Energy & Buildings 178 (2018) 318–330

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Evaluation of a hybrid photo-radiometer sky model compared with the Perez sky model

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ARTICLE INFO

Article history:
Received 20 February 2018
Revised 15 August 2018
Accepted 15 August 2018
Available online 3 September 2018

Key words:
Daylight simulation
High Dynamic Range photography
Image-based lighting
Sky models

ABSTRACT

Daylight simulation results greatly rely on the accuracy of sky models. When generic CIE sky and Perez all-weather sky simulate daylighting scenes they simplify cloud distributions. The lack of cloud distributions and subtle luminance variations causes simulation result deviations. High Dynamic Range (HDR) image techniques provide a method of generating accurate and actual skies. This paper explores the accuracy of a horizontal hybrid phadiometer (HPR) sky model, which combines modeled physical descriptions of the sun and HDR sky images. The aim was to build on and enrich the findings of a previous study (Humann and McNeil, 2017).

In this study, the HDR images within four office spaces were taken. Simultaneously, global horizontal illuminance and HDR sky images were recorded outside. Simulated luminance maps were generated under both the HPR and Perez skies. Daylight Glare Probability and vertical eye illuminance (E_v) were calculated from 112 groups of luminance maps. The simulated E_v under HPR and Perez skies presented relative RMSE of 21.3% and 23.7%, respectively. The frequencies of accurate glare prediction under HPR and Perez skies were 95.5% and 93.9%, respectively. The results indicated that both the horizontal HPR sky and the Perez sky simulate equally accurate luminance maps.

1. Introduction

1.1. Sky models in daylight simulations

Daylight plays an important role in interior lighting environments. Comfortable daylit environments not only fulfill occupants' visual requirements but can also influence their circadian rhythms and psychological traits [1,2]. Harvesting sufficient daylight can reduce the energy consumption of electric light and carbon emissions [3–5]. Therefore, it is significant for architects to design well daylit environments. Since daylight varies both by daily and by season, simulation software is necessary for architects and designers to accurately predict daylighting performance for design projects.

One concern of simulation is to what extent can simulation results be compared with field measurements. There are multiple factors that influence the resultant accuracy in daylight simulations, like building geometries, material properties, software algorithms, and sky models [6]. A sky model is the primary lighting source in daylight simulations. Generic CIE sky models [7–9] and the Perez all-weather sky model [10] are currently in wide use. The development of High Dynamic Range (HDR) image techniques led to another method of generating sky models, image based sky models [6,11–13].

The International Commission on Illumination (CIE) has adopted 15 standard skies ranging from clear to overcast conditions. CIE skies are mathematical models that use the sun's zenith angles, azimuth angles, and conceptualized arbitrary sky elements to generate sky luminous intensities [7–9]. However, there are only six types of CIE sky models available in gensky: a standard CIE clear sky with or without the sun, a standard CIE intermediate sky with or without the sun, a standard CIE overcast sky, and completely uniform cloudy sky [14]. Simple inputs of a location, given time, and selection of a sky condition can generate a CIE sky model by gensky. Due to their simplicity and ease of use, CIE sky models are commonly used in daylight simulations, especially by beginners. Yet, previous studies concluded that CIE sky models cannot simulate accurate results. Inanici and co-workers concluded that CIE skies consistently underestimate interior lighting distributions [6,15], which was confirmed by Cauwerts and Piderit [16]. Jones and Reinhart [17] suggested using the CIE sunny sky to yield the worst glary situations, which agrees with Kong's et al. conclusion [18] that the CIE sunny sky can predict accurate Daylight Glare

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https://doi.org/10.1016/j.enbuild.2018.08.022

Probability (DGP) results [19]. Limited by six sky conditions and the mathematical methods, generic CIE sky models are suitable to calculate interior daylighting performance under specific conditions or compare design alternatives [6,15] rather than being utilized in validation studies.

The Perez all-weather sky model combines a mathematical framework with a set of coefficients stemmed from sky-scan data. It covers diverse sky conditions ranging from totally overcast to very clear [10]. The inputs of a location, given time, direct normal and diffuse horizontal solar irradiance, for example, generate a Perez sky in gendaylit [20]. Solar irradiance or illuminance data can be collected onsite or downloaded online. EnergyPlus provides abundant weather data that covers a variety of cities in different formats, like Typical Meteorological Year (TMY) files and Chinese Standard Weather Data (CSWD) [21]. Unlike CIE sky models that can only be used in point-in-time simulations, the Perez sky model is also employed in annual climate-based simulations [22]. Due to the Perez sky's high level of accuracy and simplicity procedures of utilization, it has been widely used in software and methods validation studies [23–25].

1.2. Image-based sky models

Luminance distributions of actual skies, which involves light scatted by water and dust, are more complex than the skies generated by the Perez or CIE sky models. Image-based sky models are capable of including the sky complexity by utilizing HDR images as the lighting source in simulations [11,12]. A horizontal HDR sky image provides lighting and cloud distributions, and a vertical HDR sky image documents a site's luminous surrounding environments.

One difficulty of capturing skies via HDR image techniques is the extreme luminance values of the solar corona. The inability of one camera to record the whole luminance range of the sun causes underestimation of HDR sky models. To the authors' knowledge, there are two solutions to address this issue. One solution is to separate the solar corona from the diffuse sky component by taking two HDR images simultaneously [13,26]. Inanici and others used f/16 with 3.0 ND filters to capture the solar disk and f/4 to capture diffuse skies. In order to avoid the underestimation of the solar corona and the overestimation of the luminance values of the remaining sky, Inanici used direct horizontal and diffuse horizontal solar radiation to calibrate the solar corona and the remaining sky image, respectively. Then, the two calibrated HDR images were fused together. The solar corona was extracted by mksource from the fused HDR sky image. Inanici and others validated the image-based sky model through both horizontal illuminance and luminance maps. The studies concluded that the image-based sky model generate comparable simulation results when compared with the simulation results under the Perez sky model [6,15].

The other solution to separate the solar corona from the diffuse sky component is to block the solar corona when taking HDR images. Chiou and Huang employed a shadow ring to block the sun from a camera sensor and complemented the blocked portion of the images in Adobe Photoshop following certain luminance gradation pattern [27]. Although their study concentrated on the diffuse sky component, it concluded the accuracy of the method that uses measured diffuse horizontal illuminance to calibrate HDR diffuse sky images [27]. Humann and McNeil proposed a hybrid photo-radiometer (HPR) sky model by integrating modeled physical descriptions of the sun and HDR sky images [28]. Their method used only one camera to capture diffuse skies and removed the insufficiently captured solar corona with a black disk if the sun was not occluded by clouds. Then, one calibrated HDR image of the diffuse sky component and the solar disk generated in gendaylit were integrated as an HPR sky. As the camera sensor cannot record the light spectrum outside of the visible range (400–700 nm), illuminance (lux) values for the direct and diffuse sky components rather than full spectrum irradiance (W/m^2) values were used in the HPR sky model [28].

Compared with the solution of using two cameras to separate the solar corona from the diffuse sky component, Humann and McNeil's method simplifies the procedures of data collection and post-processing. Using one camera to mainly take the diffuse sky component, their method narrows the range of exposure values and shortens the image-capture duration. Generating the solar disk in the Perez sky model, this method solves the luminance overflow caused by the sun. Furthermore, this method eliminates the need for ND filters and corrections of chromatic shift. Since their method has only been validated in a physical scale model study using illuminance values, this research uses four office spaces within two buildings to test the accuracy of the horizontal HPR sky model in real environments. As previous studies reached the consensus concerning the inaccuracy of CIE sky models and the accuracy of the Perez sky model, this study only uses the Perez all-weather sky model for comparison. The purpose of this present work includes:

1. Validate the horizontal HPR sky through field measurements under diverse sky conditions;
2. Enrich the application of the horizontal HPR sky model to diverse interior spaces covering different orientations, spatial organizations, and façade configurations.

2. Method

2.1. The settings

Two buildings in Milwaukee, WI with different spatial organizations and façade configurations were chosen: School of Architecture and Urban Planning (AUP) at the University of Wisconsin-Milwaukee (UWM) and Hammel, Green and Abrahams Architects and Engineers Inc. (HGA) in downtown Milwaukee. Fig. 1 shows the two buildings' locations in the pink dots.

2.1.1. School of architecture and urban planning (AUP)

AUP (43.0 N, 87.9 W) is an L-shape four-floor educational facility at UWM. Fig. 2 shows AUP's exterior perspective. The offices and studios at AUP have interior venetian blinds that occupants can manually control. The three select offices were: Office 326 on the third floor facing south, Office 422 on the fourth floor facing south, and Office 479 on the fourth floor facing east (Fig. 3). Offices 326 and 422 are 3 m-by-6.2 m rectangles, and Office 479 is a 4.1 m-by-7.8 m rectangle (Fig. 4). All the offices are private ones containing one or two occupants.

2.1.2. Hammel, Green and Abrahams architects and engineers inc. (HGA)

HGA Milwaukee office (43.0 N, 87.9 W) is an open-plan office with over 150 workstations. The building is a five-floor mixed-function building with the HGA Milwaukee office on the first floor and residential spaces on the remaining four floors. Fig. 5 shows HGA's exterior perspective. The southwest elevation faces the Milwaukee River. The office measures 95.5 m along the southwest axis and 32.2 m along the northeast axis. As shown in Fig. 6, the open-plan office was divided into four tiers based on the slope of the site.

2.2. Interior daylight luminance distributions

2.2.1. Acquisition of interior daylight distribution

A Canon 6D with a SIGMA f/3.5 fisheye lens was used to take interior HDR images. Low Dynamic Range (LDR) images were taken for each scene at f/5.6 with the shutter speed varying between