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Climate-Based Daylight Modeling (CBDM) for an atrium: An experimentally validated novel daylight performance

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ABSTRACT

In the present paper, a new daylight performance metric, Daylight Illuminance Ratio (DIR) has been developed for an atrium space to take into account the direct and diffuse components (Sun and sky). The daylight performance on each inner surface of a square atrium has been investigated and validated with hourly measured experimental data under clear sky conditions. There is good agreement between theoretical and experimental values, with a correlation coefficient (r) of 0.92–0.96 and a root mean square percentage error (e) of 8.53–10.21%. Results show that the interior surface of the west and north walls receive more daylight in June (summer) and October (winter), respectively. The presented metric can be used to predict vertical illuminance at a given point on the atrium walls.

1. Introduction

In recent years, energy efficiency has become more of a priority for building designers as energy consumption and global warming concerns have expanded. Commercial buildings consume significant amounts of energy and energy consumption is expected to increase rapidly in the future (Aldawoud and Clark, 2008). For commercial and residential buildings specifically, using electric lighting is considered a key problem that can lead to excessive energy usage as it affects cooling and heating loads requirements of the buildings. An atrium, in addition to allowing for better connection between interior spaces, is a place for social activities, and is often outfitted with aesthetic and iconic features (Hung and Chow, 2001; Ghasemi et al., 2015a,b; Li and Lam, 2003a,b). One of the important benefits of an atrium is that it provides daylight into the core of a building, however, a poorly designed atrium results in excessive energy consumption due to insufficient daylighting and/or solar radiation management (Ghasemi et al., 2013). As a result, researchers and designers often seek to optimize the size of the atrium to lower the energy demands of buildings and encourage further awareness of energy-conscious design (Aldawoud and Clark, 2008; Department of Energy, 2004; Tsangrassoulis and Bourdakis, 2003; Sudan and Tiwari, 2014; Sudan et al., 2015a).

1.1. Atrium and their daylight performance

In the field of architecture, atria and courtyards are similar elements relative to daylighting performance. Aldawoud and Clark (2008) reported that low buildings with open courtyards give better energy performance as compared to atria, whereas high rise buildings give contrary results. Therefore, the daylight prospects can't be considered equally for both atria and courtyards (Lam, 1986). The natural light in the adjoining spaces is a primary consideration in many atria, and the makeup of the vertical wall is crucial. The literature suggests that the following parameters impact the received daylight illuminance levels within the atrium: (1) Roof system and fenestration; (2) the atrium's orientation and geometry; and (3) its enclosing surfaces, including the interior wall and floor reflectances. Features of the adjoining spaces, such as their size, openings, and surface reflectances, impact the daylight levels received in those spaces from an atrium (Ahmad and Rasdi, 2000; Samant, 2011). The atrium shape and geometry are vital elements which directly affect the daylight illuminance levels inside the atrium and within adjoining spaces. The geometry of an atrium can be defined by its length, width, and height (Calcagni and Paroncini, 2004; Al-Turki and Schiler, 1997; Yi et al., 2009; Ghasemi et al., 2015a,b).

Cole (1990) identified the effects of the glazed area of the atrium walls on the daylight levels in adjacent spaces. However, Samant and Yang (2007) point out that the reflectance of the wall surface is almost negligible for illuminance across the atrium floor. Acosta et al. (2013) determined the sky component for a courtyard using predictive methods, considering a diffuse component only. They calculated the sky component for different points on the floor of square courtyards under overcast sky conditions using two lighting computer programs. This

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Nomenclature

AB	interior surface of east wall
AD	interior surface of north wall
BC	interior surface of south wall
CD	interior surface of west wall
DF	percentage daylight factor (%)
ERC	externally reflected component (%)
$E_{v,P,i}$	vertical illuminance on the atrium wall surface (Lux or lm/m^2)
$ERIR_v$	vertical External Reflected Illuminance Ratio (%)
$E_{P,o}$	outside illuminance on horizontal surface (Lux or lm/m^2)
Ex	experimental data
IRC	percentage internally reflected component (%)
I_N	intensity of the beam radiation (W/m^2)
I_b	beam radiation (W/m^2)
I_d	diffuse radiation (W/m^2)
$IRIR_v$	vertical Internal Reflected Illuminance Ratio (%)
I_{in}	total radiation on the surface (W/m^2)
L	length of the atrium (mm)
M	modulated/theoretical data
R	internal average reflectance of the atrium
SC	sky component (%)
SIR_v	vertical Sky Illuminance Ratio (%)
W	width of the atrium (mm)
WI	Well Index
WID	Well Index depth
x	position of the observational point along the width (mm)
y	depth of the observational point (mm)
z	position of the observational point along the length of the atrium (mm)
E_{ext}	illuminance in the extraterrestrial region (mm)
E_N	incident direct (or beam) illuminance (mm)

Greek letters

θ_z	Zenith (degrees)
θ_i	angle of incidence (degrees)
τ	transmittance of glazing

study was based on Perez et al. (1993) sky models.

1.2. Existing daylight metrics

In the past decade, there have been a number of metrics to assess daylight performance, and they can generally be categorized as either static or dynamic daylight metrics. Daylight factor (DF) was used as a performance metric to evaluate the daylight delivered to a point. It is a static daylight metric that quantifies the amount of the diffuse daylight at points within a space under an overcast sky condition (Leslie et al., 2012). It was used in earlier studies as a performance metric to evaluate daylight quality. Direct light coming from the Sun is excluded (Hopkinson et al., 1954; CIBSE, 1999; Cantin and Dubois, 2011). Thus, what the daylight factor communicates is very different from a prediction of the actual illumination levels that result from the full range of naturally occurring Sun and sky conditions (Mardaljevic, 2009). According to several researchers, daylight factor has noticeable disadvantages: first, it is denoted as a percentage and does not address the normal variations that occur throughout the year and across different climate conditions; hence it does not deliver absolute values of illuminance (Mardaljevic et al., 2009). It is insensitive to climate, orientation, and the intended locale of the building (Kota and Haberl, 2009). In other words, the value of the DF would be the same if the building had either South-facing or North-facing glazing, if located at a different latitude – or in any city in any country (Mardaljevic et al., 2009). Second, in building design, maximizing *DF* leads to admission of as much daylight as possible through building envelopes with a large ratio of glazed to opaque area (Reinhart et al., 2006).

Dynamic daylight performance metrics are amelioration to the static daylight metrics. The key advantages of dynamic metrics compared to the static metrics are that they include the direct and diffuse component of the daylight; variations of the daylight across seasons, and time of the day; the aperture orientation; and localized site climatic conditions. The present metrics have been developed by incorporating all of these parameters. To determine the daylight availability and potential exposure to sunlight in an interior space, a number of Climate-Based Daylight Modeling (CBDM) metrics have been proposed, such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and Annual Sunlight Exposure (ASE). These metrics are called “dynamic daylight metrics” in the sense that they consider variations in sky conditions over the year, which depends on local weather data (Mangkuto et al., 2016). DA has noted limitations. Such as it does not consider partial contribution to the daylight illuminance value when it falls below the threshold illuminance level and still may decrease the electric lighting loads. Also, there is no upper limit to the illuminance when the maximum desired daylight level is exceeded (Nabil and Mardaljevic, 2005). Continuous Daylight Autonomy (cDA) can be applied to address these conditions.

In this research, the main objective is to develop a climate-based daylight metric to determine vertical illuminance on the atrium walls. This illuminance represents the amount of daylight being delivered to the adjoining space. The proposed metric incorporates most of the important parameters such as intended locale of the building, size, shape, orientation, and the effect of the varying skies (or Sun position), and includes both the direct and diffuse components from the Sun and sky. Climate-Based Daylight Modeling (CBDM) can provide important data on actual daylight performance of an atrium building.

2. Mathematical modeling

The present study addressed the above issues by applying a CBDM approach in the evaluation of buildings in assessing interior daylight illuminance. CBDM is a dynamic approach that defines various luminous quantities using Sun and sky conditions derived from meteorological datasets.

2.1. Definitions of key terms

2.1.1. Atrium Well Index (WI)

The daylight performance of an atrium depends on its geometry. Well Index (WI) is a quantifier that describes the geometric proportions of an atrium. WI is a function of atrium height (H), width (W) and length (L) (Calcagni and Paroncini (2004) (Fig. 1)). WI is given by Eq. (1):

$$WI = \frac{H \times (W + L)}{2 \times W \times L} \tag{1}$$

2.1.2. Well Index depth (WID)

It is a function of depth of the observation point (y), atrium width (W) and length (L) (Fig. 1). It can be represented as follows for a point centered on the wall:

$$WID = \frac{y \times (W + L)}{2 \times W \times L} \tag{2}$$