Applied Energy 144 (2015) 152–164

Contents lists available at ScienceDirect

Applied Energy

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

Glazing solar heat gain analysis and optimization at varying orientations and placements in aspect of distributed radiation at the interior surfaces

K.J. Kontoleon *

Laboratory of Building Construction & Building Physics (LBCP), Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki (A.U.Th.), P.O. Box: 429, Gr-541 24 Thessaloniki, Greece

HIGHLIGHTS

- The solar heat gain into an enclosure is analysed.
- A "sunlit-pattern" approach is proposed to determine the sunlit areas.
- The distribution of solar radiation considers the varying position of the sun.
- The solar heat gain for various glazing orientations is determined.
- The glazing size and placement are optimized.

ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form 19 January 2015
Accepted 21 January 2015
Available online 27 February 2015

Keywords:
Solar radiation
Radiation distribution
Glazing orientation and placement
Glazing optimization

ABSTRACT

This paper aims at introducing a novel methodology to calculate the distribution of incoming solar energy on the internal surfaces of closed spaces with an opening at various orientations and placements. While the incoming diffuse solar radiation and the reflected solar radiation are as usually distributed with the use of absorptance–weighted area ratios the penetrating direct radiation is distributed according to the formed sunlit areas on the interior surfaces. The determination of the sunlit areas into the enclosure is accomplished by forming at each time step a, so-called, "sunlit pattern" with four letter-characters specifying the particular illuminated interior surfaces that are stricken by the sun's rays. Though this study is carried out for the Mediterranean climatic conditions, the methodology is general and can be applied to other regions. Following this methodology the optimum glazing setup to maximize the solar heat gain per square meter during the heating period is formulated and solved as a constrained optimization problem. To this effect, the well-known pattern search methodology has been appropriately adapted to deal with the highly nonlinear nature of this problem, particularly when the glazing distance from the right sidewall is variable. Representative computer results are provided showing the optimization problem complexity by varying the glazing width to height and the floor width to floor depth ratios.

1. Introduction

The interest in low energy building design demands tools that can assist engineers and architects when evaluating energy use in buildings. The adoption of passive building design with regard to orientation and window size, have won a wide acceptance. Windows play a key role in the energy efficiency of both residential and commercial buildings. Varying their glazing area and placement influences the heating load and energy consumption of a building, according to the orientation of the considered façade. In some situations the loads of a zone will be affected greatly by the distribution of solar energy. This is especially true for buildings with high passive solar gains. The effective placement of thermal mass requires an accurate calculation of interior sunlit surfaces.

Several studies dealing with the entering solar energy in enclosed spaces have been reported over the years; in particular, there are many studies dealing with traditional modelling. The literature from this area is very comprehensive. For instance, in [1] the solar energy inside an enclosure considers the effective solar absorptance. In many such studies the thermal networks for the dynamic modelling of buildings is adopted. This intuitive method allows the systematic formulation and solution of general and complicated problems since any building can be modelled by analogy with an electric circuit or, equivalently, as a system of first-order differential equations [2]. In other studies the steady state

* Tel./fax: +30 2310 995772.
E-mail address: karolos_kontoleon@yahoo.com

http://dx.doi.org/10.1016/j.apenergy.2015.01.087
0306-2619/

Nomenclature

ψ	azimuth angle of the sun
ξ	window azimuth due north
ζ	window azimuth due south
γ	angle, $\psi - \xi$
β	solar altitude angle of the sun
L_A	location latitude
δ	declination angle
θ_m	incidence angle
φ	tilt angle
h	hour angle
A	apparent solar irradiation coefficient
B	atmospheric extinction coefficient
C	diffuse radiation factor
F_s	shape factor
F_g	angle factor
ρ_g	reflectivity of the ground
τ	glazing transmissivity
I_{DN}	direct normal radiation
$I_{B,m}$	direct radiation on the interior surface m
SLA_m	sunlit area on surface m
$Q_{B,m}$	direct solar heat-gain on surface m
I_{DS}	diffuse radiation
I_{RS}	ground reflected radiation
α_m	absorptivity of interior surface m
ρ_m	reflectivity of interior surface m
A_m	area of surface m
S_m	absorbance-weighted ratio for surface m
n	number of radiation redistribution cycles
$Q_m^{(n)}$	solar heat gain of surface m
m	indices for interior surfaces; **F**, **B**, **L**, **R**, **C**, **E**, **G** for the floor, back wall, left wall, right wall, ceiling, front wall and the glazing, respectively
W, L, H	floor width, floor depth and interior space height, respectively
W_A, W_W, W_H	glazing area, glazing width and glazing height, respectively
W_R, W_F	distance of glazing from the interior right wall and the floor, respectively
V	vector with elements $V(j)$, j = 1–7

modelling is used [3]. In all such studies the mathematical or thermal models comprise heat flow paths for the individual elements of an enclosure [4]. Also, a finite difference calculation with emphasis on the flow of air in a window cavity with varying spacing has been reported [5]. Roughly, the various methods can be categorized according to their accuracy, complexity and computational effort. In simple methods the distribution of incoming solar radiation is ignored and the solar heat gain through a window is determined using its transmittance for the incident entering direct radiation and the hemispherical average transmittance to account for diffuse-sky and the reflected from the ground radiation [6]. Such methods overestimate the solar gains, particularly when the glazed area is large, by assuming that all the entering radiation will be absorbed by the opaque surfaces (black body cavity hypothesis). Setting aside the geometry and optical properties of the interior walls and assuming that the entering solar radiation through glazed surfaces is completely absorbed is not physically correct. An appropriate method must consider the indoor space geometry and that some part of the entering short wave radiation can be reflected to the outside.

Although the majority of the published papers are focused on the distribution of solar radiation in enclosures that are modelled with a theoretical approach, there have been some studies with experimental or combined modelling. Such an interesting experimental study to distribute direct solar gain inside a rectangle parallelepiped room with a single, south oriented window was presented in [7]. In this work, instantaneous measurements of the sunlit areas on the internal surfaces of a room were taken every hour on two specific days; a good agreement was found between the measured and the calculated values with the main error arising by the lack of sharpness between shadowed and sun lighted areas. Also, in [8] a mathematical procedure to model the correct coupling of direct solar gain to the thermal mass, distributed inside a prototypical space, was presented. The modelling considered the dynamics as a result of the sun's motion across the sky, the changing geometry and the shifting location of the internal sunlit areas. Following this methodology, in [9] the absorbed solar energy for an interior surface of a room was determined using the radiosity–irradiation method (RIM) that employs view factors and solves for the radiosity, irradiation and absorbed radiant energy for a surface [10]. Another related study [11] focuses on the importance of distribution of direct and diffuse solar radiation inside complex enclosures. The dynamic distribution of direct and diffuse solar radiation was approached in [12] using sun patch geometry based on graphics and image processing. The so-called solar patches are determined by first working on an infinite plane and then by repeated polygon clippings [13]. Reflections of solar radiation were considered as purely diffusive and Gebhart's method [14] was applied to distribute solar radiation in the enclosure. In some available building energy simulation programs, as TRNSYS [15,16], it is assumed that the direct solar radiation, after passing through an opening, loses most of its directional character and is emitted diffusely towards all the interior surfaces of an enclosure; the calculation proceeds in the same way as for the diffuse radiation. The incoming diffuse solar radiation and the reflected direct solar radiation is distributed with the use of absorptance–weighted area ratios. In this way, the fraction of incoming direct radiation that is absorbed by any surface is given by the product of the solar absorptance times the distribution coefficient of the surface. For direct (beam) radiation, distribution factors are introduced taking into account the percentage of incoming beam radiation that strikes the surface. An improved methodology to distribute the incoming direct radiation is given in [17]; thus, while the diffuse and reflected direct radiation are distributed with the use of the absorptance–weighted ratios, the entering direct radiation is distributed using view factors [18]. In its later version [19,20] the model for the diffuse radiation applies Gebhart factors [21] that are defined as fractions of the emission of a surface (including multiple reflections) that is absorbed by another surface. Direct radiation is handled by sunlit factor matrices generated at the pre-processing stage of the simulation. In other published work, the surfaces of the enclosure are discretized for determining the area hit by direct solar radiation [22]; also a more accurate evaluation of the solar contributions from several glazed surfaces at different exposures is exploited in [23].

Other distribution approaches rely on the processing of detailed geometrical information with regard to internal surfaces, the borders of the enclosure's openings and the time varying position of the sun. In [24], particular focus is given on external shading and internal insolation calculations. For the internal distribution of solar radiation computations are performed to determine the sunlit fractions of the window that strike each internal surface. All sunlit surfaces are projected onto the plane of the window and clipped against its remaining sunlit parts, as obtained from the