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Numerical and experimental validation for the thermal transmittance of windows with cellular shades

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ABSTRACT

Some highly energy efficient window attachment products are available today, but more rapid market adoption would be facilitated by fair performance metrics. It is important to have validated simulation tools to provide a basis for this analysis. This paper outlines a review and validation of the ISO 15099 center-of-glass zero-solar-load heat transfer correlations for windows with cellular shades. Thermal transmittance was measured experimentally, simulated using computational fluid dynamics (CFD) analysis, and simulated utilizing correlations from ISO 15099 as implemented in Berkeley Lab WINDOW and THERM software. CFD analysis showed ISO 15099 underestimates heat flux of rectangular cavities by up to 60% when aspect ratio (AR) = 1 and overestimates heat flux up to 20% when AR = 0.5. CFD analysis also showed that wave-type surfaces of cellular shades have less than 2% impact on heat flux through the cavities and less than 5% for natural convection of room-side surface. WINDOW was shown to accurately represent heat flux of the measured configurations to a mean relative error of 0.5% and standard deviation of 3.8%. Several shade parameters showed significant influence on correlation accuracy, including distance between shade and glass, inconsistency in cell stretch, size of perimeter gaps, and the mounting hardware.

1. Introduction

Virtually every home in the U.S. has some form of shades, blinds, drapes or other window attachments, but few have been designed for energy savings. High performance solutions for residential and commercial window attachments therefore offer large short-term energy savings potential. Due to the wide variety of window attachment solutions, energy savings can be accomplished in all climates by utilizing systems that reduce heating energy, reduce cooling energy, or both. These products can also reduce mechanical heating and/or cooling system sizing and improve indoor thermal comfort.

Some high performance products are available today but more rapid market adoption would be facilitated by better optimization and selection criteria, e.g. fair performance comparison and rating labels. There are also opportunities to re-engineer and enhance existing products to dramatically improve their performance, both in terms of intrinsic properties and in operations.

In order to provide a common basis of comparison, and to design more cost effective high performance window attachments, it is important to have validated simulation tools. These tools enable rapid design development and optimization through the use of parametric analysis and solution optimization. Several different approaches to simulate windows with attachments have been studied and developed. The primary focus of these works has been the experimental measurement, simulation, and simplified model development of solar heat gain for horizontal (Venetian) blinds located inside glazing unit glass and in room (room side).

Relatively little research has been done to characterize the nighttime (zero solar load) U-factor impacts of attachment products other than horizontal blinds, including in-plane products such as solar screens, roller shades, insect screens, drapes, and cellular shades. Little research focused on measurements or model development for thermal transmittance of cellular shades could be found in the literature. The available works performed by Dodge [10], Peterson [19], and Steven Winter Associates [20] all use systems in uncontrolled environments and minimal measurement locations; typically, one temperature sensor per surface. While informative, the results from these studies are not suitable for model development or validation.

The thermal performance of in-plane attachment products can, in general, be simulated similar to sealed (insulated) glazing with modifications to account for long-wave (IR) radiant transmission, gas flow across attachment layers, and shape factors affecting convection over the surface. Wright [23] developed a resistance network model and van Dijk and Oversloot [9] developed a model utilizing buoyancy driven pressure difference modifications to the

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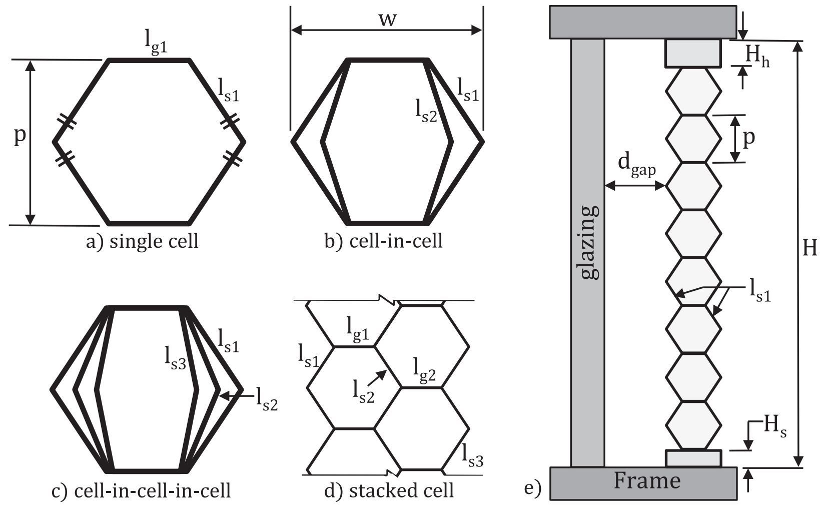

Fig. 1. Geometry of a) single-cell, b) cell-in-cell, c) cell-in-cell-in-cell, d) stacked double cell, and e) side view of room-side mounted shade installed in window.

surface convection coefficient of sealed cavities to account for gas flow across layers. The van Dijk model is utilized in the ISO 15099 standard , WIS [15], and Berkeley Lab WINDOW simulation programs [21]. Collins and Wright [7] showed that early implementations of this model incorrectly accounted for IR transmission through layers, but this has since been corrected in the WINDOW software. Laouadi [16] expanded on the van Dijk/ISO 15099 model by adding product type specific correlations for equivalent properties, flow between layers, and surface coefficients.

The most common simplified model for ventilated window systems determines the surface convection coefficients based on the opening characteristics of layers adjacent to ventilated cavities. Berkeley Lab WINDOW includes several specialized window attachment models based on the ventilated window system method including: cellular shades, horizontal louvered blinds and perforated screens. In addition, the Complex Glazing Database (CGDB) contains complex attachment product optical performance data, and has been publicly released. In order to have confidence in the newly developed attachment models, they must be validated through extensive testing and detailed computational fluid dynamics (CFD) simulation. This paper outlines a review and validation of the ISO 15099 center-of-glass (COG) heat transfer correlations for cellular shades through measurement and simulation. The impact on no-solar-load system thermal transmittance due to dimensional and material variations of the shades is measured experimentally, simulated using CFD analysis, and simulated utilizing simplified correlations from ISO 15099 with the Berkeley Lab WINDOW and THERM software.

2. Methodology

Correlations to determine thermal transmittance (U-factor) of shading devices arranged parallel to the window plane are defined in ISO 15099. While the model is physically based, the standard does not cite any validation of the approach through either measurements or detailed simulation. An extensive literature review of research on heat flux through shading systems and a detailed analysis of the ISO 15099 ventilated algorithm was completed by Hart, et al. [13]. Validation for shading devices with perimeter gaps and porous surfaces such as solar screens, roller shades, and horizontal venetian blinds was also completed in that work. Validation of the correlations as they apply to cellular shades is presented here.

The typical geometries of cellular shade cells and layers as a whole are first defined to form a basis of the product category. The methodology for simulating COG thermal transmittance utilizing the ISO 15099 correlations with these geometries within the Berkeley Lab WINDOW, THERM and Radiance framework is then presented.

Detailed CFD simulations using finite element analysis (FEA) and steady-state measurements of cellular shade systems were performed for comparison to the ISO 15099 correlations. Modifications to the Berkeley Lab software suite implementation of the correlations are proposed to provide higher correlation of measured and simulated thermal transmittance of the systems.

2.1. Geometry

Two aspects of cellular shade geometry were considered; the cells themselves and the layer as a whole. The four cell geometries considered in this work are single-cell, cell-in-cell, cell-in-cell-in-cell, and stacked double cell. These geometries are shown in Fig. 1a–d. The significant dimensions include the cell width (w), cell height or pitch (p), side length (l_s), and glue-line length (l_g). The comparable side lengths were considered to be equal, as shown in Fig. 1a. Cell wall thickness has insignificant impact on overall layer thermal performance for the materials considered, so a typical material thickness of 0.2 mm was assumed. Indoor, or room-side, mounted cellular shades were studied exclusively in this work. The typical geometry relative to the glazing system is shown in Fig. 1e.

- p: Height (pitch) of cell [m]
- w: Width of cell [m]
- H: Height of shade [m]
- H_h: Height of shade head rail [m]
- H_s: Height of shade sill rail [m]
- d_{gap}: Shade-window gap depth [m]
- l_{g1}: Glue-line length number 1 [m]
- l_{g2}: Glue-line length number 2 (if present) [m]
- l_{s1}: Length 1st cavity wall [m]
- l_{s2}: Length 2nd cavity wall (if present) [m]
- l_{s3}: Length 3rd cavity wall (if present) [m]

2.2. Correlations

The correlations developed in ISO 15099 to predict the heat flux through window systems have been implemented in one and two dimensions with the Berkeley Lab WINDOW and THERM software