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Analytical solutions to evaluate solar radiation overheating in simplified glazed rooms

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ABSTRACT

Calculation methods for the energy demand of buildings require the evaluation of the solar energy which is transmitted indoors through the transparent elements of the building envelope. This energy contributes to raise indoor temperature. Some of the outdoor solar beam and diffuse radiation impinging on the exterior surface of the glazings is transmitted indoors and is diffusely reflected on interior surface. After multiple diffuse reflections between walls and glazings, a proportion of this incoming radiation is absorbed by the opaque walls and the interior surface of the glazings raising the indoor temperature.

The objective of this study is to present analytical solutions for a very simple room with a glazing subjected to solar radiation with a normal angle of incidence. Namely, this study yields analytical expressions for: *(i)* the effective absorptance, *(ii)* the back absorptance of the glazing subjected to indoor diffuse irradiance and *(iii)* the indoor temperature. The effective absorptance of the room is compared with that obtained in Ref. [1] and advanced numerical simulations are carried out by means of IDA ICE [2] to validate the analytical expression for the indoor temperature.

1. Introduction

During the last two decades, all international initiatives have been aimed at reducing energy consumption as well as diminishing global warming.

Kyoto Protocol [3] was replaced by the current Paris Agreement [4] and the EU 2020 strategy, places special emphasis on these issues. Specifically, in the European Union [5], aims to improve the energy performance of buildings, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. Energy consumption in buildings represents, worldwide, approximately one third of the total energy consumption. This percentage varies depending on the location and the systems used, such as building enclosure, where glazing has strengthened its position as an essential construction material in low energy buildings.

Lai and Hokoi [6] reviewed the important content of studies on opaque, transparent or semi transparent solar facades. Solar facades are designed to specifically reject or absorb and reutilizes solar heat. Huang and lei Niu [7] reviewed numerous studies on optimization of the building envelope based on simulated performances. Energy performance, thermal comfort and visual comfort is optimized as a multi-objective building envelope target. The influence of daylight, thermal loss and solar gain may lead to an optimum design [8].

The increased focus on intelligent building design and constant technological advances in glass products means that integrating large glazed surfaces in low energy or passive buildings has now become even more achievable. Technological innovation such as the use of double and triple glazed units with inert gas filling and invisible low-emissivity and solar-control coatings have significantly improved the insulation properties of windows and facades, as well as new methods of modulating solar heat and light transmission, [9]. Such glazing products allow natural daylight into buildings and can maximize or limit solar heat gains, depending on the desired thermal objectives and energy balance. Nowadays, architects and building engineers believe that energy efficiency has turned into one of the most determining aspects for the election of the constructive typology. The solar *g* factor and the thermal transmittance, *U*-value [10], emerge as the key parameters that enable two possible energy scenarios: *(i)* energy harvesting, using windows, walls, and floors to collect, store, and distribute solar energy in the form of heat in winter and *(ii)* energy rejection of solar heat in summer, through the glass enclosure.

Improving the energy and daylighting performance of building envelope is essential issue for achieving building energy efficiency. Kim and Kim [11] discussed healthy residential environment as an

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List of symbols

Nomenclature

A_{id}, A'_{id}	Front and back diffuse absorptance of glass pane *i*
A_I, A_{Id}	Beam and diffuse secondary internal heat transfer factor
E_b, E_d	Beam and diffuse source terms for the radiosity equations, Wm^{-2}
e_i	absorbed heat flux in surface *i* or glass pane *i*, Wm^{-2}
F_{ij}	View factor from surface *i* to surface *j*
g	Solar heat gain coefficient
G_i	Irradiance on surface *i*, Wm^{-2}
h_e	Exterior heat transfer coefficient, $Wm^{-2}K$
h_g	Heat transfer coefficient of the air chamber, $Wm^{-2}K$
h_i	Interior heat transfer coefficient, $Wm^{-2}K$
I_b, I_d	Beam and diffuse radiation Wm^{-2}
J_i	Radiosity of surface *i*, Wm^{-2}
Q_i	solar absorbed heat flux in surface *i*, W
R, $R_d{}'$	Front beam reflectance and back diffuse reflectance of the glazing
S	Area of a surface, m^2
T	Temperature, K
U	Thermal transmittance of the glazing, $Wm^{-2}K$
U_b	Thermal transmittance of the walls, $Wm^{-2}K$
N	Number of enclosure surfaces

Greek

α	Absorptance of inner surfaces
α_e	Effective absorptance of inner surfaces
α_t	Total absorptance of transmitted solar energy
ε_i	Far infrared hemispherical emissivity of surface *i*
ε_r	Far infrared radiative exchange factor of two parallel surfaces
γ	Polar angle of incidence
ρ	Reflectance of inner surfaces
σ	Stefan-Boltzmann constant
τ, τ_d	Beam and diffuse transmittance of the glazing

architectural field of light.

Kim and Kim [12] reviewed daylighting systems for capturing natural light when overcrowded urbanization does not allow to optimize building orientation and window sizes. Berardi and Wang [13] considered daylighting in an atrium-type high performance house analyzing the visual comfort inside the house due to large areas of glazed openings. In Ref. [14], the performance of a window in terms of spatial daylight autonomy is optimized by its geometry and optical properties. In office environments, users prefer windows mostly for the attributes of daylight, sunlight and natural ventilation [15]. Thermotropic materials which change their light transmission behavior reversely have a great potential in achieving an excellent comprehensive performance between solar gain and daylighting [16].

To address the energy efficiency requirement, standards such as Passivhaus has been adopted by housing sectors [17].

When adopting Passivhauss standard the thermal envelope becomes highly insulated and maximizes passive solar heat gains presenting a risk of overheating [18]. Besides, fully–glazed facades increases overheating phenomena [19].

There is a growing interest in understanding overheating inside buildings and associated health risks [20]. Possible trades–off and synergies between energy efficiency strategies and resiliency to heat in residential buildings have been studied in Ref. [21].

Poorly ventilated dwellings are vulnerable to overheating particularly if their windows are not well protected against direct solar radiation [22]. In modern office buildings thermally–insulated envelopes enhance overheating even in cold climates [23]. This negative impact of solar gains on the yearly energy balance limits the amount of glazing or recommends using external solar shading devices.

Different models have been used for the calculation of solar energy distribution with different geometries and different absorbing properties, as well as the evaluation of the distribution of the illumination and the NIR.

Wall [24] compared four such approaches for solar radiation distribution in a room and concluded that a geometrical description of the enclosed space is important and transmission through windows, reflection and absorption must be accurately taken into account.

In traditional buildings, the window-wall ratio is small and it is assumed that the incoming solar radiation cannot escape through the window. This hypothesis is not suitable for buildings with glazed facades [25]. Modifications to take into account this phenomena are carried out on the basis of the Radiosity Irradiation Method. [26] was one of the first to use the Radiosity Irradiation Method (RIM) which was developed by Ref. [27] for determining the illumination within a room. The RIM algorithm uses view factors and solves the radiosity and irradiation of each surface.

Cucumo et al. [1] and Wen and Smith [28] estimated the effective solar absorptance of a room by means of a RIM model.

Gupta and Tiwari [29] studied the energy solar distribution inside greenhouse with and without a reflecting surface on north wall.

Model predictions in Ref. [1] were compared with an approximate theoretical equation which took into account the solar energy absorbed by the opaque walls. However, this approach did not account for the indoor diffuse energy which is absorbed by the glazing.

Oliveti et al. [30] discussed an accurate calculation of solar heat gain through glazed surfaces. The model used the effective absorption coefficient of the indoor environment to take into account that the entering energy is in part absorbed by the surfaces of the cavity and in part is dispersed outwards, through the same glazed surfaces. Causone et al. [31] proposed a simplified procedure to correctly calculate the magnitude of direct solar loads. Kontoleon [32] used a novel methodology to calculate the distribution of incoming solar energy on the internal surfaces based on sunlit pattern methodology allowing the distribution of the incoming direct solar radiation more realistically. Chatziangelidis and Bouris [33] developed a method that distributes the total direct solar radiation among its internal surfaces. Kumar et al. [34] worked on experimental and theoretical studies of glazing materials to reduce cooling loads within the building.

Even with precise simulation tools, the election of the correct glazing configuration remains very complicated. There are two model approaches to deal with the simulation thermal behavior: *(i)* complete models or Computational Fluid Dynamics (CFD) models and *(ii)* simplified models such as EnergyPlus [35] or IDA-ICE [2]. These last approaches are based on the evolution in time of ordinary differential equations where experimental or analytical correlations are used to deal with heat transfer mechanism of air in rooms or chambers.

Aguilar et al. [36] simulated the thermal performance of a room with a complete CFD model with turbulence. Xamán et al. [37] used a finite volume method for thermal evaluation of a room with a double glazing window evaluating complete configurations of different glazing with or without a solar control film. Konroyd-Bolden and Liao [38] used a three dimensional finite element method to study the thermal behavior of a window. Kontoleon [39] developed a thermal network method with distribution of internal solar radiation on different facade orientations to select the glazing to reduce building energy consumption. Optimizations of building aspect ratio and south window size [40] as