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# Developing Low-Conductance Window Frames: Capabilities and Limitations of Current Window Heat Transfer Design Tools

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**Abstract**

While window frames typically represent 20-30 % of the overall window area, their impact on the total window heat transfer rates may be much larger. This effect is even greater in low-conductance (highly insulating) windows which incorporate very low conductance glazings. Developing low-conductance window frames requires accurate simulation tools for product research and development. Based on a literature review and an evaluation of current methods of modeling heat transfer through window frames, we conclude that current procedures specified in ISO standards are not sufficiently adequate for accurately evaluating heat transfer through the low-conductance frames.

We conclude that the near-term priorities for improving the modeling of heat transfer through low-conductance frames are:

1. Add 2-D view-factor radiation to standard modeling and examine the current practice of averaging surface emissivity based on area weighting and the process of making an equivalent rectangular frame cavity.
2. Asses 3-D radiation effects in frame cavities and develop recommendation for inclusion into the design fenestration tools.
3. Assess existing correlations for convection in vertical cavities using CFD.

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4. Study 2-D and 3-D natural convection heat transfer in frame cavities for cavities that are proven to be deficient from item 3 above. Recommend improved correlations or full CFD modeling into ISO standards and design fenestration tools, if appropriate.
5. Study 3 D hardware short-circuits and propose methods to ensure that these effects are incorporated into ratings.
6. Study the heat transfer effects of ventilated frame cavities and propose updated correlations.

**Key words**: Fenestration, window frames, heat transfer modeling, U-value, thermal transmittance, frame cavity, international standards.

# 1 Introduction

Low U-value (highly insulating) windows require low-conductance frames. Design and development of low-conductance frames is typically undertaken using two-dimensional heat transfer tools such as THERM (Finlayson et al. 1998, LBNL 2006). The algorithms in these tools are normally based on procedures defined in two ISO standards, ISO 15099, and ISO 10077-2. Although these algorithms have been shown to be relatively accurate (10 percent) for today's typical energy-efficient windows (products with U-values of about 2.0 $W/m^2K$), the algorithms simplify several heat transfer pathways that are essential for accurate development and characterization of low-conductance frames. To support successful efforts to develop low-conductance windows with reduced frame heat transfer rates, it is important to understand the accuracy and limitations of these procedures.

Heat transfer through window frames is a function of:

- One, two, and/or three dimensional *conduction* through solid materials (Note: This paper does not address how the thermal conductivity of solids is determined.)
- Two and three dimensional *convection* and *radiation* through hollow cavities within a frame (typically extruded vinyl, fiberglass, or aluminum).
- Boundary conditions on the inside and outside of the frame (typically a small effect for highly insulating frames).

This paper examines the differences between ISO 10077-2 and ISO 15099 and suggests ways to extract the best frame heat transfer algorithms from these two standards. This paper also examines the literature on frame heat transfer to identify and prioritize the most significant shortcomings in the ISO procedures, and outlines future research that needs to be undertaken in this area.

# 2 Differences between ISO 10077-2 and ISO 15099

Two ISO standards define procedures for computing frame heat transfer rates. These standards are:

- ISO 10077-2, *Thermal performance of windows, doors, and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames (ISO/FDIS 10077-2:2003)*
- ISO 15099, *Thermal performance of windows, doors and shading devices – Detailed calculations (ISO 15099:2003)*

Conceptually, these standards are similar. However, results can differ due primarily to the procedures used to compute heat transfer through cavities. The similarities and differences are noted in the table below.

*Table 1. Table showing similarities and differences between the frame procedures in ISO 10077-2 and ISO 15099.*

| Effect | ISO 10077-2 | ISO 15099 |
|---|---|---|
| 2-D conduction | Accounted for using finite element/difference techniques. Discussion on geometric representation limited. References ISO 10211-1 to determine whether mesh is appropriately refined; focus of this document is not windows but wall sections. | Accounted for using finite element/difference techniques. Discussion on modeling curved and angular elements included. Mesh must so fine that the calculated thermal transmittance is within 1 % of an extrapolated transmittance. |
| 3-D conduction (Figure 1) | Not addressed. | Addressed in an approximate procedure to calculate heat transfer effects of point thermal bridges like bolts, etc. |
| 2-D radiation (Figure 2) | Correlations for “parallel surfaces” used. | Correlations for “parallel surfaces” used (similar to 10077-2). Guidance provided on how to divide complex cavities and how to calculate average emissivity in frame cavities with surfaces with different emissivities. View-factor radiation model presented as an option for products which project significantly |

| | | |
|---|---|---|
| | | from the plane of the windows (i.e. greenhouse or garden windows). |
| 3-D radiation | Not addressed. | Provides approximate procedure to account for 3-D radiation heat transfer on indoor surfaces. |
| 2-D/3-D convection within individual frame elements (Figure 3) | Single set of correlations presented for vertical and horizontal frame cavity elements (i.e. sills, heads, jambs, etc.). There is no source of these correlations, but they are believed to be based on the simplified treatment of vertical frame cavities (i.e. jambs). | Separate correlations for vertical and horizontal cavities presented. However, all correlations are based on 2-D cavities . |
| 3-D convection (between frame elements) | Not addressed. | Not addressed. |
| Boundary conditions (frame surface) | Fixed values used. Simplified treatment of radiation used. | Temperature dependent convective film coefficients determined and detailed radiation model presented. |
| Boundary conditions: Cavities continuously (well) ventilated to indoors or outdoors (Figure 4) | Same boundary conditions as frame surfaces used. | Same boundary conditions as frame surfaces used. |
| Cavities non-continuously (slightly) ventilated to indoors or outdoors (Figure 4) | Uses an effective conductivity based on similar shaped cavity treated as a frame cavity with increased conductivity. | Same treatment as in 10077-2. |
| Cavities connected with “throats” | “Throat” less than 2 mm treated as separate cavities. | “Throat” less than 5 mm treated as separate cavities. Nu > 1.2 used as additional criteria. |

Reviewing the similarities and differences between these two standards, we conclude that they are fundamentally similar, although 15099 is more specific and uses well documented correlations. We therefore conclude that 15099 should be used as the basis for further improvements in window frame heat transfer modeling. After a review of recent research on frame heat transfer topics in Section 3 below, we define future improvements for modeling frame heat transfer.

# 3 Summary of Recent Research on Frame Heat Transfer in Window Frames

The literature on recent frame heat transfer research can be divided into two general categories: Studies that model heat transfer of frame cavities, and studies that model interior and exterior fenestration surfaces.

## 3.1 Heat Transfer Modeling of Window Frame Cavities

Much of the work related to heat transfer issues in fenestration cavities has focused on the glazing cavity. The primary goal has been to develop accurate correlations for natural convection effects inside multiple-pane windows; see, e.g., Batchelor 1954, Eckert and Carlson 1961, Hollands et al. 1976, Raithby et al. 1977, Berkovsky and Polevikov 1977, Yin et al. 1978, ElSherbiny et al. 1982, Shewen et al. 1996, Wright 1996, and Zhao 1998. Most of these papers study natural convection between two, high aspect ratio vertical isothermal walls separated by two horizontal adiabatic or perfectly conducting walls and assumed to be infinite in z-direction (i.e., two-dimensional cavity). Some of these studies are also relevant for frame cavities. The natural convection heat transfer correlations used to find the effective conductivity for frame cavities in ISO 15099 are all based on the correlations for glazing cavities.

Studies of heat transfer in multiple-pane windows also include findings regarding which Rayleigh numbers will have secondary (or multicellular) flow (see e.g. Korpela et al. 1982, Lee and Korpela 1983, Zhao et al. 1997, Lartigue et al. 2000). Secondary flow enhances heat transfer through glazing cavities and may also take place in some typical frame cavities, see Gustavsen and Thue (2007) and Fomichev et al. (2007).

In solid window frames, heat flow is by conduction, which can be simulated using standard conduction simulation software. In window frames with internal cavities the heat transfer process is more complex, involving combined conduction, convection, and radiation. To fully describe heat transfer through such window frames, we need, ideally, to simulate fluid flow to find convection effects and to use either view-factor or ray-tracing techniques to find radiation effects inside the cavities. However, because of the computational resources and additional modeling efforts required, these simulations are rarely done in fenestration design software tools. Instead, air cavities are treated as solid materials with an effective conductivity; in other words, conduction, convection, and radiation effects are combined into an effective conductivity. Then, as for solid window frames without internal cavities, standard conduction simulation software can be used to find how well such sections insulate or to determine the U-value. Some computer packages (e.g., Blomberg 2000, Enermodal 2001, Finlayson et al. 1998, and LBNL 2006) find the effective conductivity automatically, by applying procedures specified in international standards (ISO 15099 or ISO 10077-2). In some programs, view-factors can be used to calculate radiation heat transfer effects (Finlayson et al. 1998).

Some studies have been performed that focus on heat transfer effects in window frames that have internal cavities.

Standaert (1984) studied the U-value of an aluminum frame with internal cavities. The cavities were treated as solids, and effective conductivities were assigned to each. The effective conductivities of cavities not completely surrounded by aluminum were calculated from a fixed thermal resistance of $R = 0.37$ m$^2$K/W ($\lambda_{eq} = L/R$ where $\lambda_{eq}$ is the equivalent conductivity and $L$ is the length of the cavity in the heat flow direction). Cavities completely surrounded by aluminum were assigned an effective conductivity of 0.1 W/mK. The thermal transmittance of the frame studied was 5.9 W/m$^2$K. Jonsson (1985) and Carpenter and McGowan (1989) also treated air in window-frame cavities as solid and used an equivalent conductivity to calculate heat flow. In their studies the effective conductivity concept was formulated as:

$$\lambda_{eq} = \lambda_{air} Nu + \frac{h_R L}{\left[1/\varepsilon_H + 1/\varepsilon_C - 1\right]} \qquad (1)$$

where $\lambda_{eq}$ is the equivalent conductivity, $\lambda_{air}$ is the conductivity of air, $Nu$ is the Nusselt number, $L$ is the length of the air cavity, $\varepsilon_H$ and $\varepsilon_C$ are the emissivities of the warm and cold sides of the cavity walls, respectively. $h_R$ is the black-body radiative heat transfer coefficient, which depends on temperatures of the interior walls of the cavity and also on cavity geometry. Jonsson (1985) used $h_R = 3.3$ W/m$^2$K for different cavity geometries; Carpenter and McGowan (1989) report different $h_R$ values, depending on cavity height-to-length aspect ratios. The frames studied by Carpenter and McGowan (1989) had U-values between 2.1 and 11.2 W/m$^2$K, the former value for a wooden frame and the latter for an aluminum frame. Jonsson (1985) examined windows with U-values between 2.79 and 4.23 W/m$^2$K.

Hallé et al. (1998) studied the effect of air leakage on heat transfer in window frames with internal cavities. They used computational fluid dynamic (CFD) techniques to simulate air leakage effects. The frame cavities were treated as solids. Two window frames [an aluminum frame with a polyvinyl chloride (PVC ) thermal break and a PVC frame] were examined with air leakage rates of 1.65 and 0.55 m$^3$/h per meter of crack length. For the infiltration case, the authors found that the air-frame interaction caused the air to be preheated by the frame. This decreased the apparent thermal transmittance of the frame. For the exfiltration case, air increased the frame temperature, which increases heat losses and the apparent thermal transmittance of the frame.

Gustavsen (2001) studied heat transfer in window frames with internal cavities, focusing mainly on convection effects, where he compares the frame cavity convection correlations from various standards to relevant correlations in the literature and finds that the Nusselt number correlations that are to be used for horizontal window frames according to ISO 15099 are not necessarily accurate for frame cavities with a height-to-length aspect ratio between 0.5 and 5. This is because ISO 15099 requires an interpolation to be used for these geometries. (The correlation for cavities with an aspect ratio smaller than 0.5 is based on analytical considerations, such as dominating friction of

the two frame cavity walls, and the correlation for high aspect ratio cavities, $H/L > 5$, is based on experiments for typical glazing enclosures.) For some geometries and Rayleigh numbers, the correlation works, but for others the correlation predicts Nusselt numbers that are incorrect. Gustavsen also found that the convection correlation prescribed for frame cavities in ISO 10077-2 is only valid for vertical frame cavities (jambs).

Gustavsen and coworkers have studied several aspects of heat transfer in window frames with internal cavities. Gustavsen et al. (2001a) used infrared thermography to verify that a CFD code was capable of simulating the natural convection effects taking place in window frames with internal cavities. In that study combined natural convection and radiation heat transfer in three dimensions were simulated for air-filled cavities similar to those found in the extruded frame sections of windows. The accuracy of the conjugate CFD simulations was evaluated by comparing results for surface temperature on the warm side of the specimens to results from physical experiments that used infrared (IR) thermography to map surface temperatures during steady-state thermal tests between ambient thermal chambers set at 0 and 20°C. The conjugate CFD simulations modeled the enclosed air cavities, the frame section walls, and the foam board surround panel. In general, there was excellent agreement between the simulations and experiments. Gustavsen and coworkers have used the same CFD code in later studies.

In a follow-up study, Gustavsen et al. (2001b) examined three-dimensional convection effects in simple window frames with internal cavities and concluded that the thermal transmittance (U-value) of four-sided sections (with one open internal cavity) can apparently be found by calculating the area-weighted average of the thermal transmittance of the respective single horizontal and vertical sections. However, precise surface temperature predictions require three-dimensional simulations, especially for frame corners (see Figure 5). In addition, the authors concluded that two-dimensional heat transfer simulation software agrees well with CFD simulations for heat transfer rates for the simple square-shaped frames simulated if the natural convection correlations used for the internal cavities are correct.

Gustavsen et al. (2005) used CFD modeling to assess the accuracy of the simplified frame cavity conduction/convection models presented in ISO 15099 and used in software for rating and labeling window products. Three (horizontal) representative complex cavity cross-section profiles with varying dimensions and aspect ratios were examined (see Figure 6). Stream contour plots, Figure 7, and heat transfer rates were presented. The results supported the ISO 15099 rule that complex cavities with small throats should be subdivided; however, the authors suggest that cavities with throats smaller than 7 mm should be subdivided, in contrast to the ISO 15099 rule, which places the break point at 5 mm. Furthermore, the authors found that the agreement between CFD modeling results and the results of the simplified models was moderate for the heat transfer rates through the cavities. This was explained by inaccuracies in the underlying ISO 15099 Nusselt number correlations being based on studies where cavity height/length aspect ratios were smaller than 0.5 and greater than 5 (with linear interpolation assumed in between).

Gustavsen et al. (2007) used two-dimensional CFD and conduction simulations to study heat transfer in horizontal window frames with internal cavities (the previously mentioned paper studied only cavities). Temperatures and U-values for typical horizontal window frames with internal cavities were compared; results from CFD simulations with detailed radiation modeling were used as a reference. Four different frames were studied. Two were made of PVC and two of aluminum. For each frame, six different simulations were performed, two with a CFD code and four with a building-component thermal-simulation tool using the Finite Element Method (FEM). The FEM tool addresses convection using correlations from ISO 15099; it addressed radiation with either correlations from ISO 15099 or with a detailed, view-factor-based radiation model. The practice of subdividing small frame cavities was examined, in some cases not subdividing and in some cases subdividing cavities with interconnections smaller than 5 mm (according to ISO 15099) and in some cases subdividing cavities with interconnections smaller than 7 mm. For the various frames studied, the calculated U-values were found to be quite comparable (the maximum difference between the reference CFD simulation and the other simulations was found to be 13.2 %). A maximum difference of 8.5 percent was found between the CFD simulation and the FEM simulation using ISO 15099 procedures. The ISO 15099 correlation works best for frames with high U-values. For more efficient frames, the relative differences among various simulations are larger. Finally, the effectiveness of the ISO cavity radiation algorithms was examined by comparing results from these algorithms to detailed radiation calculations (from both programs). The authors conclude that improvements in cavity heat transfer calculations can be obtained by using detailed radiation modeling (i.e., view-factor or ray-tracing models), and that incorporation of these strategies may be more important for improving the accuracy of the results than the use of CFD modeling for horizontal cavities. Figure 8 shows a stream contour plot for one of the PVC frames studied.

Gustavsen and Thue (2007) applied a commercial CFD program to study the effect of the horizontal aspect ratio ($W/L$) on heat flow through three-dimensional cavities with a high vertical aspect ratio ($H/L$). These types of cavities can be found in vertical window frames, see Figure 9. The cavities studied have two opposite isothermal vertical walls separated by four adiabatic walls. The vertical aspect ratios are 20, 40, and 80, and the horizontal aspect ratios range from 0.2 to 5. Simulations of two-dimensional cavities are also included. The simulations show that three-dimensional cavities with a horizontal aspect ratio larger than five can be considered as two-dimensional cavities to within four percent when considering heat transfer rates. This means that glazing cavity correlations are not necessarily accurate for frame cavities. A complex flow was found for several of the cavities; one example is shown in Figure 10. Nusselt number correlations for the different horizontal aspect ratios are presented.

Fomichev et al. (2007) also studied heat transfer effects in such cavities which can be found in horizontal and vertical frame cavities. They used both experimental and numerical techniques (two- and three-dimensional CFD simulations) and studied the effect of the aspect ratios (horizontal and vertical) as well as tilt angle on heat transfer rates. They concluded that two-dimensional modeling is appropriate to predict natural convection heat transfer in horizontal frame cavities (such as the ones found in frame

heads and sills) tilted around the long axis. They further concluded that three-dimensional simulations are needed to predict natural convection heat transfer in frame cavities tilted around the short axis, such as the ones found in vertical frame sections (jambs and vertical meeting rail and mullion cross-sections). Fomichev et al. (2007) also note that the frame-cavity correlation equations suggested by ISO 15099 for vertical frame cavities do not correlate well with their three-dimensional CFD simulation results. The authors suggest new correlations for both horizontal frame sections (vertical aspect ratios between 0.5 and 5) and vertical frame sections (vertical aspect ratios between 20 and 40, and horizontal aspect ratios between 0.5 and 2). The correlations depend on both Rayleigh number and tilt angle (in addition to the aspect ratios). Fomichev et al. (2007) did some additional studies of the convection heat transfer effects for ventilated frame cavities.

Svendsen et al. (2000) and Noyé et al. (2001) examined the accuracy of the radiation procedures prescribed in EN ISO 10077-2 and found that applying view-factors to account for radiation, instead of using the simplified correlation in EN ISO 10077-2, resulted in U-values that compare better with measured results. The natural convection correlations of EN ISO 10077-2 were used. Two frames were examined, one thermally broken aluminum frame and one frame made of PVC. Svendsen et al. (2000) found that division of air cavities also affects the U-value, but not as much as the change of radiation model.

## 3.2 Exterior and Interior Surface Modeling

When the thermal performance of fenestration products is determined by calculating U-value, surface conditions (surface resistances) are among the properties used. Accurate treatment of the surface conditions is therefore important so that we can accurately predict thermal transmittance and also distinguish among the ability of various designs to achieve desired glass/frame surface temperatures.

Curcija and Goss (1993) used a finite-element method to study two-dimensional, laminar convection over an isothermal indoor fenestration surface (glazing/frame assembly). Results were reported for three typical configurations: Glazing with no frame, glazing with a single-step frame, and glazing with a double-step frame. The authors present local indoor surface convective heat transfer coefficients to be used in two- and three-dimensional heat transfer analysis of fenestration systems (valid both for the glazing and frame parts of the product).

Carpenter and Elmahdy (1994) examined thermal performance of four complex fenestration systems (flat glazed skylight, domed skylight, greenhouse window and curtain wall) using computer simulation tools and guarded hot-box testing. They found discrepancies of up to 16 percent between the simulated and measured cases and explain the difference by uncertainties in the warm- and cold-side film coefficients and lower warm-side air temperatures because of stagnant airflow. They also found that thermal simulations must account for thermal bridges such as bolts in curtain walls and curbs in skylights.

Griffith et al. (1998b) and Carpenter and McGowan (1998) studied heat transfer in curtain-wall aluminum frames, focusing on the effect of bolts on heat flow and the temperature distribution on the warm-side surface of sample specimens. Both studies conclude that it is important to include the bolts when determining frame thermal performance. These studies also found that two-dimensional programs give accurate results when appropriate calculation procedures are applied.

In 1994 Curcija and Goss investigated three different ways of modeling heat transfer boundary conditions for complete (two-dimensional) fenestration systems (with wood frame). A CFD program was used to allow for fluid flow in the glazing cavity. Two of the surface models incorporated fixed indoor and outdoor coefficients, and one incorporated variable (position-dependent) coefficients. Component and overall U-values were compared. The authors found that the U-values from using variable boundary conditions were generally lower than the ones calculated using constant surface heat transfer coefficients. The average difference was approximately 15 percent. Curcija and Goss (1994) further noted that the effects of variable boundary conditions, which more accurately model local heat transfer on indoor and outdoor fenestration surfaces, create "insulated" zones in the vicinity of the edge-of-glass region that can significantly change the local heat transfer and temperature distribution when compared to constant-boundary-condition situations. This effect of lower heat transfer in these "insulated" zones could be used in the design process so that altering the design on either side of the frame could create more pronounced outdoor insulated zones and less pronounced indoor insulated zones, thereby improving the condensation resistance of the fenestration system. The results also showed that the edge-of-glass area used when simulating frame and edge of glass (with spacer) should not be defined as 63.5 mm (2.5 in) from the sight line; 102 mm (4 in) is a more realistic measure.

In 1998 Griffith et al. (1998a) and Arasteh et al. (1998) examined how improved radiation modeling (using view-factor models instead of fixed coefficients) could improve the prediction of surface temperatures when modeling projecting fenestration products. Griffith et al. (1998a) found that using view-factor modeling could improve the accuracy of the models for predicting surface temperature and lower the results for U-values for projecting windows (skylights, greenhouse windows).

Branchaud et al. (1998) examined the local heat transfer in cavities open to the exterior environment. This study shows that there can be a significant variation of the local convective heat transfer coefficient on the outdoor surface of a fenestration system. The variation is mainly a result of the product's geometry. Based on CFD simulations, the authors find, for the cavities studied, that significant convective heat transfer effects extend only up to one times the width of the cavity opening.

Schrey et al. (1998) studied the local heat transfer coefficient for two flush-mounted glazing units. One of the glazing units had a foam spacer while the other had an aluminum spacer. No window frame was included in the studies. Wright and Sullivan (1994) used two-dimensional CFD code to study the natural convection effects in a

vertical rectangular window cavity, but did not consider frame heat transfer. Secondary flow was reported.

## 3.3 Summary of Conclusions from Existing Research on Frame Heat Transfer

Based on the above literature review, we conclude that

- Computational Fluid Dynamic (CFD) tools are accurate for quantifying the details of frame heat transfer. Three dimensional (3-D) CFD models are necessary to capture convection heat transfer in vertical frame cavities.
- Experimental validation of the selected frame cavity configurations and orientations are necessary. Infrared thermography and/or hot box measurements with local heat flux and temperature measurements are recommended for validation.
- Frame cavities with throats smaller than 7 mm should be subdivided.
- A view-factor radiation model for cavities is more accurate than simple ISO correlations.
- Certain cavity correlations for horizontal heat flow need to be improved (aspect ratios between 0.5 and 5).
- New correlations have been developed for natural convection in air cavities of vertical frame cavities (jambs).
- New correlations have been developed for cavities in sloped frame products such as skylights.
- Current treatment of ventilated cavities on the outdoor side is not adequate; new correlations have been developed for a limited set of cases.

# 4 Future Work

Although all current windows and future low-conductance frames could be modeled accurately with CFD tools, this is not feasible. Building and running a CFD model takes approximately 500 times longer than performing a two-dimensional conduction run in THERM.

Table 2 lists the heat transfer effects to be addressed, and, based on our literature review, the current status and significance of each, the impact of the current status and the future work needed.

*Table 2. Window frame heat transfer effects; impacts and future work.*

| Effect | Status | Significance | Impact | Future Work |
|---|---|---|---|---|
| 2-D conduction | Accounted for. | Basis of frame rating for typical products. | Major. | |
| 3-D conduction (Figure 1) | Not adequately addressed. | Important for preventing hardware short-circuits. | Could be a major loophole if not addressed. | Analysis of effects in low conductance frames needed; if significant, models to be proposed. |
| 2-D radiation (Figure 2) | Correlations for "parallel surfaces" used. Full radiation model available. | Significant. Impact depends on cross-section and frame design. | Full radiation model shown to be up to 7 % more accurate for frame U-values (Gustavsen et al. 2007). Low-emissivity interior cavities expected to significantly reduce frame heat transfer. | Implement full view-factor radiation model in ISO. |
| 3-D radiation | Limited studies. Available as simplistic model in ISO 15099 for indoor surfaces. Full model available in CFD tools and some few 3-D conduction tools | Not expected to be significant in frame cavities. However, it is significant on indoor surfaces of projecting products. | Unknown. | Confirm "low-priority" hypothesis with 3-D/2-D studies. |
| 2-D/3-D convection within individual frame | Different correlations for horizontal and vertical frame | Convection needs to be reduced for efficient frames. | Horizontal cavity correlations within 8 % of 2-D CFD | Perform studies to better understand accuracy of correlations for vertical frame |

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| elements (Figure 3) | members. | | (Gustavsen et al. 2007). Vertical cavities (3-D by definition) to be studied. | members (computationally intensive). Understand benefits of improved correlations vs. full CFD. |
| 3-D convection (between frame elements) | Only available in CFD tools. | Could be significant for low conductance R frames with cavities. | Unknown. | Perform studies to understand implications of addressing this or not (computationally intensive). Understand benefits of improved correlations vs. full CFD. |
| Cavities continuously ventilated to outdoors (Figure 4) | Partially addressed. | Affects rated and field performance. | Could significantly affect thermal performance depending on the geometry. | Extend research to cover all aspect ratios and all typical/representative geometries. |
| Cavities non-continuously ventilated to outdoors (Figure 4) | Not available. | Affects actual performance. | Could be significant (i.e., wind washing). | Conduct CFD and measurements to determine effects of convection heat transfer and develop correlations. |
| Cavities continuously ventilated to indoors (Figure 4) | Not available. | Affects mostly field performance. | Could be significant if subject to forced convection in the room (i.e. HVAC proximity to the window) | Conduct CFD and measurements to determine effects of convection and radiation heat transfer and develop correlations for convection heat transfer and recommendations for the application of radiation model. |
| Boundary Conditions | Simplified correlations used. | Less significant because of the increasing controlling | Impacts local heat transfer, which affects condensation resistance. | Needs to be investigated. |

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|---|---|---|---|---|
| | | resistance of the frame member. | | |

# 5 Conclusions

Current technical algorithms from ISO 15099 used to quantify heat transfer through window frames members are adequate for today's typical window products. However, to ensure development and accurate rating of the next generation of low-conductance frames, improvements are needed in the simulation tools that implement these algorithms. Without such improvements, product development efforts will not necessarily yield expected energy savings. Commercially available research-level CFD tools can be used to develop improved algorithms.

Based on a review of the work to date in the area of frame heat transfer modeling, we conclude that the major near-term priorities are to:

1. Add 2-D view-factor radiation to standard modeling and examine the current practice of averaging surface emissivity based on area weighting and the process of making an equivalent rectangular frame cavity.
2. Asses 3-D radiation effects in frame cavities and develop recommendation for inclusion into the design fenestration tools.
3. Assess existing correlations for convection in vertical cavities using CFD.
4. Study 2-D and 3-D natural convection heat transfer in frame cavities for cavities that are proven to be deficient from item 3 above. Recommend improved correlations or full CFD modeling into ISO standards and design fenestration tools, if appropriate.
5. Study 3-D hardware short-circuits and propose methods to ensure that these effects are incorporated into ratings.
6. Study the heat transfer effects of ventilated frame cavities and propose updated correlations.

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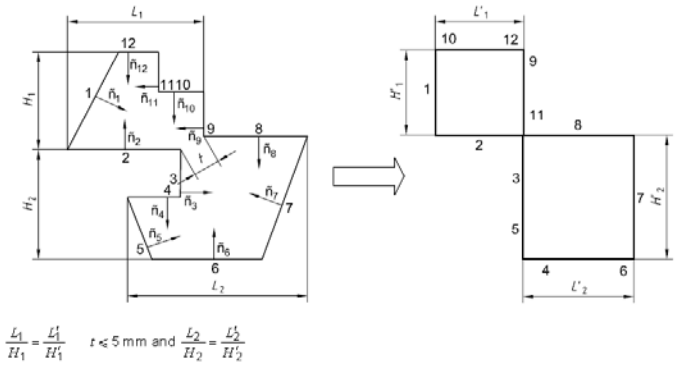
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*Figure 1. Hardware for window operation is not currently modeled when evaluating window heat transfer. However, hardware often replaces solid materials, is often made of highly conductive metal, and can be a major frame penetration. As window frames become more insulating, such thermal short-circuits can have a significant impact on the overall U-value.*



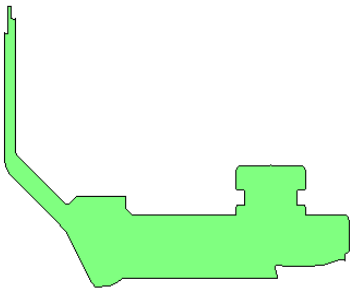



*Figure 2. Radiation heat transfer through frame cavities is simplified in ISO standards and some simulations by representing the cavities as simple rectangles. Although this is a reasonable approximation for some cavities, it can lead to significant errors for complex cavities. THERM (Finlayson et al. 1998, LBNL 2006) includes a view-factor model that allows for a first-principles treatment of radiation heat transfer.*

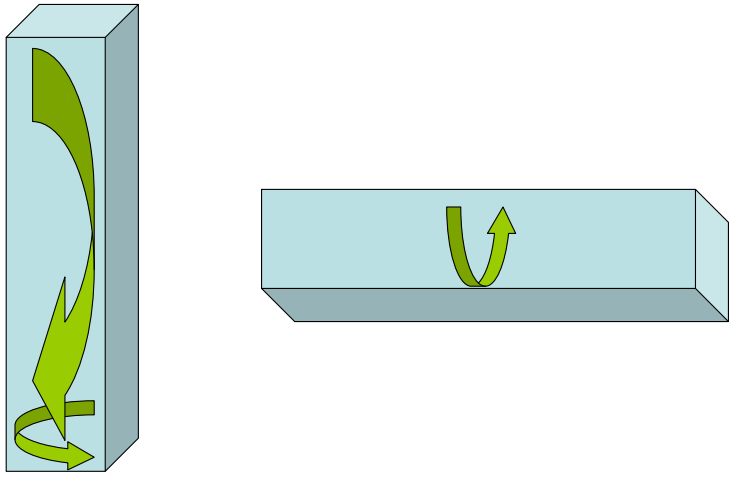


*Figure 3. Convective heat transfer through hollow horizontal frame profiles is primarily two-dimensional, whereas convection in vertical frame cavities is also three-dimensional. Correlations used in ISO standards have only been validated for horizontal frame profiles.*

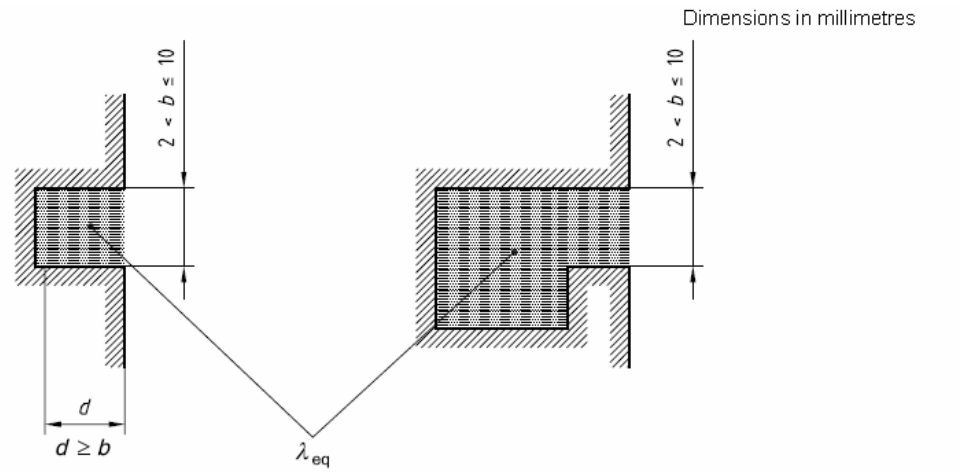



*Figure 4. "Indentations" in frame profiles are termed "ventilated" or "slightly ventilated cavities" depending on the geometry. Only minimal research has been done on heat transfer effects in such cases.*

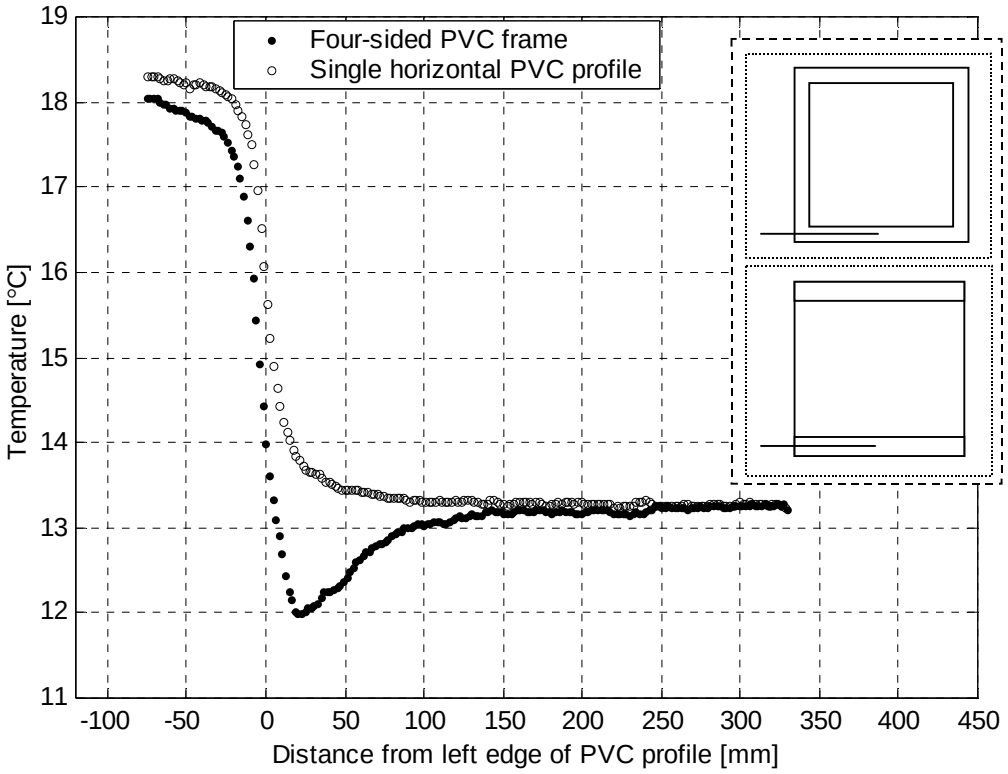



*Figure 5. Temperatures along the left lower horizontal part of the four-sided two-inch PVC frame compared to the surface temperatures along the middle of the lowest two-inch profile in the configuration made up of two separate horizontal profiles (Gustavsen et al. 2001b).*

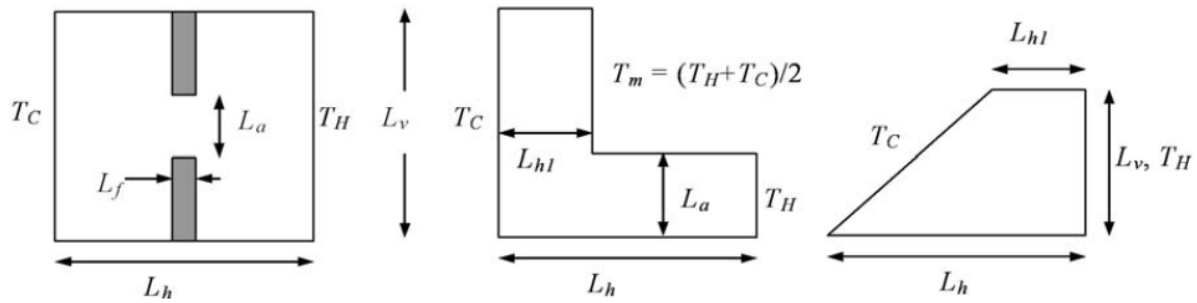



*Figure 6. Schematics of cavities studied by Gustavsen et al. (2005). The height and the width of the two cavities to the left were 30 mm. The right cavity width was 30 mm, and the heights were 10 mm and 20 mm. $L_a$ was varied to between 0 and 30 mm for the cavity to the left and between 3 and 15 mm for the cavity in the middle.*

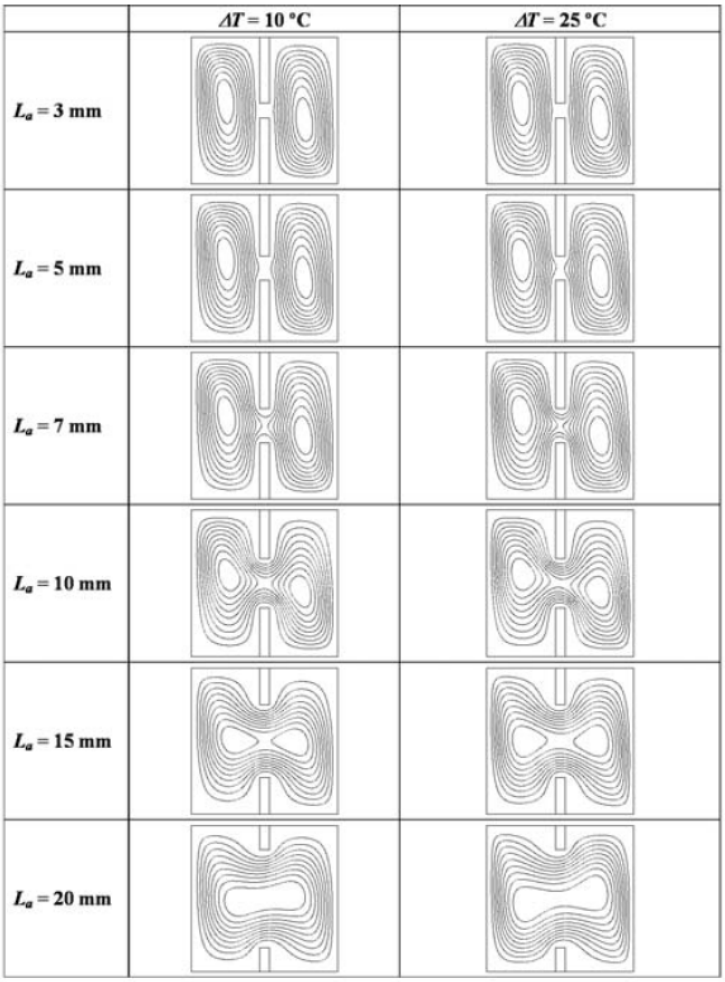



*Figure 7. Stream contours for the cavity to the left in Figure 6 (named the H-cavity). $L_a$ is the size of the gap opening, and $\Delta T$ is the difference between the hot and cold wall temperatures.*

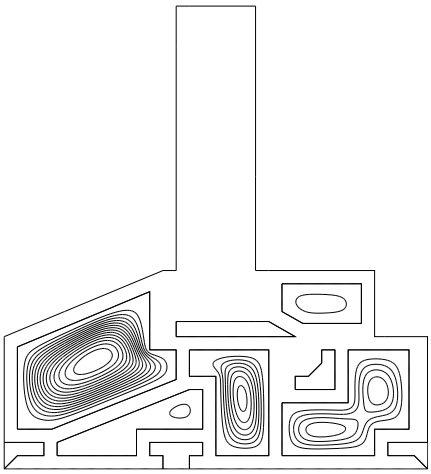


*Figure 8. Stream contours for one of the PVC frames studied by Gustavsen et al. (2007).*

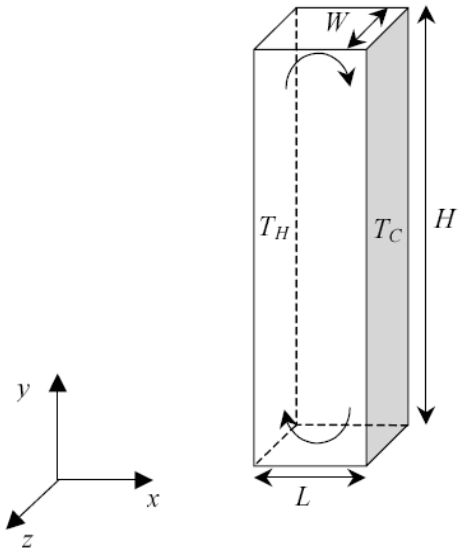



*Figure 9. Geometry studied by Gustavsen and Thue (2007). The vertical aspect ratios, H/L, were 20, 40, and 80 and the horizontal aspect ratios, W/L, ranged from 0.2 to 5.*

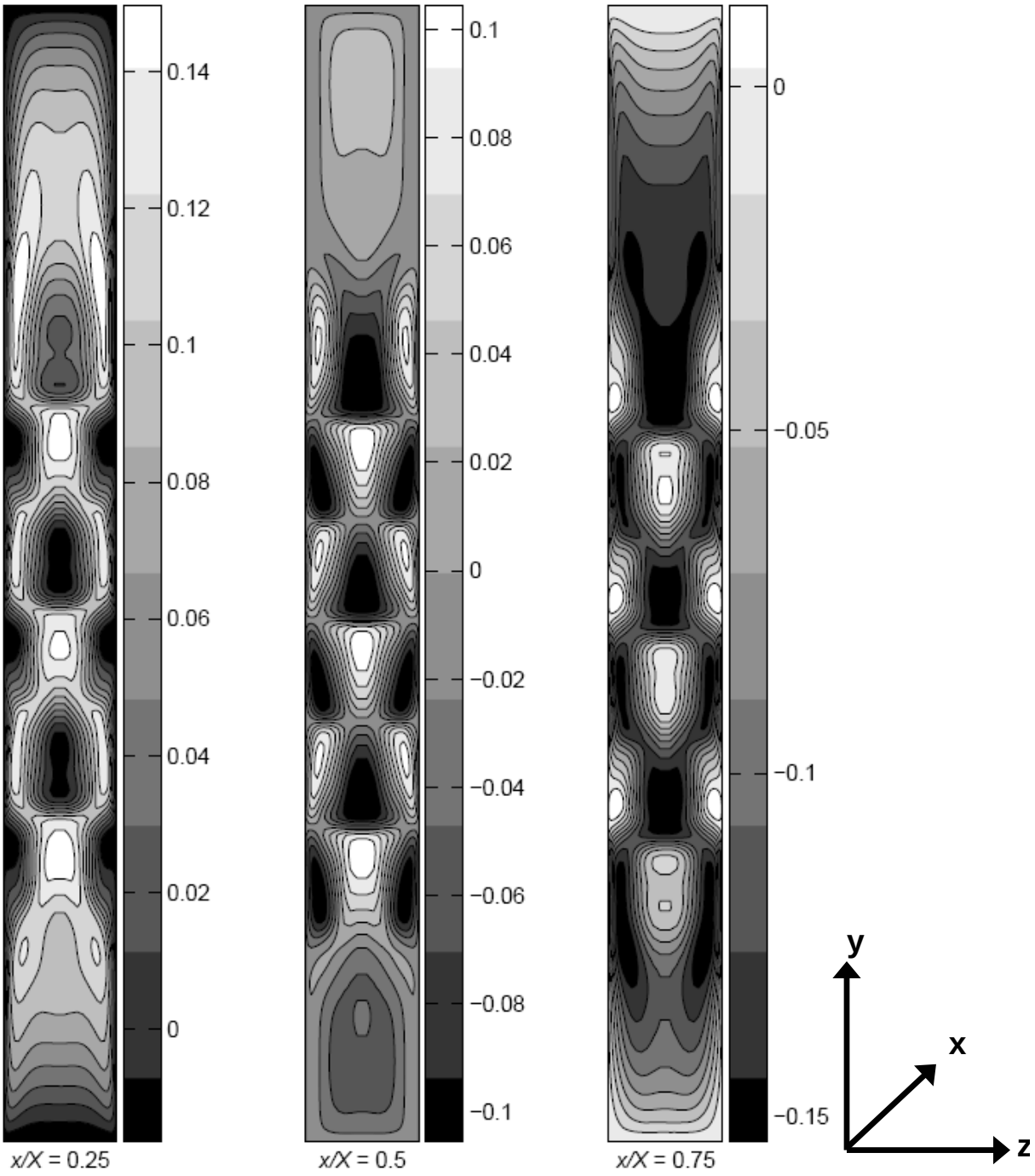



*Figure 10. y-velocity contours (m/s) at different planes in a cavity where (H/L, W/L) = (40, 2). The Rayleigh number was equal to $2\times10^4$. Each plane is parallel to the yz-plane in Figure 9. X is the total length of the cavity. The x-vector is pointing into the page, the y-vector is pointing from bottom to top, and the z-vector is pointing from left to right. The figures are not to scale (Gustavsen and Thue, 2007).*