Renewable Energy 71 (2014) 243–254

Contents lists available at ScienceDirect

Renewable Energy

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

Lighting design in courtyards: Predictive method of daylight factors under overcast sky conditions

Ignacio Acosta*, Jaime Navarro, Juan José Sendra

Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, 41012 Seville, Spain

ARTICLE INFO

Article history:
Received 26 August 2013
Accepted 13 May 2014
Available online

Keywords:
Daylight factor
Sky component
Reflected component
Courtyard
Overcast sky
Predictive method

ABSTRACT

The main aim of this article is to offer a quick and precise predictive method for calculating the daylight factor for different points on the floor of square courtyards under overcast sky conditions. First, the calculation of the predictive method of the sky component is established based on earlier studies and Tregenza algorithms. Subsequently a simulation of the daylight factors on the floor of a courtyard of variable size and reflectance is carried out using two lighting computer programs based on different calculation algorithms. Once the daylight factors are calculated, the reflected component, produced by the reflectance of light on the interior surfaces of the venue, is quantified. Finally, a predictive method of the internally reflected component is established, based on the theory of the integrating sphere. Predictive methods of sky and reflected components are used to determine daylight factors in a courtyard.

1. Introduction and objective

1.1. State of the art

The study of daylight in courtyards has developed from the analytical formulae of classic treatises [1] right up to the most recent research which uses computer simulation [2,3], since courtyards, which are essential architectural elements, let daylight and ventilation into buildings.

Early literature on courtyards studied the incidence of solar radiation. Mohsen [4] analysed different forms of houses with courtyards and developed a mathematical model that simulates the interaction occurring on courtyard floors as a result of the incidence of the sun. In more in-depth research, such as that by Bouchet et al. [5], an assessment is carried out on the lighting within a courtyard, resulting from its measurements and reflectance, and concluding the efficiency of this architectural element. Subsequent studies, collected in Wright et al. [6], draw up methods for predicting daylight factors in courtyards and atria.

As previously observed, the main purpose of courtyards is to light interior spaces, although they also provide passive ventilation in buildings. This statement is based on research by Aldawoud et al. [7] who stated that low buildings with open courtyards display better energy performance than those with atria.

Given the importance of courtyards in architecture, early research focused on the development of predictive methods which helped calculate daylight factors for interiors.

The performance of daylight inside a room can be determined by observing the daylight factors occurring on its interior surfaces. Daylight factor (DF) is the ratio of daylight illumination at a given point on a given plane, from an obstructed sky of assumed or known illuminance distribution, to the light received on a horizontal plane from an unobstructed hemisphere of this sky, expressed as a percentage [8]. Direct sunlight is excluded for both values of illumination.

As seen in Hopkinson et al. [1], daylight factors can be defined as the sum of three components: the sky component (SC), which represents the fraction of daylight from the sky, the externally reflected component (ERC), generated by exterior reflective surfaces illuminated by the sky, and the internally reflected component (IRC), produced by the reflectance of light on the interior surfaces of the venue (1).

$$DF = SC + ERC + IRC \quad (1)$$

The sky component (SC) for a specific point can be calculated using analytical formulation, considering the luminance generated by the visible fraction of sky. In a study on a vertical plane, Littlefair and other researchers use the Seshadri formula [9], which represents the sky component at a certain point as can be observed in Eq. (2):

* Corresponding author. Tel.: +34 647550654.
E-mail address: iacosta@us.es (I. Acosta).

http://dx.doi.org/10.1016/j.renene.2014.05.020
0960-1481/

$$\mathrm{SC}=\frac{2.3}{14\pi}\left(\beta-\beta'\cos\gamma\right)+\frac{2.2}{7\pi}\left(\sin\beta-\sin\beta'\cos^2\gamma\right) \quad (2)$$

where:

$$\beta'=\tan^{-1}\frac{w}{2\sqrt{d^2+y^2}}$$

$$\beta=\tan^{-1}\frac{w}{2y}$$

where w is the length of the wall on which the point is found, d the length of the opposite wall, and y the distance between this point and the upper edge of the courtyard.

In most studies on sky components the Tregenza algorithms are used [10]. This equation is used by the International Commission on Illumination to assess the accuracy of lighting computer programs [11]. One of the Tregenza algorithms, used when evaluating simulation programs, makes it possible to calculate the sky component produced by a vertical opening, as observed in Eq. (3):

$$\mathrm{SC}=\frac{1.5(b-c\cos(a))+2\arcsin(\sin(b)\sin(a))-\sin(2a)\sin(c)}{7\pi} \quad (3)$$

In contrast, the sky component produced by a horizontal opening is calculated using a different Tregenza algorithm, as observed in Eq. (4):

$$\begin{aligned}\mathrm{SC}=&\,1.5z(d\sin(a)+c\sin(b))+z\pi+z(\sin(2b)\sin(c)\\&+\sin(2a)\sin(d))-2z(\arcsin(\cos(\alpha)\cos(a))\\&+\arcsin(\sin(\alpha)\cos(b)))\end{aligned} \quad (4)$$

where:

$z=1/7\pi$.

In both equations, variables a, b, c, d and α are determined by the shape of the opening and position of the study point.

There are very few predictive methods for the sky component as most empirical formulations define daylight factors directly. One of the first researchers in the field was Philips [12], who determined the average sky component caused by skylights, based on the exchange coefficients, as concluded in Eq. (5):

$$\mathrm{SC}=e\frac{t}{w} \quad (5)$$

where:

$$e=\frac{1}{2(g+h-c-d)}$$

where t is the transmittance of glazing, w the distance between openings and g, h, c and d are variables of the measurements of the skylights.

Soon afterwards, Hopkinson [13] established a predictive method which made it possible to calculate the average sky factor (SF) produced by a horizontal opening, considering the luminance caused by the fraction of visible sky, under uniform sky conditions (6):

$$\mathrm{SF}=\frac{400LB}{\pi\left(L^2+D^2\right)} \quad (6)$$

where $2L$ and $2B$ are the length and breadth of the rectangular roof light, respectively, and D is the height of the roof light above the horizontal reference plane.

One of the most recent predictive methods for the sky component was developed by Acosta el al. [14] and offers precise calculations of the sky component on different points of the floor of a courtyard, as observed in Eq. (7):

$$\mathrm{SC}=\frac{L^2}{L^2+2.4H^2} \quad (7)$$

where L is the width of the courtyard, and H its height.

Usually, the externally reflected component (ERC) is calculated as a fraction of the equivalent sky factor (SF). According to CIBSE publications [15] this fraction varies between 10 and 20%. The externally reflected component tends to be neglected in the study of daylight factors within a courtyard, as there are usually no obstructions from the zenith.

Given the complexity of calculating the reflection of light, the formulation of the internally reflected component (IRC) cannot be based on analytical calculations. Therefore, research on the quantification of this component is based on light reflection hypotheses, mainly on the theory of the integrating sphere [16]. This theory establishes an internally reflected component as expressed in Eq. (8):

$$\mathrm{IRC}=\frac{\text{First reflected flux from interior surfaces}}{\text{Total area of internal surfaces}\,x(1-R)} \quad (8)$$

where R is the average reflectance of all interior surfaces. Basing his theories on this statement, Arndt [17] suggested that the first incident flux should be defined as the vertical configuration factor at the window multiplied by the window area (9):

$$\mathrm{IRC}=\frac{E_w}{E_h}\frac{WR}{A(1-R)} \quad (9)$$

where E_w is vertical illumination on the window, E_h the horizontal illumination from the unobstructed sky, W is the window area, A is the total room area and R is the average reflectance of all surfaces.

Dresler [18] defines the first reflected flux (FR) as the sum of the configuration factors from a number of elements of room surface each multiplied by the appropriate reflectances (10):

$$\mathrm{FR}=\sum_{i=1}^{n}F_iR_i \quad (10)$$

where F_i are the first incident fluxes on small elements of the room and R_i the corresponding reflectances.

Although the predictive methods listed in this brief state of the art were developed years ago, they are currently still in use, as can be seen in the work drafted recently by Kittler et al. [19].

Among the most notable predictive methods about daylight factors (DF) it is worth highlighting Lynes's research [20], which establishes that the average daylight factor on all the surfaces of an atrium ($\mathrm{DF_{avs}}$) is given by Eq. (11):

$$\mathrm{DF_{avs}}=\frac{WT_gT_f\theta}{2A(1-R)} \quad (11)$$

As a complementary method to predict illuminance on the ground, Littlefair [21] established that the average daylight factor for the base of an atrium ($\mathrm{DF_{av}}$) is given by Eq. (12):

$$\mathrm{DF_{av}}=\frac{WT_gT_f\theta}{A\left(1-R^2\right)} \quad (12)$$

where W is the area of the atrium roof aperture in m^2, T_g is the diffuse visible transmittance of the glazing, corrected for dirt on the