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A general method to evaluate the thermal impact of complex fenestration systems in building zones

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ABSTRACT

This paper presents a method to evaluate the thermal impact of complex fenestration systems on the energy balance of a building zone based on directional solar heat gain coefficients (DSHGC) and bi-directional scattering distribution functions (BSDF). The proposed methodology is presented as an alternative to layer-by-layer heat transfer models. An example of a layer-by-layer heat transfer model is the ISO15099 as implemented in the EnergyPlus building simulation program. The ISO15099 model relies on a number of assumptions that are not justified in the case of three-dimensional structures, air-permeable layers and deviations from ideal geometries, which are common features in commercial daylighting and solar-control systems. In this paper, the proposed methodology is implemented in the Fener simulation engine and compared with EnergyPlus for systems for which the assumptions of the ISO15099 model are valid. Then, the Fener program is used to simulate the thermal behaviour of a zone with a fenestration system that contains sawtooth-shaped retro-reflecting interior blinds, which cannot be directly modelled with the ISO15099 model. The impact of different control strategies on the thermal performance of the zone is demonstrated for this case study.

Contents

1. Introduction

Complex fenestration systems (CFS) refer to any window technology that incorporates a light-scattering, light-redirecting or switchable layer. Although these systems have the potential to improve the thermal and visual comfort of indoor spaces as well as to save lighting, cooling and heating energy, the thermal performance of CFS, particularly of solar shading and daylighting systems, is often not described adequately by current building energy simulation programs. These programs usually incorporate a thermal model of fenestration systems based on a layer-by-layer heat transfer approach. In the case of EnergyPlus [1], the method contained in

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List of symbols

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g	directional solar heat gain coefficient
q_i	secondary internal heat transfer factor
R	thermal resistance [m^2 K W^{-1}]
R	bi-directional reflectance matrix
T	bi-directional transmittance matrix
U	U-value or global heat transfer coefficient [W m^{-2} K^{-1}]
α	absorptance
θ	polar or incidence angle [°]
λ	thermal conductivity [W m^{-1} K^{-1}]
Λ	propagation matrix
ρ	reflectivity
ρc	volumetric heat capacity [J m^{-3} K^{-1}]
τ	transmissivity
Ω	solid angle [sr]

Subscripts

dif	diffuse
dir	directional
e	solar spectral range
gu	glazing unit
h	hemispherical
i	indoor/inner
n	normal
o	outdoor/outer
sd	shading device
sum	summer
v	visible
win	winter

Acronyms

BSDF	bi-directional scattering distribution function
DGU	double glazing unit
DSHGC	directional solar heat gain coefficient
extShade	exterior shade
extVB	exterior venetian blinds
intShade	interior shade

the ISO15099 is implemented [2,3]. This method assumes that each layer of the fenestration system is quasi-homogeneous, so that the heat transfer is always perpendicular to the window plane (except for ventilated cavities). This method fails for three-dimensional structures (e.g. insulating panels), air-permeable layers (e.g. roller shutters and blinds) and deviations between target and real geometries. In those cases, unjustified assumptions are made, which compromise the validity of the results.

This paper presents an alternative method that is able to capture the heat transfer complexity of such systems. It is based on models that have already been published but are not yet extensively used. In particular, the model of Kuhn et al. [4], hereafter referred to as the Kuhn model, in which any complex fenestration system is represented by a two-layer virtual system, with properties that are derived from the directional solar heat gain coefficients (DSHGC), the U-value, and the directional-hemispherical transmittance and reflectance of the actual system. The method proposed in this study constitutes an upgrade of the Kuhn model, directly using bidirectional scatter distribution functions (BSDF) as the optical description of the fenestration system. A BSDF is the most common form of scattering characterization and can be used to communicate between designers, manufacturers and users of optical calculation programs. The BSDF formalism consists of matrices of transmission and reflection coefficients, in which each matrix element corresponds to an optical coefficient relating an incoming light direction with an outgoing light direction. In this study, the term BSDF is used to refer either to the scattering of light or of solar radiation. Recent developments in ray-tracing simulation engines and photogoniometry have made the use of BSDF datasets of full fenestration systems (i.e. glazing units + shading devices) feasible in building simulation programs, such as EnergyPlus and Radiance [5].

The characterization of CFS based on DSHGC and BSDF data proposed in this study permits the evaluation of a broad variety of fenestration systems and their control based on standardizable and measurable information, which makes it compatible with building information modelling (BIM).

This paper also shows how the proposed method can be combined with the models presented by Klems [6,7] and Kuhn [8] in order to obtain the complex angular behaviour of complete systems from the separate angular behaviour of glazing units and shading systems. Inputs for these models are the DSHGC of the glazing unit and the BSDF of the glazing unit and of the shading device. This information can be obtained experimentally and, in many cases, analytically as is illustrated in this study.

The proposed method has been implemented in the Fener simulation engine [9], a building simulation program specifically designed for the evaluation of complex fenestration systems and their control [10]. The Fener engine has also been upgraded by implementing heat transfer functions for the transient conductive heat transfer through opaque elements (i.e. walls, ceiling and floor) [11]. The proposed method as implemented in Fener is evaluated by comparing it with EnergyPlus. The comparison includes systems for which the assumptions of the ISO15099 model are valid. Finally, the Fener program is used to simulate a building zone with a fenestration system that cannot be directly modelled with the ISO15099 model. This fenestration system consists of interior venetian blinds with slats that have a sawtooth-shaped retro-reflecting structure on the upper surface. Different control strategies are compared for this system.

2. Model description

2.1. The directional solar heat gain coefficient (DSHGC)

The solar heat gain coefficient (SHGC) or g-value is a measure of the total fraction of incident solar radiation that is transmitted into the building through a fenestration system and consists of two components, the solar transmittance τ_e and the secondary internal heat transfer factor q_i, the latter resulting from heat transfer by convection and longwave radiation of that part of the incident solar radiation which has been absorbed by the system [12]. This paper focuses on the centre-of-glazing value which excludes the influence of frames, lateral losses and spacers at the glazing edges. The centre-of-glazing value is especially useful since it is independent of the glazing dimensions and therefore generally valid. The effect of the other window elements can be added in a later modelling stage.

The SHGC of a fenestration system is very sensitive to the direction of the incoming light and, in general, can vary for all possible light directions from the incoming hemisphere. Some systems, especially clear glazing, are rotationally symmetric, meaning that the SHGC only depends on the polar component of the angle of incidence (but not on the azimuthal component). Venetian blinds and other slatted or louvred devices with horizontal or vertical slats can be considered profile-angle symmetric, meaning that they only depend on the projection of the incidence angle onto a vertical or horizontal plane, perpendicular to the window plane [12]. In this study, the term directional solar heat gain coefficient (DSHGC) is defined as the SHGC of a fenestration system for different angles