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Experimental and Simulation Analysis of Thermal Transmittance of Vacuum Insulated Glazing for Predicting Service Life

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Abstract

To determine whether high performance glazing systems such as vacuum insulated glazing (VIG) units will maintain their insulating properties over their service life, a series of accelerated ageing tests must be employed. However, in order to determine whether there has been any change to the insulating properties of the insulating glazing units during the accelerated aging process, quantifiable metrics such as thermal transmittance must be periodically measured. Following current guidelines such as the National Fenestration Rating Council (NFRC) 100-2020, the thermal transmittance of glazing systems can be determined through experimental testing and/or computer simulations. This paper outlines a proposed testing procedure along with a list of assumptions used to compare thermal transmittance values calculated from experimental measurements to those calculated through computer simulations for VIG units.

The procedure will first compare the temperature dependent center-of-glass (COG) thermal transmittance (U-factor) results for VIG tested in a heat flow meter to the thermal transmittance values generated from guarded hot box testing, guided by both ISO and ASTM protocols. The experimentally measured results will then be used as a means of validating the estimated COG and total thermal transmittance results generated through computer simulations following NFRC guidelines using WINDOW and THERM software. The results of both the measured and predicted thermal transmittance values will then be used as a baseline for unaged VIG samples before they are subjected to future accelerated aging testing and degradation analysis. Future measurements will seek to develop degradation curves for VIG units, enabling more accurate computer simulation to better predict the total operational energy savings and thermal comfort metrics of VIG during service life. This will support broader adoption of high-performance glazing systems.

Keywords: Vacuum Insulated Glazing; Thermal Transmittance; Measurement; Simulation

Introduction

VIG systems pose unique challenges to the conventional methods used to measure material thermal conductivity. These challenges arise from their anticipated low center-of-glass (COG) thermal transmittance (U-factor), thin profile, and the presence of highly conductive support pillars that create localized thermal bridges. The COG thermal transmittance (U_{COG}) represents the heat transfer through the central area of the glazing unit excluding edge and frame effect. In order to quantify the thermal transmittance of VIG units independently of a frame, a review of previous experimental studies and current fenestration evaluation standards was completed, as summarized in the following sections.

In 1993, Collins, et al. designed and constructed a small area guarded hot-plate (GHP) apparatus to measure the local heat flux across the evacuated cavity of a VIG with high reproducibility and accuracy (Collins, et al., 1993). The meter plate of the small area GHP was sized accordingly to allow for the thermal conductivity of the vacuum cavity to be calculated independently of the thermal bridging effects caused by surrounding support pillars or edge seal. In 1999, experimental measurements were performed using a guarded hot-box (GHB) to determine the total U-factor (U_T) of a VIG unit. The measured results were then compared to calculated values generated from area weighted (AW) calculations, which were based on

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measurements taken using a small area GHP (Simko, Elmahdy, & Collins, 1999). The small area GHP apparatus was used to quantify local heat flux values across unique cross sections of a VIG including, a pillar free area, a singular pillar and a section of edge seal. The U_T of the glazing system was then calculated by combining the individually measured heat flux values using an AW approach. The AW averaged U_T value generated using GHP measurements was then compared to GHB test results. Before performing the GHB testing, the authors used a calibrated transfer standard (CTS) to characterize the convective heat transfer coefficients that would be subject to either side of the VIG sample during testing. For the analysis, additional thermocouples were attached to both internal and external surfaces of the vacuum glazing sample at predetermined points. The additional information allowed the thermal transmittance of the unknown VIG unit to be calculated by both the CTS and AW approaches confirming the determined value. The authors determined that the small area GHP could be used to obtain an AW averaged thermal transmittance value for a VIG that could be used to predict GHB results within $\pm 6\%$.

In a 2015 study by Fang et al., a GHB apparatus was used to quantify the Total Fenestration Product U-factor (U_T) of VIG units in order to validate the results obtained from computer simulations (Fang, et al., 2015), where U_T represents the total thermal transmittance of the entire glazing system including IGU and frame. The GHB was designed following standards from the British Standards Institution and ISO 8990, where the system error of the guarded hot box was calculated to be ± 5 percent and the total uncertainty in the determined heat transfer coefficient of tested samples was found to be less than 8.5 percent. The conducted testing followed the AW method, where the steady-state heat transfer coefficients acting on the test sample were calculated from measurements of steady-state air and glazing surface temperatures on both sides of the sample. Results from the GHB testing were used to validate their simulated model of a VIG, allowing the authors to perform further optimization analyses to determine the positioning of low-e coatings within a VIG.

Experimental testing was conducted by Oak Ridge National Laboratory (ORNL) to measure the U_{COG} and U_T of VIG units from two manufacturers (Padgett, 2020 Spring Meeting NFRC). U_{COG} measurements were conducted in accordance with the ASTM C518 and ISO 19916 using a heat flow meter apparatus to validate the U_{COG} calculated using the simulation tool WINDOW. Comparing measured to predicted COG results showed very close agreement with a difference of approximately 1 percent between the two methods. Further experimental testing was conducted by Underwriters Laboratories (UL) to determine the total window performance for VIG units with frames following the procedure outlined within NFRC 102-2017. Measurements of the thermal transmittance for the VIG were performed following both the Calibration Transfer Standards (CTS) and AW methods. A total of four 1.2 m x 1.5 m VIG systems were evaluated for two manufacturers VIG units set into two types of residential frames (PVC and Aluminum). The measured results were compared to predicted results generated using WINDOW (U.S. Department of Energy LBNL, 2020) and THERM (U.S. Department of Energy Lawrence Berkeley National Laboratory, 2020) simulation software and found to be in good agreement for both frame materials. The authors concluded that the simulation procedure outlined within NFRC 100-2017 could be used to reasonably predict the thermal transmittance of VIG systems.

CSA A440.2:19 - Fenestration energy performance is the latest North American fenestration standard (NAFS) published with the partners of NAFS including, American Architectural Manufacturer's Association (AAMA) and Window and Door Manufacturers Association (WDMA). The standard outlines procedures for determining the U_T of fenestration systems including glass, frame and sash systems through simulation or measurement under specified conditions. The insulating performance of glazing systems is often reported by their U_{COG} , where fenestration systems are an assembly of both frame and insulated glazing unit (IGU). NFRC100-2020 "Procedure for determining fenestration product U-factors" outlines a combination of computer simulations and/or experimental measurements that can be used to determine thermal performance for fenestration systems (National Fenestration Rating Council, 2013).

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To determine the thermal transmittance of a fenestration system through measurement, CSA A440.2:19 states that the procedure outlined within NFRC 102-2020 is to be followed, which provides amendments to the testing protocol presented in ASTM C1199-14. Following ASTM C1199-14 with the NFRC updates, both the thermal transmittance (U_S) and standardized thermal transmittance (U_{ST}) of fenestration systems at well-defined environmental conditions can be obtained. Calculating the U_{ST} value for a glazing system, allows the thermal performance of glazing systems to be compared to one another despite being measured from laboratories with potentially different thermal chamber configurations. The U_{ST} value can also be used to validate the thermal transmittance results of glazing units obtained through computer simulations. NFRC states that ISO 15099 approved software is to be used to calculate both the COG and total U-factor of both the IGUs and glazing systems. Examples of ISO approved software include WINDOW and THERM.

Beyond North America, ISO 19916-1:2017 outlines an experimental protocol to evaluate COG U-factor for VIG (ISO 19916, 2017). Within the standard, both the Guarded Hot Plate (GHP) ISO 8301 and Heat Flow Meter (HFM) ISO 8302 are listed as approved apparatus for establishing the COG thermal transmittance of a VIG. Following the standard, buffer plates are to be used in both GHP and HFM apparatus when measuring the performance of glazing units to create uniform contact between the metering surfaces of the instrument and the surfaces of the sample and to protect the surface of the equipment from scratches. In the case of VIG units that have been manufactured with protruding evacuation ports, a section of the buffer plate can be hollowed out to protect and accommodate the protrusion, creating a uniform surface for analysis. The material selected for the buffer plates must not change in thickness due to compression inflicted during testing, and the thermal conductivity of the material cannot be influenced by absorbed moisture. Following a simple calculation procedure, the thermal transmittance of the sample can be calculated by subtracting the known thermal resistance for the buffer plates from the total measured thermal resistance for the buffer plates plus the sample.

Through review of previous studies and measurement standards, a test protocol has been proposed to evaluate the thermal transmittance of VIG using both GHB and HFM. By developing a test protocol and carrying out the series of tests, challenges that may arise in measuring the thermal transmittance of high-performance glazing systems such as VIG can be identified. Once measured, the thermal transmittance values will be used to validate computer simulations of VIG systems and act as baseline values for accelerated ageing analysis.

Proposed test procedure

In order to quantify the thermal transmittance of a VIG unit independently of a frame, a series of experimental measurements are proposed. A GHB will be used to measure the overall thermal transmittance of a VIG including the heat transfer through the edge seal, while a HFM will be used to measure the COG thermal transmittance and temperature dependent thermal conductivity.

The proposed GHB testing will follow ASTM C1199 protocol, where a CTS will be used to establish the convective surface heat transfer coefficients on both the room and environment side of the chamber. Typically, in the process of characterizing the performance of the GHB prior to evaluating a sample, a CTS of similar thickness and thermal resistance to the sample should be used to establish the convective surface heat transfer coefficients on either side of the GHB. When testing VIG, this poses a challenge, as VIG are highly insulative for their thickness. As such, it is proposed that two CTS of different thickness and resulting thermal resistance be used to bound the anticipated thermal transmittance of the unknown VIGs.

Expanded Polystyrene (EPS) foam that has been aged under lab conditions for greater than ninety days will be used as the core material for the construction of the two CTS, where the nominal thicknesses for the two CTS cores are 12.7 mm (0.5 inch) and 76.2 mm (3 inch). Before being incorporated into the CTS assemblies, the thermal conductivity of the EPS cores will be established through HFM testing. Following the procedure outlined within ASTM C1199, the temperature dependent thermal conductivity of the cores will be analyzed at the mean sample temperatures of -10°C, 0°C and 10°C (14°F, 32°F, 50°F). The

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parameters for the two CTS used can be found in Table 1. Following methods established in previous studies, additional thermal couples will be placed on the surfaces of the samples being analyzed, such that the total thermal transmittance of the samples can be confirmed through AW calculations. The experimental parameters that will be used in the GHB measurements are specified within NFRC 102 and are highlighted in Table 2. As outlined within NFRC 100, the same parameters are to be used as the boundary conditions within simulations, allowing for the comparison of standardized thermal transmittance values between methods.

Table 1: Parameters for CTS used in GHB testing

Component	Details
Glass Lites	610 mm x 610 mm (24" x 24"), 4 mm (0.15") thick clear annealed glass
Thermocouples	Evenly spaced 3 x 3 array of T-type thermocouples on both sides of CTS Thermocouples soldered to 20 mm x 20 mm (0.7" x 0.7") copper shims
EPS Cores	Measured thickness 1) 11.4 mm (0.4") 2) 75.4 mm (2.9")

Table 2: Summary of testing parameters for GHB as specified in NFRC 102

Description	Value
Room side ambient air temperature	21.0° C ± 0.3° C (69.8°F ± 0.5° F)
Mean sample temperature	1.5°C ± 0.3° C (34.7°F ± 0.5° F)
Weather side ambient air temperature	-18.0° C ± 0.3° C (-0.4°F ± 0.5° F)
Room side (Natural convection)	7.67 W m ⁻² K ⁻¹ (1.35 Btu hr ⁻¹ ft ⁻² °F ⁻¹) ± 5%
Weather side convection	30.0 W m ⁻² K ⁻¹ (5.28 Btu hr ⁻¹ ft ⁻² °F ⁻¹) ± 10%

In order to determine an appropriate sample size to be analyzed, both NFRC 102-2020 and current durability standards for IGU including CAN-CGSB 12.8, and ASTM E2190 were consulted. The durability standards for IGU specify that rectangular 355 mm x 505 mm (14" x 20") samples be analyzed for manufacturing quality. However, following the guidelines of NFRC, when the thermal transmittance of a product is unknown and cannot be estimated through simulation, the COG thermal transmittance of a 1 m (39.3") square sample is to be measured through GHB testing. As a HFM capable of measuring a 1 m (39.3") square sample was not available to compare results obtained through GHB measurement, a 610 mm (24") square sample was selected to be measured in both the GHB and HFM.

Further rationale for selecting square samples over rectangular samples comes from the possible uncertainties in measurements as a result of shape. In order to accommodate rectangular samples, some heat flow meter models require that their sides or doors be left open to the ambient lab, while others require the use of mask material to square up the samples being analyzed. When the sides of a HFM are left uninsulated, lateral heat transfer can occur between the meter plates and the surrounding environment. The effects of lateral heat transfer can be minimized by analyzing the thermal transmittance of samples at a mean temperature equal to that of the surrounding environmental conditions. However, significant errors can be introduced into the measurements when attempting to quantify the temperature dependent thermal conductivity of materials at mean temperatures that deviate from the surrounding ambient conditions if steps to mitigate the risk are not taken. VIG units may be susceptible to lateral heat transfer, as the glass and edge seal material are highly conductive relative to the vacuum cavity. Challenges also arise when looking for suitable mask materials to use, as the thermal resistance of the mask is to be proportional to that of the sample being analyzed, which when considering VIG, requires finding another highly insulative material in a thin format.

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In addition to the 610 mm (24”) square samples, the COG thermal transmittance of a second smaller set of 305 mm (12”) square VIG samples will also be analyzed through HFM measurements. The analysis of second sample size will further validate computer simulations, and quantify any effects sample size may have on the COG thermal transmittance of a VIG. The smaller sample size will also fit into a HFM capable of reaching a wider range of mean temperatures, allowing the temperature dependent thermal conductivity of VIG units to be analyzed.

As outlined in ISO 19916-1:2017, buffer plates are to be used during HFM testing. The material selected for use in the buffer plates for this testing was neoprene rubber with a durometer of 60, with each sheet having a nominal thickness of 12.7 mm (0.5”). In order to measure the thermal transmittance of the sample when using buffer plates, two measurements are required. The first measurement includes the sample and the two buffer plates while the second measurement includes just the two buffer plates. These two measurements are performed to be able to subtract out the thermal resistance associated with the buffer plates.

Based partially on equipment constraints, the mean sample temperatures that were selected to be analyzed within the large format HFM were selected such that they bound the mean sample temperature being analyzed in the GHB (as seen in Table 3). This allowed at least one mean sample temperature from which calculated thermal transmittance could be compared between HFM and GHB, while still having values above and below this value to allow interpolation when mean temperatures during the tests are not identical. As the smaller format HFM had a greater range of possible plate temperatures over which to analyze the sample, it was selected to measure the temperature dependent thermal conductivity of the VIGs. The experimental parameters over which the temperature dependent thermal conductivity is determined can be seen in Table 3. Both of the HFM tests include one thermal conductivity measurement performed at a mean temperature equal to that of the surrounding lab, in order to have one data point where the errors associated with lateral heat transfer was minimized.

Table 3: Summary of testing parameters for HFM

Description	Value
Large area HFM Mean sample temperatures	0°C, 1.5°C, 5°C and Ambient (32°F, 34.7°F, 41°F and Ambient)
Small area HFM Mean sample temperatures	-10°C, 0°C, 10°C and Ambient (14°F, 32°F, 50°F and Ambient)
Temperature difference across sample	20°C (36°F)

To estimate the COG and total thermal transmittance of a VIG through computer simulations, NFRC 100 specifies that ISO approved software such as WINDOW and THERM are to be used. The modes of heat transfer used in the analysis of VIG and their formulas are outlined in WINDOW Technical Documentation (U.S. Department of Energy LBNL, 2018). These programs assume a fixed vacuum pressure within the cavity and determine the conductivity of the cavity using a formula for low pressure gas (Hart & Curcija, 2013). However, studies have shown that the internal vacuum within a VIG may degrade over time (Koebel, Manz, Mayerhofer, & Keller, 2010) (Likins-White, Tenent, & Zhai, 2023). Measured thermal transmittance values could then be used to validate computer simulations of VIG systems, where after validation, both the measured and predicted thermal transmittance values could be used as a baseline for any future accelerated ageing analysis.

Future durability studies (following ASTM or CAN/CGSB protocols) or accelerated ageing analysis performed on VIG could establish baseline thermal transmittance values for samples before subjecting samples to testing conditions. Thermal transmittance values obtained after testing could then be used to quantify any drop in performance that may have resulted from performing durability analysis or accelerated testing.

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Future work

As changes to material properties over time are not usually considered in whole building energy modeling, the magnitude of the operational energy required for a building over its service life may not be accurately accounted for. As such, future work may first look to quantify the drop in performance that may result from seal failure of high-performance glazing systems and determine what mechanisms may contribute to that degradation of internal vacuum pressure and resulting drop in thermal resistance of VIG. Building off of an understanding of the mechanisms causing deterioration, accelerated ageing test protocols could be developed with design loads tailored for locations where determining service life may be of interest. Accelerated testing protocols and periodic performance measurements could then be used to develop degradation curves for high performance glazing systems such as VIG, allowing computer simulation to better predict the total operational energy requirements and thermal comfort metrics of VIG units over their service life.

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