A New Method of Representing Highly-Conducting Window Frames in Building Simulation Models

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Abstract

Highly conducting metal window frames are still common in many countries. At standard NFRC environmental conditions (NFRC 2016), such metal frames can exhibit U-factors exceeding 15 W/(m^2·K). Window frames are inhomogeneous window elements where heat transfer is two- and three-dimensional. Their thermal performance is represented through a frame U-factor, U_f, which is calculated for projected frame surface area. However, it is currently not possible to correctly represent such frames in building simulation models. This is because surface film coefficients (outdoor and indoor) are based on the usual assumption that heat flow across the building envelope is one-dimensional. This is generally true for a window's parent wall or glazing surface, but not for the window frame itself. The upper limit to the simple, 1-D U-factor is about 6 W/(m^2·K).

We present a simple method for correcting surface heat transfer coefficients in building models, so that highly conducting metal frames can be correctly modeled and also to provide more accurate surface heat transfer coefficients for more insulating frames. To demonstrate robustness of the technique, the process is repeated at various boundary conditions.

Introduction

At standard NFRC environmental conditions, thermally unbroken metal frames typically exhibit actual U-factors exceeding 6 W/(m^2·K) and can be more than 15 W/(m^2·K). Such U-factors are routinely and correctly calculated using 2-D heat transfer software tools and have been extensively validated by physical testing using guarded hot boxes (LBNL 2016). Calculated heat transfer includes information about both the projected area of the frame (in a vertical plane) and the total, "wetted" area of the exposed frame surface. Even when the frame's thermal resistance (from outside surface to inside surface) is negligible – true for most unbroken metal frames – the apparent, simple 1-D U-factor cannot exceed about 6 W/(m^2·K) due to the air film thermal resistances. Yet as described above, we know that real frame U-factors can be more than twice this value.

The key to resolving this conundrum is as follows. Window-frame film coefficients, both exterior and interior, are typically larger than the film coefficients applying to the same window's parent wall. This is because window frames and other complex 2-D shapes exhibit increased convective and radiative heat transfer, similar to a finned heat sink or on the cooling fins of an air-cooled engine. This "fin effect" can result in very large film coefficients, both outdoors and indoors.

At present it is not computationally feasible to perform 2-D, heat transfer modeling on every framing element in a building, for all 8760 hours of the year. The next best option is to estimate the real-world, frame film coefficients based on knowledge of the frame geometry, and use these "fin-inflated" coefficients to calculate the true frame heat flow, rather than using standard 1-D coefficients applying to the parent wall.

We present a simple method for deriving corrected, fin-inflated coefficients and propose that these may be input to a building energy model. To demonstrate robustness of the technique, the process is repeated at various boundary conditions. The latter vary from standard NFRC conditions through to high-wind conditions.

Background Theory

Frame model

Consider a window frame (light blue in Figure 1) with U-factor U_f = 10 W/(m^2·K). The corresponding thermal resistance, including outdoor and indoor air films, is 0.1 m^2·K/W. At standard NFRC 100-2010 environmental conditions (NFRC 2016), the outdoor total film coefficient for one-dimensional heat flow through a vertical building element, for both convective and radiative heat transfer, h_o, is approximately 30 W/(m^2·K). The indoor coefficient h_i is approximately 8 W/(m^2·K). The equivalent thermal circuit is represented in Figure 1, where the outdoor and indoor air temperatures are:

$$T_o = -18^{o}\mathrm{C}$$
$$T_i = 21^{o}\mathrm{C}$$

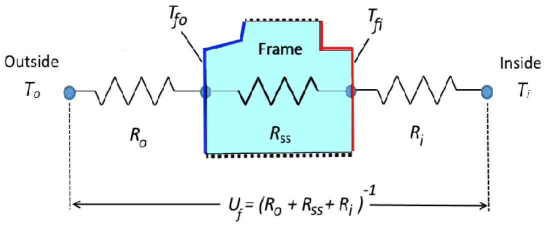

Figure 1. Thermal circuit for window frame.

At standard NFRC environmental conditions, in Figure 1, R_{ss} is the surface-to-surface thermal resistance of the frame, excluding its air films. The outside and inside, total resistances are represented by R_o and R_i respectively. Length-weighted, average frame surface temperatures are T_{fo} and T_{fi} respectively. The arbitrary, asymmetric frame in Figure 1 is depicted notionally as a window sill, but could be any framing element in a fenestration system. The upper and lower surfaces, shown by dotted lines, are assumed to be adiabatic. The exterior, cold left face of the frame is shown in dark blue, while the interior, right, warm face is shown in red.

The total length of the outside blue face is its "wetted" length, denoted WL_o . The total length of the inside, red face is its inside wetted length, denoted WL_i . These dimensions are complemented by the "projected frame dimension", *PFD*. The PFD is projected onto the vertical plane (plane parallel to the glass).

The frame U-factor, including air films is U_f as shown in Figure 1 and is given by

$$U_f = 1/(R_o + R_{ss} + R_i) \qquad (1)$$

Substituting for U_f, h_o and h_i and solving for R_{ss} yields

$$R_{ss} = 1/10 - 1/30 - 1/8 = -0.0583 \text{ m}^2\cdot\text{K/W}$$

which is not possible, since a frame's thermal resistance cannot be negative. The key to resolving this conundrum is that for window frames, their film coefficients are almost never the standard 1-D values (30 and 8) used above. Instead, larger "fin-inflated" film coefficients apply.

Calculation of true R_o and R_i

If the constant heat transfer coefficient is applied to frame surfaces, the heat flux from the outside frame surface to the exterior environment is

$$Q_o = h_o \cdot WL_o \cdot x \cdot (T_{fo} - T_o) \qquad (2)$$

where h_o = regular, 1-D outdoor total film coefficient

x = length of frame normal to frame cross-section plane (third dimension)

Similarly, the heat flux from the inside frame surface to the interior environment is

$$Q_i = h_i \cdot WL_i \cdot x \cdot (T_i - T_{fi}) \qquad (3)$$

where h_i = regular, 1-D indoor total film coefficient.

From conservation of energy,

$$Q_i - Q_o = 0 \qquad (4)$$

The outdoor heat flux can also be expressed as

$$Q_o = U_f \cdot PFD \cdot x \cdot (T_i - T_o) \qquad (5)$$

where Q_o is expressed in terms of heat flow through the interior projected frame surface, rather than the exterior surface.

For the indoor heat flux:

The indoor heat flux can be expressed as

$$Q_i = U_f \cdot PFD \cdot x \cdot (T_i - T_o)$$

which is the same as (5).

Equating (3) and (5) yields

$$\frac{h_i \cdot WL_i\,(T_i - T_{fi})}{U_f \cdot PFD \cdot (T_i - T_o)} = 1$$

where for a given frame length, the x terms are common and cancel out.

Thus

$$U_f = H_i \cdot \left[\frac{T_i - T_{fi}}{T_i - T_o} \right]$$

where the general, corrected, fin-inflated indoor film coefficient is given by

$$H_i = \left[\frac{WL_i}{PFD} \right] \cdot h_i \qquad (6)$$

For the outdoor heat flux:

Equating (2) and (5) yields

$$\frac{h_o \cdot WL_o \cdot (T_{fo} - T_o)}{U_f \cdot PFD \cdot (T_i - T_o)} = 1$$

Thus

$$U_f = H_o \cdot \left[\frac{T_{fo} - T_o}{T_i - T_o} \right]$$

where the general, corrected, fin-inflated outdoor film coefficient is given by

$$H_o = [\frac{WL_o}{PFD}] \cdot h_o \qquad (7)$$

Since $R_o = 1/H_o$ and $R_i = 1/H_i$, Equation 1 may also be expressed as

$$U_f = [\frac{1}{H_o} + R_{ss} + \frac{1}{H_i}]^{-1} \qquad (8)$$

Fin-inflated film coefficients would be corrected film coefficients that are passed to annual energy simulation programs, such as EnergyPlus.

Worked Examples

Example 1: thermally unbroken aluminum frame

The extruded window frame sill shown in Figure 2 was modeled using THERM 7.4.3 (LBNL 2016) at various outdoor and indoor boundary conditions. The frame section includes a "stub" of a glazing unit in its gasket (shown in top center, light blue and dark green respectively). The frame has several air cavities shown in light green. Table 1 shows the conditions modeled and the resulting, implied surface-to-surface thermal resistance of the frame *(R_{ss})*, calculated using Equation 8. The implied frame resistance obtained using Equation 8, based on corrected film coefficients H_o and H_i (new method) is contrasted with results based on uncorrected film coefficients h_o and h_i (old method).

The results in Table 1 are shown in Figure 3, where the film coefficient on the horizontal axis is on a logarithmic scale. The input, outdoor coefficient h_o was varied by a factor of 10, while holding h_i constant. In addition the input, indoor coefficient h_i was varied by a factor of 4, while holding h_o constant. Despite these wide ranges, the implied R_{ss} varied by less than 3%. When the film coefficients were varied over a smaller and more realistic range (factor of 3 for either outdoor or indoor), the change in R_{ss} was reduced to less than 1%. Thus, R_{ss} is nearly invariant, which is to be expected if the model in Equation 8 is a good representation of reality.

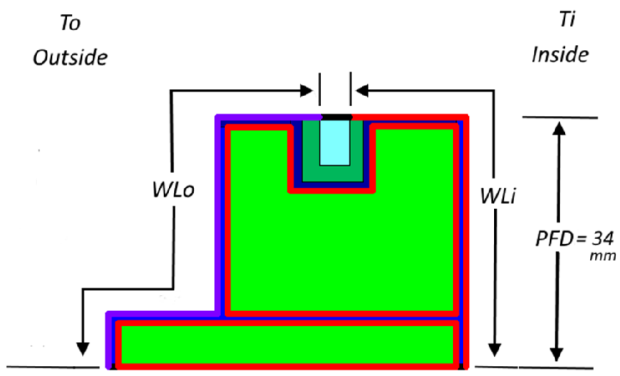

Figure 2. (Above) - aluminum or uPVC window sill.

Table 1. Dependence of R_{ss} on h_o and h_i (thermally unbroken aluminum frame).

h_o W/(m²·K)	h_i W/(m²·K)	U_f W/(m²·K)	R_{ss} (implied, old method) m²·K/W	R_{ss} (implied, new method) m²·K/W
30	8	9.33	-0.0511	0.00316
100	8	10.59	-0.0406	0.00314
300	8	11.03	-0.0377	0.00308
30	16	15.54	-0.0315	0.00315
30	30	22.57	-0.0224	0.00315
30	60	30.42	-0.0171	0.00314

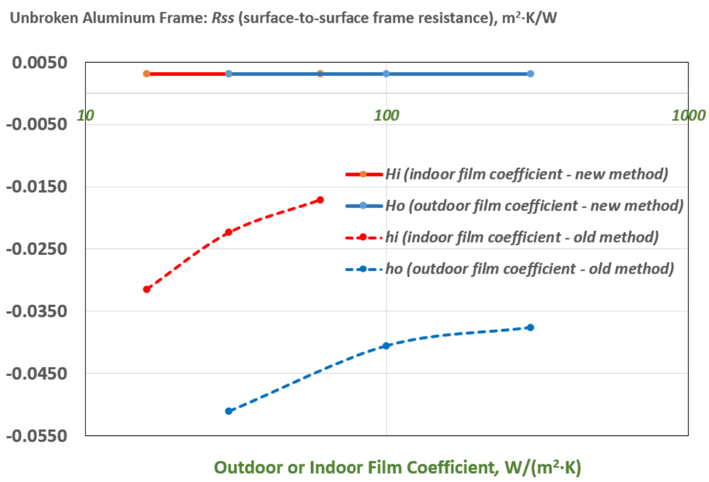

Figure 3. Variation of R_{ss} with outdoor and indoor total film coefficients, for thermally unbroken aluminum frame.

Example 2: uPVC (vinyl) insulating frame

The modeling and calculation process described above was repeated for a uPVC version of the frame shown in Figure 2. Results are shown in Table 2 and Figure 4. As with the metal frame example, the implied frame resistance obtained from Equation 8 using corrected film coefficients H_o and H_i (new method) is contrasted with results based on uncorrected film coefficients h_o and h_i (old method).

Table 2. Dependence of R_{ss} on h_o and h_i , for a uPVC (vinyl) frame.

h_o W/(m²·K)	h_i W/(m²·K)	U_f W/(m²·K)	R_{ss} (implied, old method) m²·K/W	R_{ss} (implied, new method) m²·K/W
30	8	3.13	0.161	0.215
100	8	3.46	0.154	0.198
300	8	3.62	0.148	0.188
30	16	3.77	0.169	0.204
30	30	4.23	0.170	0.195
30	60	4.63	0.166	0.186

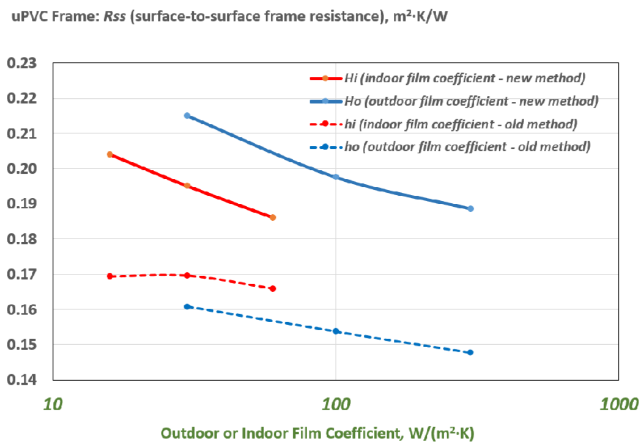

Figure 4. Variation of R_{ss} with outdoor and indoor total film coefficients, for uPVC frame.

Conclusions and Recommendations

1. From heat transfer theory, the intrinsic, surface-to-surface frame resistance R_{ss} for highly conductive frames is expected to be nearly constant regardless of surrounding environmental conditions.
2. For highly conductive frames, the implied R_{ss} yielded by Equation 8, after correction for the "fin effect", is constant to within 1% at normal conditions. The correction is very substantial and it restores the calculated frame resistance to a positive (albeit small) value instead of a physically impossible negative value.
3. For insulating frames that have air cavities (e.g., uPVC frames), the new method yields a noticeably greater R_{ss} compared with that obtained with uncorrected film coefficients. The fin-corrected R_{ss} varies with surrounding environmental conditions due to convection heat transfer in insulating air cavities. However the fin-corrected frame resistances are still 20 or 30% greater than those obtained with no correction. This justifies the use of the new method with insulating frames in addition to deploying it for conductive frames.
4. We recommend this new technique for obtaining fin-corrected film coefficients for all frame materials. Its value is particularly noticeable when dealing with highly conductive frames. This is also an issue of fairness, in that the new method will correctly represent the relatively poor performance of highly conductive frames in building energy simulations. This contrasts with the current situation in which highly conducting frames appear to perform better than in reality.

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