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/(m²·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/(m²·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/(m²·K) and can be more than 15 W/(m²·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/(m²·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/(m²·K). The corresponding thermal resistance, including outdoor and indoor air films, is 0.1 m²·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/(m²·K). The indoor coefficient $h_i$ is approximately 8 W/(m²·K). The equivalent thermal circuit is represented in Figure 1, where the outdoor and indoor air temperatures are:

$$T_o = -18{}^\circ C$$

$$T_i = 21{}^\circ C$$
Proceedings of the 15th IBPSA Conference  
San Francisco, CA, USA, Aug. 7-9, 2017

\[ x = \text{length of frame normal to frame cross-section plane (third dimension)} \]

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

\[ Q_i = h_i \cdot WL_x \cdot (T_i - T_o) \tag{3} \]

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

From conservation of energy,

\[ Q_i - Q_o = 0 \tag{4} \]

The outdoor heat flux can also be expressed as

\[ Q_o = U_f \cdot PFD \cdot x \cdot (T_i - T_o) \tag{5} \]

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

\[ \frac{h_i \cdot WL_x \cdot (T_i - T_f)}{U_f \cdot PFD \cdot (T_i - T_o)} = 1 \]

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

Thus

\[ U_f = H_i \cdot \left[ \frac{T_i - T_f}{T_i - T_o} \right] \]

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

\[ H_i = \left[ \frac{WL_x}{PFD} \right] \cdot h_i \tag{6} \]

**For the outdoor heat flux:**

Equating (2) and (5) yields

\[ \frac{h_o \cdot WL_o \cdot (T_o - T_a)}{U_f \cdot PFD \cdot (T_i - T_o)} = 1 \]

Thus

\[ U_f = H_o \cdot \left[ \frac{T_o - T_a}{T_i - T_o} \right] \]

**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

\[ Q_o = h_o \cdot WL_o \cdot x \cdot (T_{0} - T_o) \tag{2} \]

where \( h_o \) = regular, 1-D outdoor total film coefficient.
where the general, corrected, fin-inflated outdoor film coefficient is given by

\[
H_o = \left(\frac{W_{lo}}{PFD}\right) \cdot h_o
\]  

(7)

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

\[
U_f = \left(\frac{1}{H_o} + R_{ss} + \frac{1}{H_i}\right)^{-1}
\]  

(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.
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.

<table>
<thead>
<tr>
<th>$h_o$ W/(m²·K)</th>
<th>$h_i$ W/(m²·K)</th>
<th>$U_f$ m²·K/W</th>
<th>$R_{ss}$ (implied, old method) m²·K/W</th>
<th>$R_{ss}$ (implied, new method) m²·K/W</th>
</tr>
</thead>
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<tr>
<td>30</td>
<td>8</td>
<td>3.13</td>
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<td>0.215</td>
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<tr>
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<td>4.63</td>
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<td>0.186</td>
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</table>

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.

Acknowledgement

We thank Dr Angelo Delsante, formerly of CSIRO Sustainable Ecosystems (Australia), for his very helpful discussions and contributions during the development of this paper.

References

