfaces oriented to the cardinal directions were carried out. Littlefair's study resulted in two formulae for estimating direct luminous efficacy Eq. (4) and global luminous efficacy Eq. (5).

$$Effs = 51.8 + 1.646\,\gamma_s - 0.01513\,\gamma_s^2 \tag{4}$$

$$Effg = 104.4 + 0.18\,\gamma_s - 0.0009\,\gamma_s^2 \tag{5}$$

No formula for *Effd* was proposed.

2.2. Description of the Perez model

Perez used measurements from 13 cities to derive his model. The hourly direct and global irradiance, three hourly surface dew point temperatures T_{dew} and precipitation W data were used as input. This luminous efficacy model is based on three parameters: solar zenith

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