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A review of thermal and optical characterisation of complex window systems and their building performance prediction

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HIGHLIGHTS

- Window plays a key role in establishing the thermal and luminous environments within buildings.
- Review of the methods used to predict the thermal and optical behaviour of complex window systems.
- State-of-the-art review of advanced daylight assessment metrics.
- State-of-the-art review of the comprehensive building simulation approaches for windows.

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ABSTRACT

Window systems play a key role in establishing both the thermal and luminous environments within buildings, as well as the consequent energy required to maintain these for the comfort of their occupants. Various strategies have been employed to improve the thermal and optical performance of window systems. Some of these approaches result in products with relatively complex structures. Thus, it becomes difficult to characterise their optical and thermal properties for use in building performance prediction. This review discusses the experimental and numerical methods used to predict the thermal and optical behaviour of complex window systems. Following a discussion of thermal characterisation methods available in the literature that include experimental test methods, theoretical calculation methods and Computational Fluid Dynamic methods, sophisticated optical methods, such as use of Bidirectional Scatter Distribution Functions (BSDF) to optically characterise complex window systems, are introduced. The application of BSDF allows advanced daylight assessment metrics along with daylight evaluation tools to be used to realise dynamic annual prediction of the luminous environment. Finally, this paper reviews methods that permit the prediction of the combined thermal, daylight and energy behaviour of buildings that make use of complex window systems.

1. Introduction

Windows in building envelopes are critical components that determine direct solar energy gains and daylight, facilitate the view into and out of a building, and influence overall building energy consumption [1–3]. However, the material properties of glass when used in conventional windows raise concerns in response to the recent sustainability agenda, in particular in relation to the responsible use of energy in buildings. The most common issues are:

(1) Overheating during the seasons resulting in high cooling loads due to significant direct solar gain through window systems [4–6];
(2) Significant heat loss during cold seasons due to the relatively high *U-value* compared with walls or ceilings [7–12];
(3) Visual discomfort from glare in work spaces [13–15];
(4) Glare caused by the reflection of sunlight from glazing to a building's immediate surroundings or the city more widely [16];
(5) Air infiltration through defects between glazing and frame due to poor workmanship [17,18];
(6) Degradation and fading of building components or furniture due to the presence of high levels of transmitted sunlight in the internal environment [19,20].

Improvements to the design and manufacture of window systems seek to optimise the effective use of solar resource, minimise undesired energy losses and effectively moderate the indoor environment. The two main strategies that have been applied are: (1) increasing thermal resistance using approaches such as multiple glass panes, inert gases as

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Nomenclature

Symbols

c_p	specific heat capacity, J/kg K
$Const.$	constant, –
d	thickness of glass pane, m
D_λ	spectral distribution, –
e	exponent, –
E_v	vertical eye illuminance, lux
E_o	exterior IR incident on window plane, W/m^2
E_i	interior IR incident on window plane, W/m^2
F	view factor, –
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
h	also thermal conductance, W/m^2 K
J	radiosity, W/m^2
k	thermal conductivity, W/m K
L_s	luminance of source, cd/m^2
N	number, –
p	pressure, Pa
P	position index, –
q	heat flux, W/m^2
R	thermal resistance, mK/W
s	thickness of the window air cavity, m
S_h	radiative heat transfer
S_i	radiation (short-wave, and long-wave from zone internal sources) absorbed by face i, W/m^2
T	temperature, °C
U	thermal transmittance, W/m^2 K
u,v	velocity components
ν	kinematic viscosity, m^2/s
$V(\lambda)$	spectral luminous efficiency for photonic vision, –
x,y	Cartesian coordinates, –
ΔT	temperature difference, K
$\Delta\lambda$	wavelength interval, nm
β	thermal expansion coefficient, 1/K
ε	emissivity, –
σ	Stefan-Boltzmann constant, W/m^2 K^4
θ	zenith angle, °
φ	azimuth angle, °
λ	wavelength, nm
τ	transmittance, –
μ	dynamic viscosity of gas, kg/ms
ρ	density of air, kg/m^3
ω_s	solid angle, sr

Dimensionless Numbers

Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number

Subscripts

e	external
g	gas
p	glass pane
H	hot
i	internal
i, j, k	counter
m	mean
t	total
r	radiation

cavity fill, low emissivity coatings, and vacuum glazing; (2) controlling solar radiation and daylight through application of tinted coatings, reflective coatings, interstitial shading devices, and smart window techniques (e.g. electrochromic, thermochromic, photochromic glazing). Some of these approaches result in window systems with relatively complex structures, which increases the challenge of accurately characterising their behaviour for use in studies of building performance. The process of characterisation for these complex glazing systems involves investigations that explore and quantify both their thermal and optical behaviours. There is little in the literature, however, that reviews these methods of characterisation or explores their use to inform the predicted performance of buildings employing these

Table 1
Standards for determining thermal properties using experimental methods.

Region	Name	Title	Method
International	ISO 12567 [21]	Thermal performance of **windows and doors** – Determination of thermal transmittance by the hot-box method – Part 1: Complete windows and doors	Hot-box
	ISO 9869 [22]	Thermal insulation – **Building elements** – In-situ measurement of thermal resistance and thermal transmittance Part1: Heat flow meter method	In-situ
	ISO 8990 [23]	Thermal insulation – Determination of steady-state thermal transmission properties – Calibrated and guarded hot box	Hot-box
	ISO 8301 [24]	Thermal insulation – Determination of steady-state thermal resistance and related properties – Heat flow meter apparatus	Heat flow meter
	ISO 8302 [25]	Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus	Hot-plate
USA	ASTM C1363 [26]	Standard test method for thermal performance of **building materials and envelope** assemblies by means of a hot box apparatus	Hot-box
	ASTM C1199 [27]	Standard test method for measuring the steady-state thermal transmittance of **fenestration systems** using hot box methods	Hot-box
	ASTM C1046 [28]	Standard practice for in-situ measurement of heat flux and temperature on **building envelope** components	In-Situ
Europe	EN 674 [29]	**Glass** in building—Determination of thermal transmittance (U value)—Guarded hot plate method	Hot-plate
	EN 675 [30]	**Glass** in building—Determination of thermal transmittance (U value)—Heat flow meter method	Heat flow meter
	EN 1946-2 [31]	Thermal performance of **building products and components**. Specific criteria for the assessment of laboratories measuring heat transfer properties. Measurements by guarded hot plate method	Hot-plate
	EN 1946-3 [32]	Thermal performance of **building products and components** – Specific criteria for the assessment of laboratories measuring heat transfer properties—Part 3: Measurements by heat flow meter method	Heat flow meter
Russian	GOST 26602.1 [33]	**Windows and doors**. Methods of determination of resistance of thermal transmission	Hot-box