Modeling Thermal Performance of VIG: WINDOW and THERM software tools

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Abstract:

Vacuum insulated glazing (VIG) units, also known as evacuated glazing units (EGU) have unique construction and potential for truly exceptional thermal insulating performance, rivaling that of an insulated wall. Its unique construction, though requires special modeling technique to predict their thermal performance. Typical double or triple glazed Insulated Glazing Unit (IGU) has air or inert gas fill at near-atmospheric pressure and the panes are separated only at the edges, utilizing standard or insulating edge spacers. Heat transfer in IGU occurs by the combined effects of convection and radiation heat transfer and conduction heat transfer at the edges. In VIG units, convection is absent due to low pressure between the glass panes (less than 0.1 mTorr, or 0.01 Pa). However, in order to maintain spacing between glass panes, matrix of very small spacers or pillars is placed in an uniform pattern, typically between 2 and 5 cm apart. These pillars represent point thermal bridges, through which conduction heat transfer occurs. This heat transfer is three-dimensional and cannot be approximated by 2D models. In addition, conduction heat transfer also occurs at the VIG edges, where unit is permanently sealed to keep the vacuum. These unique construction differences between IGU and VIG require substantially different heat transfer model for VIG. While radiation heat transfer is modeled the same (i.e., infinite parallel plates radiation heat exchange) the conduction heat transfer through pillars is modeled using physics of point thermal bridges, resulting in heat transfer correlations as a function of geometry, size and spacing of pillars. Edge seals of VIG are modeled similar to edge of IGU units, using 2-D numerical modeling method. These correlations and methods are implemented in WINDOW and THERM software tools, which are used to predict thermal and optical performance of windows and other fenestration systems. In this paper, we will present model and results of simulation using LBNL's WINDOW and THERM software tools.

INTRODUCTION

Vacuum Insulating Glazing (VIG) offers great promise of increasing thermal resistance of glazing and windows closer to the value of insulated wall at the thickness of single glazing or standard insulating glazing unit and being fully transparent. While first prototypes of vacuum insulated glazing was introduced in late 1980s, over the past 30 years until recently the performance of VIG has been stagnant at around R5-R7 with one major glass company offering units commercially. More recently there has been additional activity to bring VIG performance closer to R-10 and several companies are now starting to offer such units.

Typical double or triple glazed Insulated Glazing Unit (IGU) has air or inert gas fill at near-atmospheric pressure and the panes are separated only at the edges, utilizing standard or insulating edge spacers. Heat transfer in IGU occurs by the combined effects of convection and radiation heat transfer and conduction heat transfer at the edges. In VIG units, convection is absent due to low pressure between the glass panes (less than 0.1 mTorr, or 0.01 Pa). However, in order to maintain spacing between glass panes, matrix of very small spacers or pillars is placed in an uniform pattern, typically between 2 and 5 cm apart. These pillars represent point thermal bridges, through which conduction heat transfer occurs. This heat transfer is three-dimensional and cannot be approximated by 2D models. However, it is not necessary to do full 3D modeling to characterize these point thermal bridges. The center of glazing (COG) thermal performance of VIG is calculated using the methodology developed from the work by University of Sydney (Ref), the same organization that developed first viable VIG prototypes. Simplified set of equations based on the physics of point thermal bridges of different geometry is employed, resulting in heat transfer correlations as a function of geometry, size and spacing of pillars. Radiation heat transfer is modeled the same as with IGUs (i.e., infinite parallel plates radiation heat exchange). Conduction through air is modeled using low-pressure gas theory.

Conduction heat transfer that occurs at the VIG edges, where unit is permanently sealed to keep the vacuum is modeled using 2-D numerical modeling methods in the similar way that standard IGUs are modeled as part of window sash and frame.

These correlations and methods are implemented in WINDOW and THERM software tools (LBNL 2018a, LBNL 2018b, and Curcija et al. 2018), which are used to predict thermal and optical performance of windows and other fenestration systems. In this paper, we will present model and results of simulation using LBNL's WINDOW and THERM software tools.

CENTER OF GLAZING HEAT TRANSFER

Overall heat transfer coefficient or U-factor for the central portion of glazing is calculated from the series of thermal resistances, as depicted in Figure 1.

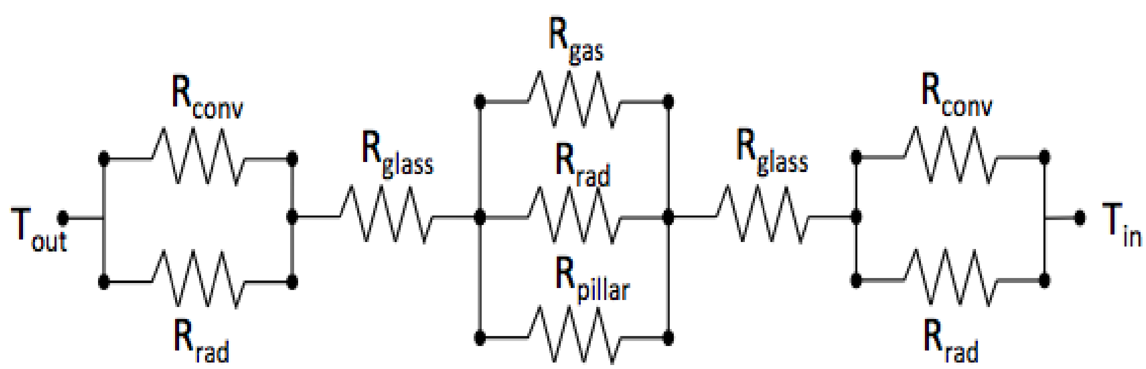

Figure 1. Thermal Resistance Network for VIG Glazing

The following set of formulas are used to calculate U-factor:

$$U = \frac{1}{R_{tot}} = \frac{1}{R_o + R_{glazing} + R_i}$$

Where:

R_o = exterior surface resistance (m2·K/W)

R_i = interior surface resistance (m2·K/W)

$$R_{glazing} = R_{glass} + R_{gap}$$

R_{glass} = glass pane resistance (m2·K/W)

$$R_{glass} = \frac{t_{glass}}{k_{glass}}$$

Where:

t_{gl} = glass thickness (m)

k_{gl} = glass conductivity (W/m·K)

R_{gap} = vacuum gap resistance (m2·K/W)

$$R_{gap} = \frac{1}{C_{gas} + C_{pa}} = \frac{1}{C_{COND} + C_{RAD} + C_{pa}}$$

Where:·

C_{COND} = Conductance of air [W/(m^2·K)]

$$C_{COND} = \alpha \left[\frac{\gamma + 1}{\gamma - 1}\right]\left[\frac{R}{8\pi MT}\right]^{\frac{1}{2}} \cdot P$$

Where:

$$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \alpha_1 (1 - \alpha_2)}$$

Where:

α_1, α_2 = Accommodation coefficients of the gas molecules. Dependent on the temperature, surface conditions, etc. For the present configuration and conditions, $\alpha_1, \alpha_2 \cong 0.5$.

ϒ = Specific heat ratio, ϒair=1.40.

R = Universal gas constant, R = 8,314.462175 (J/mol·K)

M = Molecular Weight, Mair = 28.97 [mol/g]

T_{1c} = Exterior temperature (K)

T_{2c} = Interior temperature (K)

P = Gas pressure (N/m2)

C_{RAD} = Radiation conductance [W/(m^2·K)]

$$C_{RAD} = \frac{1}{\varepsilon_1^{-1} + \varepsilon_2^{-1} - 1} \sigma \frac{\left(T_1^4 - T_2^4\right)}{T_1 - T_2}$$

Where:

σ = Stefan-Boltzmann Constant 5.67x10-8(W/m2·K4)

ε_1 = Emissivity of the first facing glass surface (-)

ε_2 = Emissivity of the Second facing glass surface (-)

T_1 = Temperature of the first facing glass surface (K)

T_2 = Temperature of the second facing glass surface (K)

C_{pa} = Pillar array conductance [W/(m^2·K)]

$$C_{pa} = \frac{2ka}{\lambda^2 \left(1 + \frac{2kh}{\pi k_p a}\right)}$$

Where:

a = Pillar radius (m)

h = Pillar height (m)

κ_p = Pillar conductivity (W/m·K)

λ = Pillar spacing (m)

RANGE OF THERMAL PERFORMANCE FOR CENTER OF GLAZING

The following figures show range of U-factors for different parameters used in VIG units.

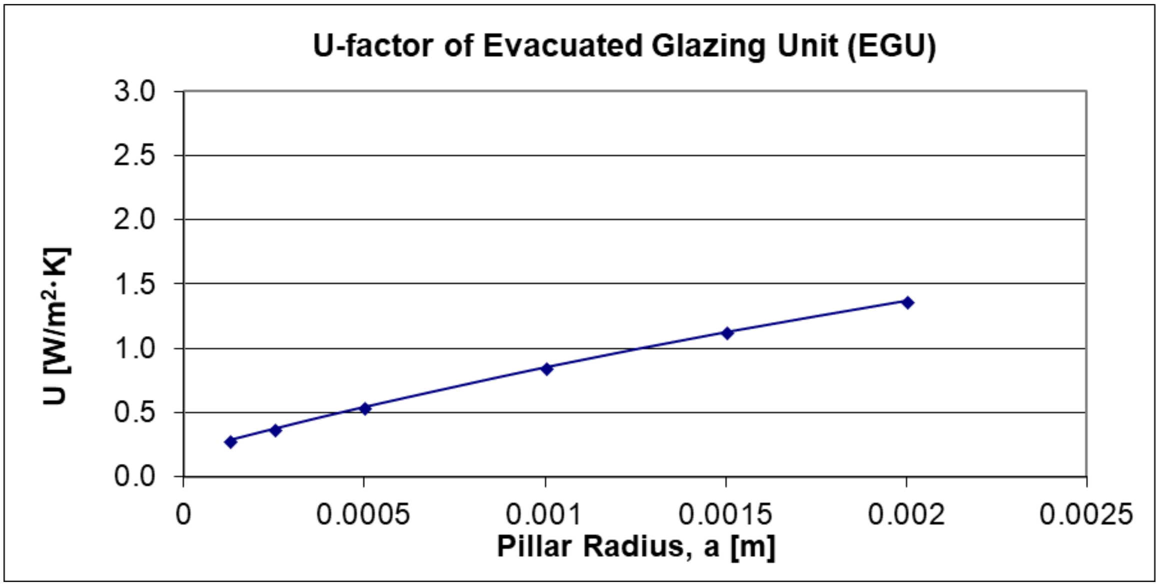

Figure 2. U-factor of an Evacuated Glazing Unit vs. Pillar Radius

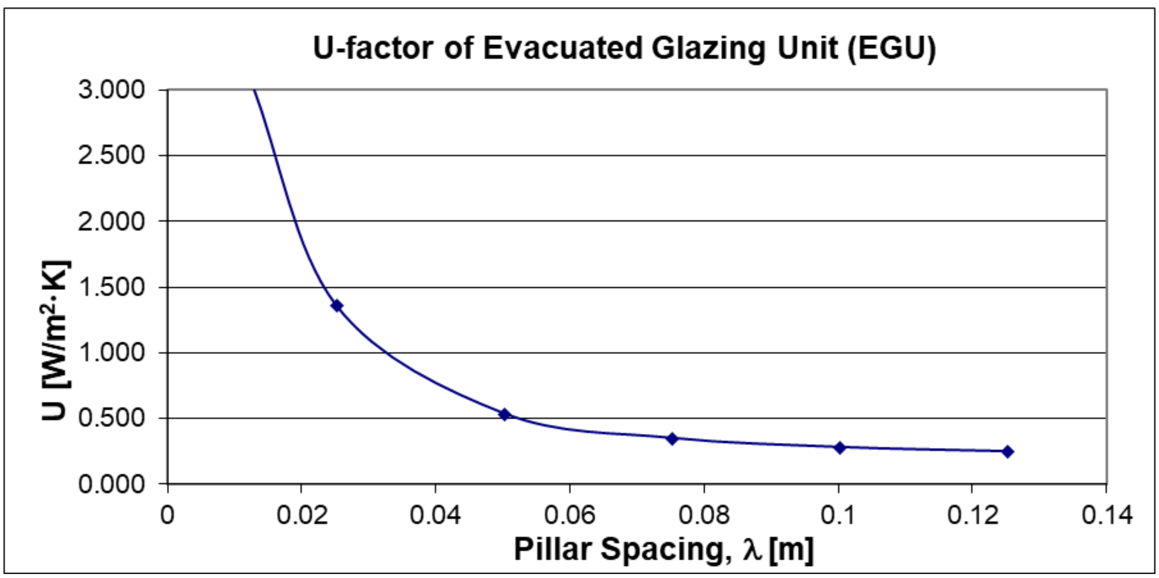

Figure 3. U-factor of an Evacuated Glazing Unit vs. Pillar Spacing

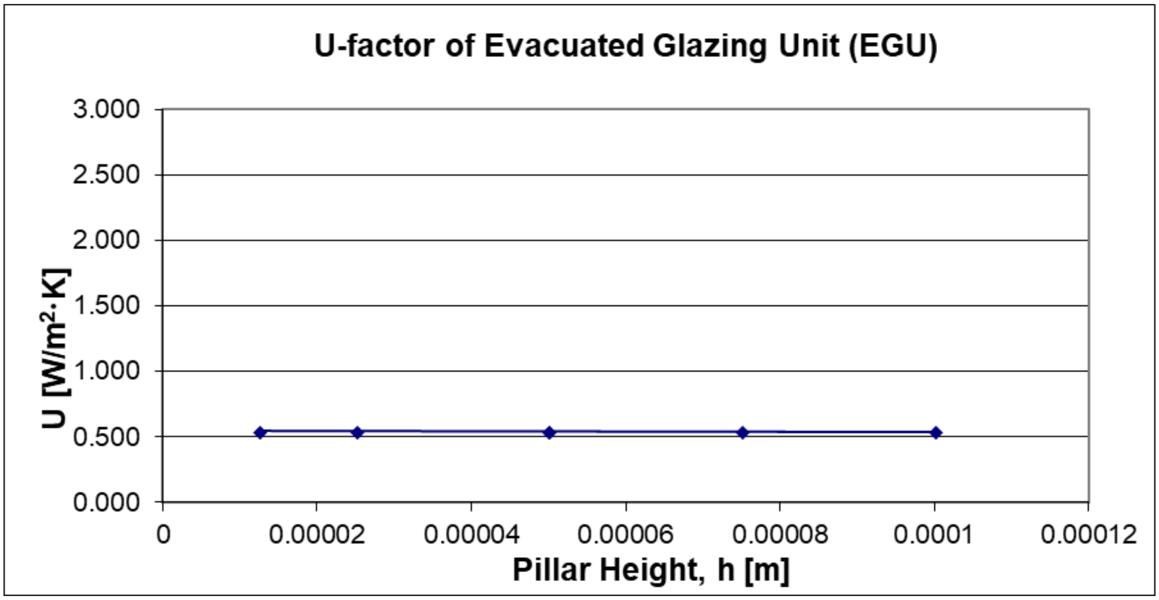

Figure 4. U-factor of an Evacuated Glazing Unit vs. Pillar Height

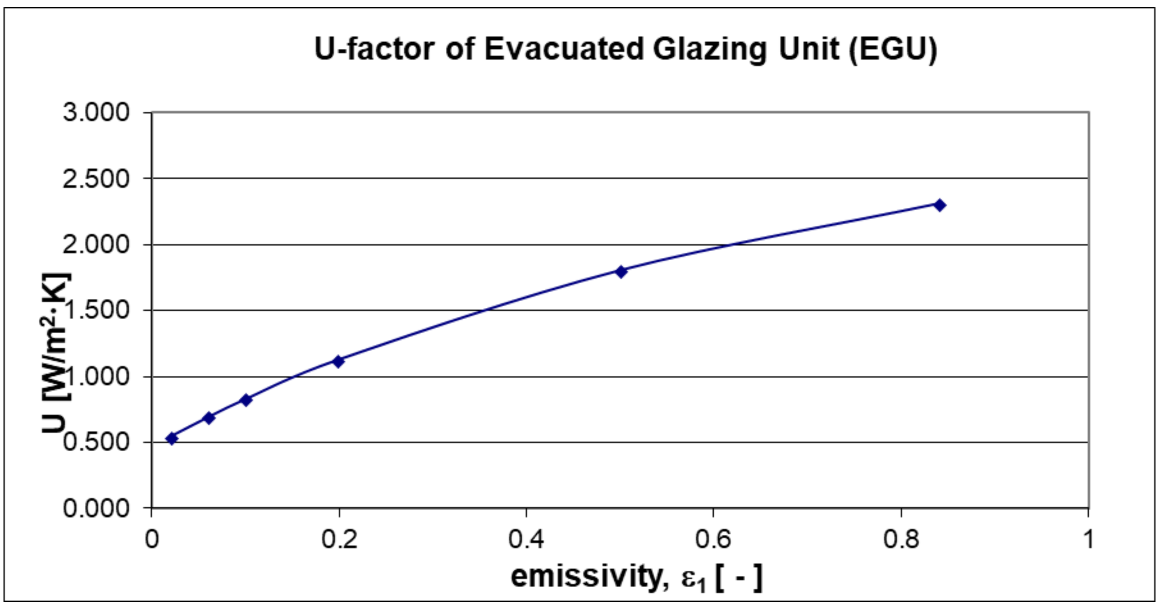

Figure 5. U-factor of an Evacuated Glazing Unit vs. Glass Surface Emissivity

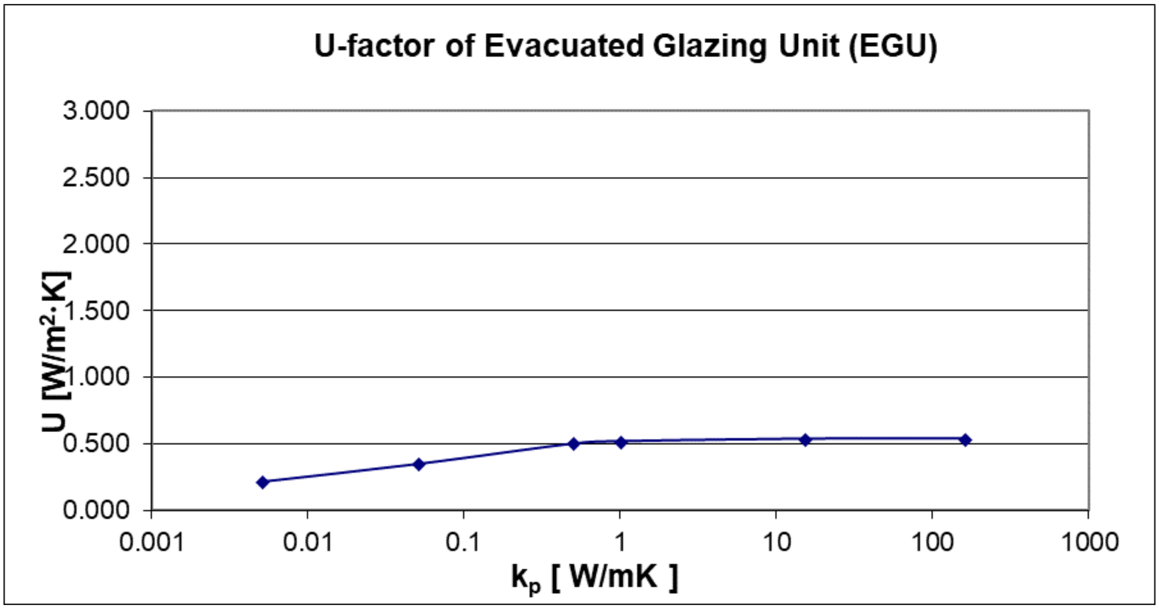

Figure 6. U-factor of an Evacuated Glazing Unit vs. Pillar Conductivity

EDGE OF GLAZING AND FRAME HEAT TRANSFER

Edge of glazing and frame heat transfer for VIG windows is modeled similar to standard IGUs, since edge area is sealed continuously and 2-D model of each cross-section (e.g., sill, jamb, head, etc.) can be area-weighted the same way that window with standard IGU is calculated (see Figure 7). F2 and F4 are jamb cross-sections, while Area F1 is head and area F3 is sill. Areas delineated by dashed line are corresponding edge-of-glazing areas. The rest of the glazing is considered center of glazing, calculated using equations in a previous section.

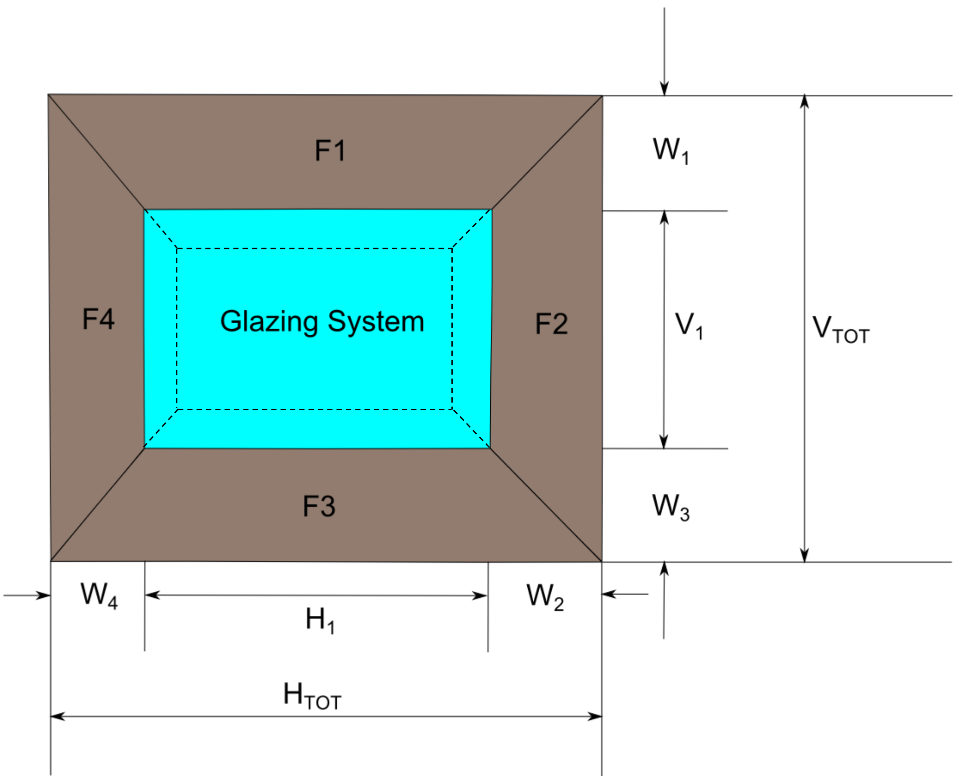

Figure 7. Areas Involved in Calculation of Window U-factors by Area-Weighting Procedure

Each frame area and corresponding edge of glazing are modeled as 2-D cross-sections, where glazing inserted into the frame has length of 150 mm, with edge of glazing tagged for 63.5 mm. Figure 8 shows example of 2-D cross-section of the sill region of the frame with double-glazed IGU inserted into the frame. Note that glazing being modeled is larger than required 63.5 mm for the edge of glazing, so that portion of the glazing is not tagged as edge. The discrepancy is due to the requirement to have at least 150 mm of glazing in order to properly model radiation heat transfer, as well as assuring that the 2-D heat transfer effects do not extend beyond the end of glazing section. This heat transfer is modeled in THERM program (LBNL 2018), which is 2-D finite element method-based numerical modeling software tool.

Boundary conditions are applied to the exposed frame and glazing surfaces. Outdoor boundary condition (NFRC 100 Exterior) are applied to the left side of the boundary (both glazing and frame), while Indoor boundary condition is applied separately to frame and glazing. Glazing convection heat transfer coefficient has been calculated by WINDOW software tool, based on the configuration and environmental conditions. This calculated convective heat transfer coefficient is passed to THERM from WINDOW when glazing system is imported into THERM from WINDOW. Frame convection heat transfer is based on frame material. Radiation heat transfer is modeled as grey-body, view-factor based detailed heat transfer.

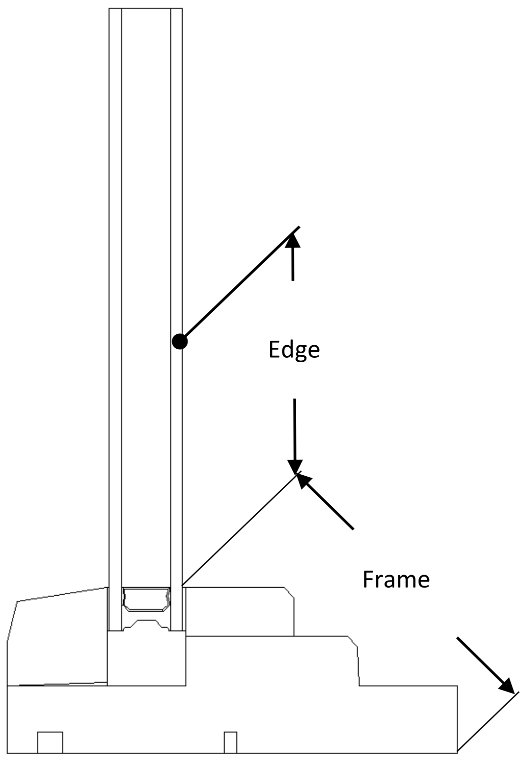

Figure 8. 2-D Cross Section of the Wood Window Sill

RESIDENTIAL AND COMMERCIAL WINDOW MODELING RESULTS

Two different windows were selected for modeling, one representative of residential windows, wood frame fixed window and the other is representative of commercial windows, a thermally-broken Aluminum Alloy fixed window. Figure 9 shows examples of residential and commercial window sill cross-sections.

Three different glazing configurations were modeled for each of the windows. The following parameters were used to model each of the glazing systems:

Table 1. Glazing Configurations

	Single Glazing	**Double Glazing**	**Triple Glazing**	**VIG**
Glass 1	Clear	Low-e	Low-e	Low-e
Glass 2	-	Clear	Clear	Clear
Glass 3	-	-	Low-e	-
Gap(s)	-	Air	Krypton	Air at 0.1 mTorr
Pillar geometry	-	-	-	0.5 mm diameter, 50.8 mm spacing

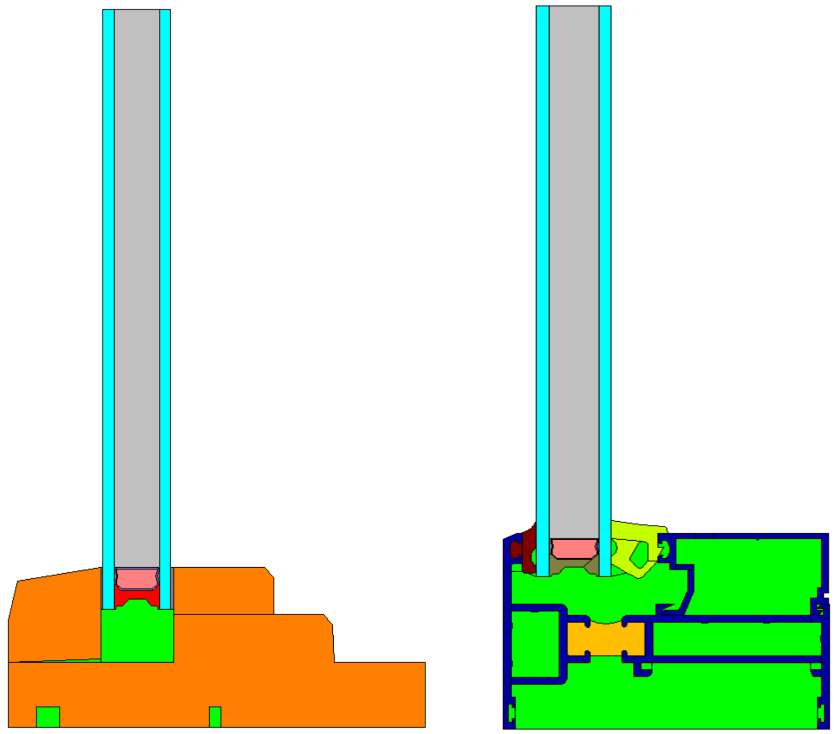

Figure 9. Examples of Residential and Commercial Window Cross-Sections (Sill)

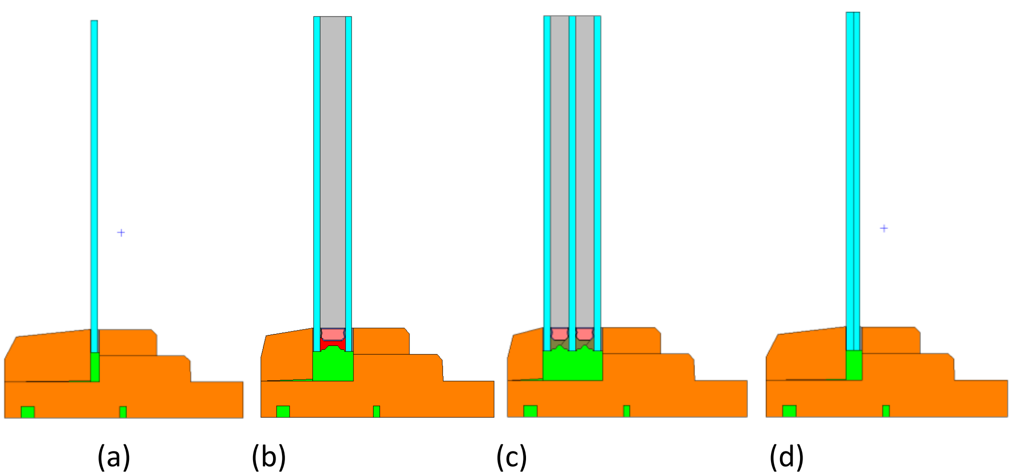

Figure 10. Wood Window Sill Cross-Section with Four Glazing Types; (a) Single Glazing; (b) Double Glazing; (c) Triple Glazing; and (d) VIG

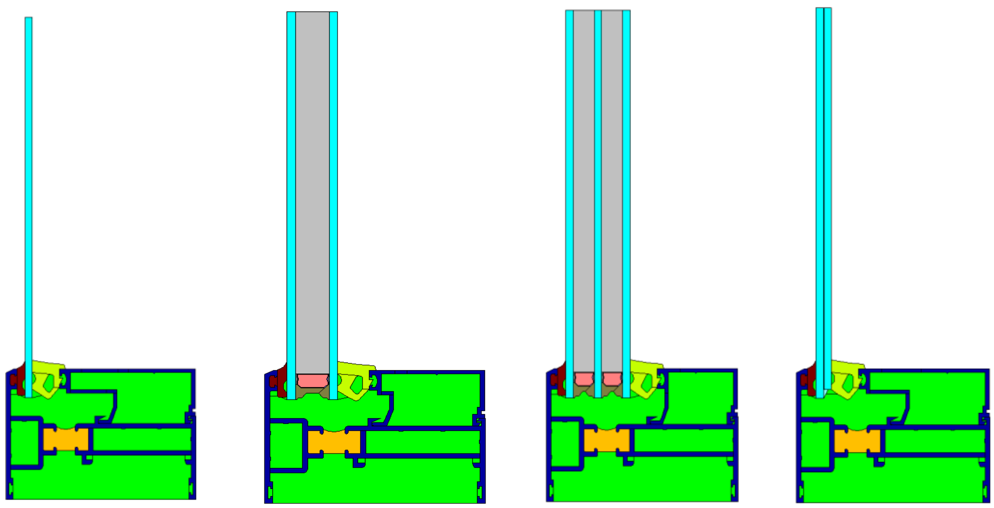

Figure 11. Thermally-Broken Aluminum Alloy Window Sill Cross-Section with Four Glazing Types; (a) Single Glazing; (b) Double Glazing; (c) Triple Glazing; and (d) VIG

WINDOW software tool is used to calculate thermal and solar-optical performance of glazing systems. Results of this modeling are presented in Table 2.

Table 2. Thermal and Solar Optical Performance of Glazing Systems

Glazing Type	Thickness	U	SHGC	VT
	mm	W/(m^2·K)	-	-
Single Glazing	3.048	5.710	0.860	0.899
Double Glazing	18.825	1.653	0.391	0.723
Triple Glazing	27.601	0.603	0.330	0.582
VIG	6.452	0.519	0.339	0.641

Two types of VIG were modeled in this study, rigid edge seal and flexible edge seal. Rigid edge seal is represented by solder glass and flexible edge seal is represented by metal foil sealing at the edge. Schematic of these seals are depicted in Figure 12.

Each of the cross-sections (sill, jamb and head) were modeled in THERM for 2 windows and with 5 glazing systems (30 models), where VIG glazing was modeled in two different configurations, rigid and flexible edge seal. Whole window thermal and solar-optical performance was calculated in WINDOW, by first importing THERM results into the frame library and then assembling whole windows from frame and glazing libraries. Performance for 10 whole windows (5 residential and 5 commercial) was calculated and presented in

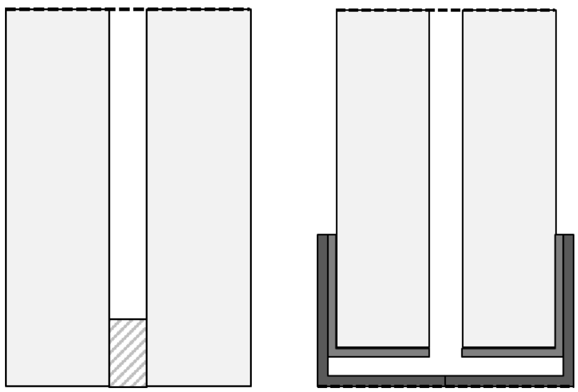

Figure 12. Vacuum Insulated Glazing (VIG); (a) Rigid Seal; (b) Flexible Seal

Table 3. Thermal and Solar Optical Performance of Whole Windows

Window Type		Size	U	SHGC	VT
		m	W/(m²·K)	-	-
Residential	**Single Glazing**	1.2 x 1.5	5.242	0.755	0.787
	Double Glazing	1.2 x 1.5	1.774	0.345	0.633
	Triple Glazing	1.2 x 1.5	0.869	0.292	0.510
	VIG – Rigid Edge Seal	1.2 x 1.5	0.862	0.299	0.561
	VIG – Flexible Edge Seal	1.2 x 1.5	0.819	0.299	0.561
Commercial	**Single Glazing**	1.2 x 1.5	5.434	0.721	0.742
	Double Glazing	1.2 x 1.5	2.119	0.332	0.596
	Triple Glazing	1.2 x 1.5	1.258	0.282	0.480
	VIG – Rigid Edge Seal	1.2 x 1.5	1.302	0.290	0.529
	VIG – Flexible Edge Seal	1.2 x 1.5	1.366	0.291	0.529

The graph shown in Figure 13 illustrates comparison of U-factors for example residential and commercial windows. It is clear from the graph that lower performance frames (such as selected thermally broken Aluminum Alloy frame vs selected wood frame) bring the whole window performance down as glazing becomes more insulated. It is also illustrative that in wood frame both VIG options have better thermal performance than Triple-glazed Krypton-filled unit, while in Aluminum Alloy frame, both VIG glazing units have slightly worse performance than Triple-glazed Krypton-filled unit.

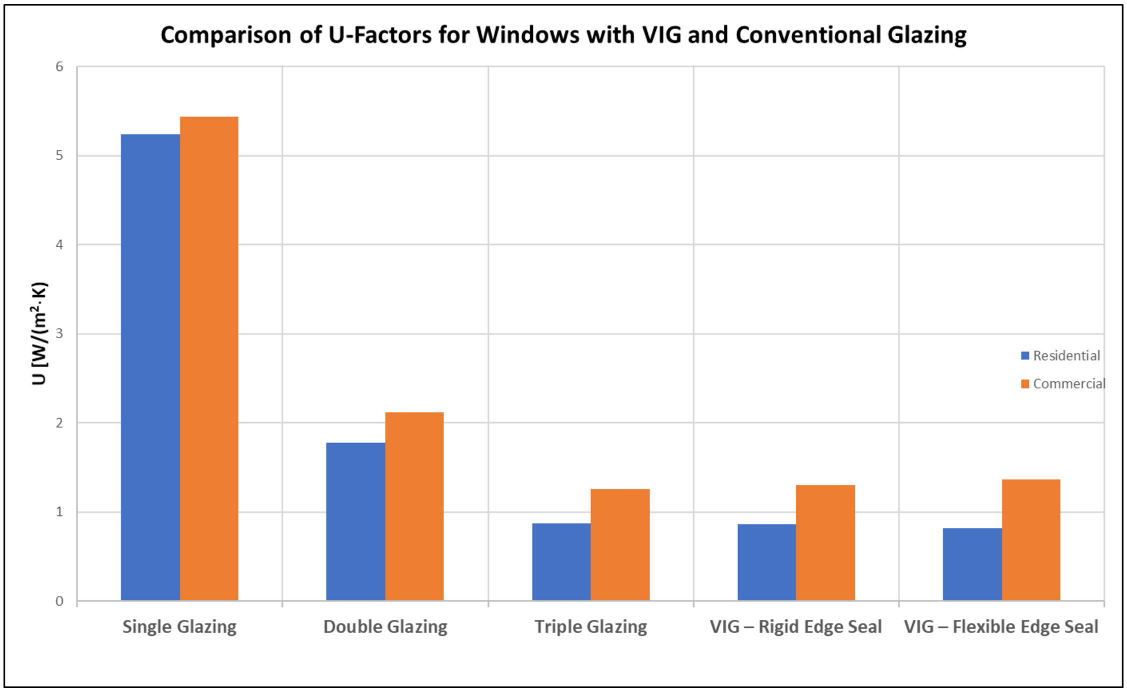

Figure 13. Comparison of U-Factors for Windows with VIG and Conventional Glazing

CONCLUSIONS AND RECOMMENDATIONS

Thermal and Solar-optical performance of VIG and windows incorporating VIG can be successfully modeled in WINDOW and THERM. New set of equations, applicable to low-pressure gasses and point thermal bridges, both present in VIG units, have been incorporated into WINDOW software tool. Modeling of frame and edge-of-glazing cross-sections did not require use of new models, so this paper just presented how were existing modeling methods applied to VIG.

Two different VIG options were explored and modeled. Rigid and flexible edge seal were modeled to cover two major sealing techniques, either commercially available or currently being researched. Flexible seal showed slightly better thermal performance and better condensation resistance. However, the difference is fairly small and will require further research work to optimize performance.

Results of modeling show that VIG units with spacer/pillar separation of 50 mm or more perform better than triple-glazing with Krypton fill. Wood frame windows exhibit better thermal performance in both VIG options have better thermal performance than Triple-glazed Krypton-filled unit, while in Aluminum Alloy frame, both VIG glazing units have slightly worse performance than Triple-glazed Krypton-filled unit.

While this paper did not explore validation of these algorithms, separate research work has confirmed validity of this modeling method (Collins and Robinson 1991, Collins and Fischer-Cripps 1991, Corruccini 1959, Simko 1996, Hart and Curcija 2013).

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