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Development of a comprehensive method to analyse glazing systems with Parallel Slat Transparent Insulation material (PS-TIM)

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HIGHLIGHTS

- A comprehensive method to predict the building performance when applying complex window systems was proposed.
- Energy and daylight performance in a prototype office were evaluated using dynamic building simulation tools.
- The method enables to observe inter-relationship between thermal and optical characteristics of complex window systems.

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ABSTRACT

In order to provide enhanced levels of indoor comfort and building energy conservation, significant improvements have been made in the design of glazed facades and window systems, yielding increases in thermal resistance while simultaneously maintaining access to daylight. Some of these approaches result in glazing systems with relatively complex structures and it is difficult to characterise their optical and thermal properties for use in building simulation. In this research, a comprehensive model has been developed to accurately predict the thermal and optical properties of complex glazing systems, and a workflow developed to yield detailed daylight and energy performance (heating, cooling and lighting) predictions of these systems when applied in buildings. Through this approach, the thermal characteristics of complex fenestration systems are obtained from a validated Computational Fluid Dynamics model, and a ray-tracing technique is used to obtain *Bidirectional Scattering Distribution Function* (BSDF) data to represent their optical characteristics. These characterises may be used in building simulation software (in this case EnergyPlus) to obtain building heating, cooling and lighting energy estimates for a room incorporating complex glazing systems. Detailed visual comfort predictions including *useful daylight illuminance*, *daylight uniformity* and *glare* may also be made, using a complementary optical model run using RADIANCE simulations. This workflow is implemented to investigate a room served by different Parallel Slat Transparent Insulation Materials (PS-TIM), which represents an example of a complex fenestration system. The workflow is used to explore the effect of slat pitch (i.e. the distance between neighbouring slats) on performance and was found to provide reasonable daylight and energy performance prediction. The results indicate that use of glazing systems with PS-TIM can provide homogenous daylight distribution and up to 33.6% energy reduction when the simulation is run using weather data for London.

1. Introduction

Buildings currently account for 30–40% of total energy consumption worldwide [1–4]. The design and specification of the building envelope is a major determining factor of building energy use during operation [5–7]. Windows in building envelopes play a critical role by determining the penetration of solar energy and daylight, controlling the view into and out of a building and influencing the overall building energy consumption [8–10]. Innovative window systems, where interstitial structures, such as horizontal Venetian blinds, pleated blinds, and Parallel Slat Transparent Insulation Materials (PS-TIM), are sandwiched between the panes of double glazed window are proposed as strategies to effectively reduce heat transfer, while maintaining access to daylight [11–21]. When exploring the performance of these complicated building elements in buildings, numerical simulation methods are indispensable in helping to create a detailed hour by hour picture of performance or to identify optimal design solutions using parametric analysis. Various building simulation tools, such as EnergyPlus, ESP-r, IES, TRNSYS, TAS and RADIANCE can be used to explore the energy, thermal and daylight performance for buildings with complex

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Nomenclature

Symbols

A	aspect ratio (–)
$a–f$	coefficients for polynomial regression (–)
D	daylight matrix (–)
E_e	exterior IR incident on window plane (W/m^2)
E_i	interior IR incident on window plane (W/m^2)
E_v	vertical illuminance (lux)
h	heat transfer coefficient (W/m^2·K)
i	illuminance at point of interest for a single time step (–)
I	illuminance at point of interest for a time series (–)
k	thermal conductivity (W/m·K)
L	height of the window air cavity (m)
s	width (m) – also sky vector in Eq. (6) (–)
S	radiation (short-wave, and long-wave from zone internal sources) absorbed by surface (W/m^2) – also sky matrix in Eq. (7) (–)
T	transmission matrix (–)
t	temperature (K/°C)
t_m	mean temperature (°C)
Δt	temperature difference (°C)
V	view matrix (–)
ε	emissivity (–)
σ	Stefan-Boltzmann constant (W/m^2·K^4)
Gr	Grashof number (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)

Subscripts

e	external
g	gap
i	internal
m	mean
s	interstitial structure/slat
v	vertical
PS-TIM	Parallel Slat Transparent Insulation Material

fenestration systems [1,20,22–26]. The challenges related to representing complex window systems in these simulation tools include: 1) precise characterisation of the thermal and optical characteristics of fenestration systems, in which two- or three-dimensional heat transfer and/or light transmittance might exist due to the presence of complex structural geometries; 2) the potential need to model adaptive features associated with the operation of complex fenestration systems (e.g. switchable glazing, moveable shading, etc.), that may affect a number of properties (e.g. thermal, visual) simultaneously.

Building energy simulation programs are not currently well set up for accurate modelling of these complex fenestration systems, often because of the simplified thermal and optical models used to solve for heat transfer and light transmission. e.g. one dimensional methods are used for both heat transfer and light transmitted through fenestration systems [27]. Glazing systems with complex configurations are often represented using pre-computed solar heat gain coefficients and visible transmittances, which despite being determined using radiosity methods, are none the less lacking in terms of representing the highly complex, angle-dependent interaction implicit when they are subject to realistic patterns of incident radiation [28,29]. In addition, analysis is currently restricted to the geometric forms associated with blinds, shades and screens, and it is challenging to characterise less common structures (e.g. tubular shading structures, nonlinear shading systems, etc.). The launch of EnergyPlus V7.2 provided the capability to include Bidirectional Scattering Distribution Functions (BSDF) in the modelling process, and this has significantly enhanced the software's capability to predict energy and daylighting performance of buildings with complex fenestration systems [27]. Published articles relating to the use of BSDFs in EnergyPlus are not common. This is, in large part, due to the challenge of obtaining the specific BSDF data for window systems under prediction [28,30]. For the purpose of precisely modelling optical performance of complex fenestration systems in EnergyPlus, RADIANCE provides a ray-tracing tool to numerically calculate BSDFs and a software utility, WINDOW, establishes a bridge for its implementation in EnergyPlus [29]. Femandes et al. [31] have undertaken modelling using BSDFs to represent complex fenestration systems in order to quantify the potential of energy saving and peak demand reduction in a space served by an angular selective window system (i.e. expanded metal mesh, tubular shading structures, and micro-perforated screens). The results revealed that energy savings of between 28 and 47% may be achieved in the perimeter zone when applying the angular selective window system under the climates of Chicago and Houston. Hoffmann et al. [32] investigated the impact of twelve different shading devices on whole building energy performance under the moderate San Francisco climate and a hot and dry Southern California climate. They used their study to develop optimised strategies to balance solar gain with glare and daylight levels. The optical properties of the shading systems were defined using the BSDF method and hourly scheduled surface gains. The results showed that shading geometry and slat material characteristics significantly affected the heat gain from solar radiation and distribution of transmitted daylight.

When dealing with adaptive fenestration systems, models need to accommodate the changes in window thermo-optical properties that occur in response to changes in energy flux incident on the building. Firlag et al. [33] investigated the use of dynamic control algorithms (using the Energy Management System (EMS) feature in EnergyPlus) to control an external roller blind mounted onto a double-glazed window, as well as an inter-pane cellular shading device within a triple-glazed window. Both systems were applied to a typical residential building and simulated under four different climates (Atlanta, Minneapolis, Phoenix and Washington DC). They also used BSDF data to represent the window systems and linked these to algorithms that simulated dynamic controls. It was concluded that using automated shading devices with the proposed control algorithms can reduce solar heat gain, resulting in a 11.6–13.0% reduction in building energy consumption.

In practice, the integration of an interstitial structure within the air cavity of a double glazing unit not only influences solar gain, it also has a significant effect on the free convection and long-wave radiative heat transfer between the two panes of glass. Although, efforts have been made to combine *BSDFs* with building energy simulation [26,32,33] to achieve a more accurate representation of solar gains (as well as daylight distribution) within the analysis of building employing complex fenestration systems, the effect of these interstitial structures on free convection and long-wave radiation heat transfer within the glazing cavity has not been considered. In practice, these greatly affect thermal and energy predictions [11,12].

This paper proposes a method that offers a comprehensive representation of complex fenestration systems applied to buildings. The approach differs from previous studies through the inclusion of a comprehensive model to represent thermal behaviour and its combination with an effective method for representing optical performance within existing building energy performance software. Computational Fluid Dynamics modelling is used to determine the thermal characteristics and a ray-tracing technique is used to predict the optical characteristics what are then converted into a BSDF format. All of these were input into building simulation software, EnergyPlus, to obtain