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Modeling the direct sun component in buildings using matrix algebraic approaches: Methods and validation

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ABSTRACT

Simulation tools that enable annual energy performance analysis of optically-complex fenestration systems have been widely adopted by the building industry for use in building design, code development, and the development of rating and certification programs for commercially-available shading and daylighting products. The tools rely on a three-phase matrix operation to compute solar heat gains, using as input low-resolution bidirectional scattering distribution function (BSDF) data (10–15° angular resolution; BSDF data define the angle-dependent behavior of light-scattering materials and systems). Measurement standards and product libraries for BSDF data are undergoing development to support solar heat gain calculations. Simulation of other metrics such as discomfort glare, annual solar exposure, and potentially thermal discomfort, however, require algorithms and BSDF input data that more accurately model the spatial distribution of transmitted and reflected irradiance or illuminance from the sun (0.5° resolution).

This study describes such algorithms and input data, then validates the tools (i.e., an interpolation tool for measured BSDF data and the five-phase method) through comparisons with ray-tracing simulations and field monitored data from a full-scale testbed. Simulations of daylight-redirecting films, a micro-louvered screen, and venetian blinds using variable resolution, tensor tree BSDF input data derived from interpolated scanning goniophotometer measurements were shown to agree with field monitored data to within 20% for greater than 75% of the measurement period for illuminance-based performance parameters. The three-phase method delivered significantly less accurate results. We discuss the ramifications of these findings on industry and provide recommendations to increase end user awareness of the current limitations of existing software tools and BSDF product libraries.

1. Introduction

Window shades, films, and other types of “attachments” have significant potential to reduce energy consumption in residential and commercial buildings through rejection or admission of solar heat gains and daylight and improvements to the thermal properties of the window. Such systems are estimated to have a technical potential to save 1.0–2.8 EJ (0.98–2.62 quads, where 1 quad = 10^{15} Btu) annually in energy use in the U.S. compared to the current building stock (Arasteh et al., 2006). There has been considerable interest in fenestration attachments recently because they can reduce the energy use of existing buildings cost effectively in the near-term (Lee et al., 2009; DOE, 2014). In 2014, the U.S. Department of Energy (DOE) initiated an industry-led program to develop a rating and certification program for residential window attachments. Providing third-party information to the consumer for more informed purchasing decisions is an effective strategy for increasing market adoption of energy-efficiency technologies. The resultant Attachments Energy Rating Council (AERC) developed a rating and labeling scheme that reflects annual heating and cooling energy use in residential buildings (AERC, 2017). A similar rating and certification program is planned for commercial buildings. In Europe, the European Solar-Shading Organization (ES-SO) is also working to develop a rating and certification program for window attachments (ES-SO, 2017).

For these and other related market pull activities, simulation models and input data are needed to quantify the impact of light scattering or “optically-complex” fenestration systems on heating, ventilation, and air-conditioning (HVAC) energy use, lighting energy use, comfort, and

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indoor environmental quality. Algorithm development and measurement protocols for characterizing the angle-dependent solar-optical properties of static and operable complex fenestration systems have been under development worldwide for some time, particularly with respect to solar heat gains. These algorithms model solar irradiance contributions from the sun and sky to the room interior by subdividing the skydome hemisphere into a grid of large-area patches (10–15° angular resolution) then integrating the irradiance contributions from the subdivided sky to derive total incoming radiation through the fenestration system. Simulation of other metrics such as discomfort glare, daylighting, and those related to thermal comfort if the subject is irradiated, however, require algorithms that more accurately model the spatial distribution of transmitted and reflected irradiance from direct sunlight within the room interior.

The objective of this study is to explain the differences in methods and accuracy when modeling the effects of direct sunlight using a matrix algebraic approach, specifically for daylighting applications of optically-complex fenestration systems (CFS). Section 2 describes the modeling approaches for evaluating solar heat gains and daylighting. Section 3 describes how angle-dependent BSDF properties are measured and/or simulated to support daylighting applications. Section 4 describes the results of validation studies that (1) estimate the error associated with interpolated measured BSDF data, (2) assess the accuracy of the entire modeling work flow (algorithms, input data, interpolation tools) using measured data from an outdoor full-scale testbed, and (3) isolate errors from the three- and five-phase matrix algebraic methods through comparisons with ground truth ray-tracing calculations. Ramifications on industry activities related to design, product development, and rating and certification activities are discussed with suggestions for future work.

2. Modeling daylight performance using a matrix algebraic approach

In 1994, Klems proposed a time-efficient method for determining solar heat gains through complex fenestration systems (Klems, 1994a,b). The matrix algebraic method achieved a practical balance between time-consuming calorimetric measurements and first principle calculations, enabling accurate building energy performance evaluations in a fraction of the time needed by prior methods. The method relies on angle-dependent transmittance and reflectance or "scattering" measurements for each layer of the fenestration system. The properties of multi-layered fenestration systems (consisting of parallel glazing and shading layers) are built up computationally from individual measured layer properties using a transmission and multiple reflection calculation. The resultant bidirectional scattering distribution functions (BSDF) or angle-dependent luminous coefficients for a given incident angle (Fig. 1) are multiplied by the incident irradiance from each grid element of the incoming hemisphere, then summed to obtain total outgoing transmitted irradiance into the room. The direct-hemispherical transmission for incident direction (θ_1,ϕ_1) is thus given by:

$$\tau(\theta_1,\phi_1) = \int_0^{2\pi}\int_0^{\pi/2} BTDF(\theta_1,\phi_1,\theta_2,\phi_2)\cos\theta_2\sin\theta_2 d\theta_2 d\phi_2 \quad (1)$$

with integration of irradiance over all directions (θ_2,ϕ_2) in the outgoing scattering hemisphere. In Eq. (1), θ and φ define the boundaries of each grid element or "patch" of the hemispherical basis (Fig. 1). Or more simply:

$$\tau(patch_i) = \sum_{k=1}^{145} BTDF(patch_i,patch_k)\Omega_k \quad (2)$$

Eq. (2) shows the integration of flux over the Klems BTDF hemispherical basis (145 incoming and 145 outgoing grid elements), where Ω_k is the projected solid angle for the kth patch of the basis. A layer-by-layer matrix calculation is done using a similar approach in order to determine absorbed and inward-flowing solar radiation from the

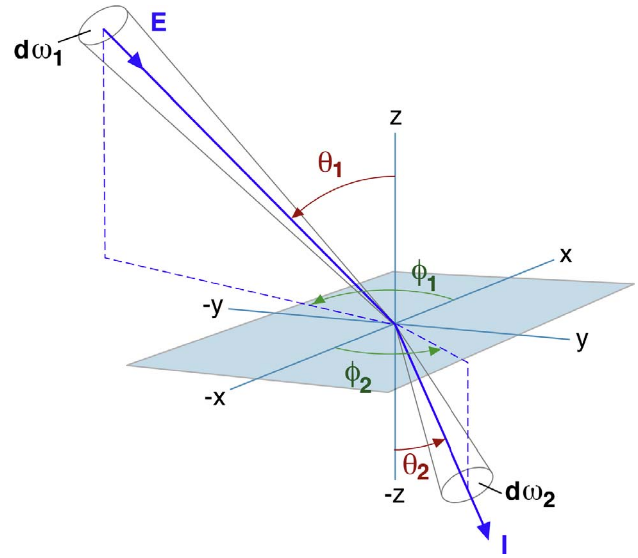

Fig. 1. Incoming and outgoing angles relative to the sample material (shown as a blue plane). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fenestration system. The sum of the transmitted and absorbed and inward flowing fraction of radiation equals the total solar heat gain from the fenestration system.

Note that the subdivision of the hemisphere into a grid of solid angles, known as the directional "basis", is defined for different purposes. Klems, for example, modified the Tregenza (sky) hemispherical subdivision for the purpose of solar heat gain calculations, giving higher resolution in incident angle and a weighting of the patches proportional to their solid angle and projected area. The angular resolution of this basis is approximately ± 5° in incident angle and much coarser in azimuth. Other bases developed for daylighting applications are listed in Section 3.

Between 2011 and 2014, Klems and others at the Lawrence Berkeley National Laboratory (LBNL) modified the WINDOW and EnergyPlus simulation tools to incorporate Klems' approach for calculating solar heat gains, resulting in new releases of the software tools WINDOW 7 (2017) and EnergyPlus 8.1 (2017).

2.1. Modeling daylight using the three-phase method

In 2006, Ward adapted the Klems matrix algebraic approach to enable computation of annual daylighting performance in interior spaces using Radiance (Ward Larson and Shakespeare, 1998; Saxena et al., 2010; Ward et al., 2011). This "three-phase" matrix approach (Eq. (3)), which was a variant on (Tregenza and Waters, 1983) then Reinhart and Herkel's earlier daylight coefficient (dc) approach (Reinhart and Herkel, 2000; Reinhart and Walkenhorst, 2001), incorporates the BSDF matrix ("T") representing the fenestration system:

$$\mathbf{E} = \mathbf{VTDS} \quad (3)$$

where

- **E** is the resulting annual series of the desired illuminance (or luminance, L) at a specified location in the interior space;
- **S** is the sky matrix, representing the luminance of the subdivided sky hemisphere, including the orb of the sun for the overall year;
- **D** is the daylight matrix, which relates the flux transfer between the sky hemisphere and the outdoor surface of the window/fenestration system;
- **T** is the transmission matrix or BSDF for the fenestration system, which relates the incident flux on the fenestration system to the outgoing exiting flux from the fenestration system into the room; and,