Two-Dimensional Computational Fluid Dynamics and Conduction Simulations of Heat Transfer in Horizontal Window Frames with Internal Cavities

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ABSTRACT

This paper assesses the accuracy of the simplified frame cavity conduction/convection and radiation models presented in ISO 15099 and used in software for rating and labeling window products. Temperatures and U-factors for typical horizontal window frames with internal cavities are compared; results from Computational Fluid Dynamics (CFD) simulations with detailed radiation modeling are used as a reference.

Four different frames were studied. Two were made of polyvinyl chloride (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). This 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. Calculations were performed using the CFD code with and without fluid flow in the window frame cavities; the calculations without fluid flow were performed to verify that the CFD code and the building-component thermal-simulation tool produced consistent results. With the FEM-code, the practice of subdividing small frame cavities was examined, in some cases not subdividing, in some cases subdividing cavities with interconnections smaller than five millimeters (mm) (ISO 15099) and in some cases subdividing cavities with interconnections smaller than seven mm (a breakpoint that has been suggested in other studies). For the various frames, the calculated U-factors were found to be quite comparable (the maximum difference between the reference CFD simulation and the other simulations was found to be 13.2 percent). 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-factors. For more efficient frames, the relative differences among various simulations are larger.

Temperature was also compared, at selected locations on the frames. Small differences was found in the results from model to model.

Finally, the effectiveness of the ISO cavity radiation algorithms was examined by comparing results from these algorithms to detailed radiation calculations (from both programs). Our results suggest 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 results than the use of CFD modeling for horizontal cavities.

INTRODUCTION

Window frames made of polyvinyl chloride (PVC) or aluminum contain air cavities, which have a significant effect on the frames' insulation capabilities. To understand total frame thermal conductance, it is important to accurately characterize the thermal impact of air cavities. The importance of these cavities is of particular concern in more highly insulating products.

This paper assesses the accuracy of the simplified frame cavity conduction/convection and radiation models presented in ISO 15099 and used in software (e.g., Blomberg 2000, Enermodal 2001, and Finlayson et al. 1998) for rating and labeling window products. Temperatures and U-factors for several typical horizontal window frames that have internal cavities are compared; results from Computational Fluid Dynamics (CFD) simulations with detailed radiation modeling are used as a reference. Unless otherwise noted, the term "CFD", as used below, include detailed ray-tracing-based radiation modeling as well as direct modeling of convection heat transfer.

Four different window frames were examined: two made of polyvinyl chloride (PVC) and two made of aluminum. For each frame, six different simulations were performed: two with a CFD code and four with a building-component thermal-simulation tool which uses the finite element method (FEM). The FEM tool addresses convection using correlations from ISO 15099; it addresses radiation with either correlations from ISO 15099 or by using a detailed, view-factor-based radiation model. CFD calculations were performed with and without fluid flow in the window frame cavities. The calculations without fluid flow were performed to verify that the CFD code and the building-component thermal-simulation tool produced consistent results.

Various sources prescribe rules for using building-component thermal-simulation programs to simulate heat transfer in window frames (ASHRAE 1996; CEN 2003; ISO 2003). In a companion paper (Gustavsen et al. 2005), horizontal frame cavities were studied to assess the accuracy of current ISO 15099 procedures for modeling convection. In that analysis, the agreement between CFD modeling results and the results of the simplified models was moderate for heat-transfer rates through frame cavities. The differences may be a result of the underlying ISO 15099 Nusselt number correlations being based on studies in which cavity height/length aspect ratios were smaller than 0.5 and greater than five (with linear interpolation assumed in between).

In addition, the results presented in Gustavsen et al. (2005) indicate that subdivision of complex cavities with small interconnections, as prescribed in the ISO 15099, is justified. However, the data in that study suggest that horizontal cavities with interconnections smaller than seven millimeters (mm) should be subdivided, in contrast to the ISO 15099 rule, which sets the break point at five mm. In this paper, the focus is on on how these different breakpoints for subdividing the cavities influence the simulated U-factors and temperature distributions of real/realistic horizontal frames. When using the building component simulation code, the frame cavities were or were not subdivided as follows: in case 3, the cavities were not divided; in case 4, the cavities were divided when the interconnections were smaller than five mm; and in case 5, the cavities were divided when the interconnections were smaller than seven mm. In addition, one case identical to case 4 was simulated using view factors instead of the ISO 15099 radiation model to calculate radiation; this is case 6.

The results presented in this paper are only for horizontal frame members because convection in vertical jambs requires three-dimensional CFD simulations that are beyond the scope of this project.

WINDOW FRAMES

The four simulated window frames that we studied are shown in Figures 1 and 2. Figure 1 shows, on the left, a PVC frame with complex cavities and, on the right, a relatively simple aluminum frame. This particular aluminum frame, which has a thermal break, was chosen because of its simple, almost rectangular cavities. Figure 2 displays a complex aluminum frame on the left and a modified commercial PVC frame on the right. The modification of the PVC frame consisted of removing insulation material from some of the air cavities to fully expose the cavities to convection and radiation effects. The thermal breaks in the aluminum frames are noted in the figures. To simplify reporting of results, the frames are identified as S1 through S4. One of the PVC frames, S1 in Figure 1, was simulated with a double glazing unit filled with a solid insulating material. In the other frames, the glazing was replaced by a solid insulating panel, as prescribed in the international standard EN ISO 10077-2 (CEN 2003).

NUMERICAL PROCEDURE

The simulations were performed with a finite-element method (FEM) building-component thermal-simulation program (Finlayson et al. 1998), which uses the procedure and heat-transfer correlations of ISO

15099, and a CFD program (Fluent 2005). We refer to the former as the “FEM program”. Double precision was used in both programs.

Simulations with the FEM tool

A finite-element method (FEM) was used to solve the conductive heat-transfer equation. The quadrilateral mesh is automatically generated. Refinement was performed in accordance with section 6.3.2b. of ISO 15099 (ISO 2003). The energy error norm was less than six percent in all cases, which results in an error less than one percent in the thermal transmittance of the frames. More information on the thermal simulation program algorithms can be found in Appendix C in Finlayson et al. (1998). The FEM program uses correlations to model convective heat transfer in air cavities, and view factors or fixed radiation coefficients can be used to calculate radiation heat transfer. The convection and radiation coefficients for the frame cavities were calculated according to ISO 15099 (these procedures are also reported in Gustavsen et al. 2005).

Surface temperatures of cavity walls are among the parameters used to find the equivalent conductivity for frame cavities. At the start of a numerical simulation these temperatures are set to predefined values that do not necessarily reflect the final temperature distribution of the simulated frame. To find the correct equivalent conductivity for each cavity, cavity wall temperatures have to be adjusted during the calculation. In the FEM program, this adjustment is made automatically, and the temperature tolerance is 1 °C (this value is the same in ISO 15099). Thus, when two successive iterations produce temperatures within 1 °C of the previous run for all cavity walls, the criterion is satisfied. In the CFD program, the air cavity wall temperatures are found as a part of the solution process.

CFD Simulations

In the CFD program, a control-volume method is used to solve the coupled heat and fluid-flow equations. Conduction, advection, and radiation are simulated numerically. The maximum Rayleigh number found for the frame cavities is about 3×10^4. All the cavities of the simulated window frames have vertical-to-horizontal aspect ratios smaller than six. For such Rayleigh numbers and aspect ratios, Zhao (1997) reports steady laminar flow. Although most of the cavities presented are not rectangular, incompressible and steady laminar flow is assumed. Further, viscous dissipation is not addressed, and all thermophysical properties are assumed to be constant except for the buoyancy term of the y-momentum equation where the Boussinesq approximation is used. The Semi-Implicit Method for Pressure-linked Equations Consistent (SIMPLEC) was used to model the interaction between pressure and velocity. The energy and momentum variables at cell faces were found by using the Quadratic Upstream Interpolation for Convective Kinetics (QUICK) scheme. In addition, the CFD program uses central differences to approximate diffusion terms and relies on the PREssure Staggering Option scheme (PRESTO) to find the pressure values at the cell faces. PRESTO is similar to the staggered grid approach described by Patankar (1980). Convergence was determined by checking the scaled residuals and ensuring that they were less than 10^{-6} for all variables, except in the energy equation where the residuals have to be less than 10^{-11} (for some of the cases, the energy residuals stopped at about 5×10^{-10}). Radiation heat transfer was included in the simulations through use of the Discrete Transfer Radiation Model (DTRM), which relies on a ray-tracing technique to calculate surface-to-surface radiation. The internal cavity walls were assumed to be diffuse gray, and air did not interact with the radiative process.

Prior to the final simulations, some grid sensitivity tests were performed on frame S2 (aluminum). Grid sizes of 0.1 and 0.25 mm were tested. The first resulted in 865,750 control volumes and the latter in 141,436 control volumes. The simulations were carried out without including radiation. For grid sizes of 0.1 mm and 0.25 mm, respectively, frame U-factors of 1.9286 W m^{-2} K^{-1} and 1.9247 W m^{-2} K^{-1} were found. The difference is only 0.2 percent. Because it was determined that this difference in U-factor was not significant, we used a grid size of 0.25 mm in the final simulations for all of the frames.

The effect of increasing the number of rays in the radiation heat-transfer algorithm of the CFD code was also tested. Doubling the number of rays only resulted in a 0.1-percent change in the frame U-factor.

This study builds upon prior work, where the CFD modeling tool used in this study was compared to experimental results. In Gustavsen et al. (2001a), CFD generated surface temperatures for a variety of frame profiles (subjected to a 20 ºC temperature difference) were compared to Infrared Thermography measurements of these same surface temperatures. Excellent agreement between the CFD simulations and experimental data was noted.

U-factor Calculation

The ISO 15099 approach (ISO 2003) was used to find the U-factor for the PVC frame with glazing (S1). That is, the frame U-factor was calculated from:

$$U_{fr} = \frac{\Phi_{fr}}{b_f\left(T_{in} - T_{out}\right)} \tag{1}$$

where Φ_{fr} is the heat flow rate per unit length through the frame area, b_f is the projected width of the frame, and T_{in} and T_{out} are the indoor and outdoor air temperatures, respectively. The other frames, S2-S4, were simulated with insulation panels, as prescribed in ISO (2003) and CEN (2003), and the U-factors, U_f, were calculated from:

$$U_f = \frac{L_f^{2D} - U_p \cdot b_p}{b_f} \tag{2}$$

In Equation (2), L_f^{2D} is the thermal conductance of the entire section (with insulating panel), U_p is the thermal transmittance of the insulation panel, b_p is the visible width of the insulation panel, and b_f is the projected width of the frame. The variables b_p and b_f are shown in Figure 3.

The shapes of the two frame sections that are shown in Figure 1 (specimens S1 and S2) were identical in both simulation programs. The other two frame sections (S3 and S4) were drawn using computer-aided design (CAD) files as underlay. Some minor differences may therefore be found between the geometries in the two programs. To check the consistency of the results from the models, we conducted simulations in which all cavities were treated as solids in both programs (see the results and discussion section).

Material Properties and Boundary Conditions

Table 1 displays the material properties used in the numerical simulations. Note that the emissivity of all aluminum surfaces was set to 0.2. (An emissivity of 0.9 should generally be used for painted and anodized surfaces.)

TABLE 1
Conductivity and Emissivity of the Materials Used in the Frame Sections

Material	Conductivity [W m^{-1} K^{-1}]	Emissivity
Aluminum	160.0	0.2
Butyl rubber	0.24	0.9
Ethylene Propylene Diene Monomer (EPDM)	0.25	0.9
Foam rubber	0.03	0.9
Glass	0.9	-
Glazing cavity (solid)	0.032	-
Insulation panel	0.035	0.9
Mohair	0.14	0.9
Polyamide (nylon)	0.25	0.9
Polysulphide	0.19	0.9
Polyvinylchloride (PVC)	0.17	0.9
Spacer foam	0.2495	0.9
Urethane	0.31	0.9
Vinyl (flexible)	0.12	0.9

The air properties used in the CFD simulations were evaluated at the mean temperature of indoor and outdoor air and at atmospheric pressure, 101,325 Pa (see Table 2). For frame S1, the mean temperature was 1.66 ºC; for frames S2 and S3, it was 10 ºC (see below). Frame S4 was simulated both at a mean temperature of 1.66 and 10 ºC. The standard acceleration of gravity, 9.8 m/s^2, was used in all calculations.

TABLE 2
Air Properties Used in the CFD Simulations

$(T_{in}+T_{out})/2$	λ	c_p	μ	ρ	β

[°C]	[W m^{-1} K^{-1}]	[J kg^{-1} K^{-1}]	[kg m^{-1} s^{-1}]	[kg m^{-3}]	[K^{-1}]
1.66	0.02419	1005.1	1.7315×10^{-5}	1.2846	$3{,}6389\times10^{-3}$
10.0	0.02482	1005.5	1.7724×10^{-5}	1.2467	$3{,}5317\times10^{-3}$

CEN (2003) boundary conditions, shown in Table 3, were used in the simulations for frames S2 and S3. Table 3 also includes the boundary conditions used for frame S1, which were selected so that there would be a larger temperature difference across the frame than the temperature differences in the other samples. The glazing boundary conditions were automatically calculated in the FEM program when the glazing system was imported. These are based on center-of-glass surface temperatures. Frame S4 was simulated with both kinds of boundary conditions.

TABLE 3
Boundary Conditions (BC) Used in the Simulations

Description	**Temperature** ***T*** **[ºC]**	**Heat transfer coefficient** ***h*** **[W m^{-2} K^{-1}]**
BC 1: Frames S2, S3, and S4		
Indoor boundary condition	20.0	7.692
Outdoor boundary condition	0.0	25.0
BC 2: Frames S1 and S4		
Frame indoor boundary condition	21.11	7.61
Frame outdoor boundary condition	-17.78	29.03
Glazing indoor boundary condition	21.11	7.722
Glazing outdoor boundary condition	-17.78	28.68

RESULTS AND DISCUSSION

The subsections below discuss the U-factor comparisons, the temperature comparisons, and the accuracy of the ISO 15099 radiation model.

U-factor Comparisons

Table 4 shows the U-factors for the various simulations, the differences between the interior and exterior air temperatures used in the simulations, and the deviation of the various cases from the reference case (i.e., case CFD, fluid flow, below) in absolute U-factor changes and in percent. Several ways of simulating the various frames are compared. The simulations are labeled as listed below. Note that frame S4 is simulated with two temperature differences: 20 ºC and 38.89 ºC (boundary conditions BC 1 and BC 2, respectively, in Table 3). The latter cases are marked with an asterisk in the table.

- *CFD, fluid flow* denotes the cases simulated with the CFD code in which air is allowed to circulate. Thus, natural convection is calculated as a part of the solution process. A ray-tracing algorithm is used to account for radiation heat transfer.
- *CFD, no fluid flow* denotes the cases that are simulated with the CFD code, with no air circulation in the air cavities. The air cavities are treated as solids, and the thermal conductivities of the cavities are defined as effective conductivities from the simulations described for the next item. The *CFD, no fluid flow* cases are included in order to verify that the CFD and FEM programs produce consistent results.
- *FEM, no division* denotes the cases where ISO 15099 natural convection and radiation correlations are used for the air cavities, but with no division of air cavities. These cases are simulated with the FEM program.
- *FEM, 5-mm-rule* denotes the cases that are simulated with the FEM program according to ISO 15099 (with division of air cavities that have interconnections smaller than five mm).
- *FEM, 7-mm-rule* denotes cases simulated in a similar manner as the cases above, but with division of air cavities that have interconnections smaller than seven mm.
- *FEM, 5-mm-rule, DetRad* means the cases that are simulated according to ISO 15099 (with division of air cavities that have interconnections smaller than 5 mm), except that view-factors instead of the ISO

15099 radiation correlations are used to calculate the radiation heat transfer. These cases are simulated with the FEM program.

TABLE 4
Calculated Thermal Transmittance (U-factor) for the Various Frames. ΔT Denotes the Difference Between the Exterior and Interior Air Temperatures

Case	Description	ΔT [K]	U_f [W/m^{2}K]	ΔU ref. case 1 [W/m^{2}K]	% exceeding case 1
S1-1	CFD, fluid flow	38.89	1.583	0	0
S1-2	CFD, no fluid flow (same λ_{eff} as S1-3)	38.89	1.671	0.088	5.6
S1-3	FEM, no-division	38.89	1.678	0.095	6.0
S1-4	FEM, 5-mm-rule	38.89	1.666	0.083	5.2
S1-5	FEM, 7-mm-rule	38.89	1.634	0.051	3.2
S1-6	FEM, 5-mm-rule, DetRad	38.89	1.603	0.020	1.3
S2-1	CFD, fluid flow	20.0	2.189	0	0
S2-2	CFD, no fluid flow (same λ_{eff} as S2-3)	20.0	2.218	0.029	1.3
S2-3	FEM, no-division	20.0	2.216	0.027	1.2
S2-4	FEM, 5-mm-rule	20.0	2.216	0.027	1.2
S2-5	FEM, 7-mm-rule	20.0	2.221	0.032	1.5
S2-6	FEM, 5-mm-rule, DetRad	20.0	2.252	0.063	2.9
S3-1	CFD, fluid flow	20.0	7.555	0	0
S3-2	CFD, no fluid flow (same λ_{eff} as S3-3)	20.0	7.876	0.321	4.2
S3-3	FEM, no-division	20.0	7.891	0.336	4.4
S3-4	FEM, 5-mm-rule	20.0	7.854	0.299	4.0
S3-5	FEM, 7-mm-rule	20.0	7.783	0.228	3.0
S3-6	FEM, 5-mm-rule, DetRad	20.0	7.717	0.162	2.1
S4-1	CFD, fluid flow	20.0	1.040	0	0
S4-2	CFD, no fluid flow (same λ_{eff} as S4-3)	20.0	1.173	0.133	12.8
S4-3	FEM, no-division	20.0	1.177	0.137	13.2
S4-4	FEM, 5-mm-rule	20.0	1.128	0.088	8.5
S4-5	FEM, 7-mm-rule	20.0	1.121	0.081	7.8
S4-6	FEM, 5-mm-rule, DetRad		1.054	0.014	1.3
S4-1*[1]	CFD, fluid flow	38.89	1.049	0	0
S4-3*	FEM, no-division	38.89	1.174	0.125	11.9
S4-4*	FEM, 5-mm-rule	38.89	1.129	0.080	7.6
S4-5*	FEM, 7-mm-rule	38.89	1.120	0.071	6.8
S4-6*	FEM, 5-mm-rule, DetRad	38.89	1.059	0.010	1.0

[1)] A consistency check between the FEM and CFD models has already been carried out for this frame (for ΔT = 20 K) and is not repeated here (case S4-2* is therefore omitted).

First, we note that the U-factors of frame S3 are quite high, even higher than for a thin, flat sheet of aluminum which has a U-factor of about 5.9 (mainly because of the insulating value of the film coefficients at the interior end exterior surfaces). The reason for this is that the exposed aluminum surface on the interior of frame S3 is about the twice the projected surface dimension that is used to define the U-factor (dimension b_f, see Figure 3). This means that frame S3 and frames like it exhibit high rates of heat conduction. Invalid cavity correlations are not expected to have much effect on the U-factors of these types of frames.

The table shows that the *CFD, no fluid flow* and *FEM, no-division* cases (cases 2 and 3 for all sections) compare well. The differences are only 0.4, 0.1, 0.2, and 0.3 percent, respectively for frames S1, S2, S3, and S4. This is very good agreement considering that frames S3 and S4 were created using CAD files as underlay, which can introduce variation. The good agreement for frames S1 and S2 was anticipated because these frames were drawn from scratch in both programs, so the physical representations of the frames should be identical. This excellent agreement eliminates conduction and boundary conditions as variables.

Frame S4 was simulated with two types of boundary conditions, BC 1 and BC 2 (see Table 3). These simulations were performed to check whether the U-factors differed when we used a moderate (20 ºC, based on CEN conditions) versus a large (38.89 ºC, based on North American conditions) temperature difference across the frame. Table 5 shows that only minor differences were found among the comparable simulations. Comparing the *CFD, fluid flow* simulations for the two cases, we find U-factors of 1.040 W/m^2K for the case with the moderate temperature difference and 1.049 W/m^2K for the case with the large temperature difference. This difference is reasonable because a larger temperature difference (non-linearly) increases the natural convection inside the air cavities. Because varying the temperature differences across the frame did not appear to significantly change the U-factor results, we include only the simulations with a temperature difference of 20 ºC for frame S4 in the discussion below.

Comparing the *CFD, fluid flow* and *FEM, 5-mm-rule* cases for the four frames, we find the differences to be 5.2, 1.2, 4.0, and 8.5 percent for frames S1 to S4, respectively. Thus, the largest difference between ISO 15099 with rules for how to treat air cavities as solids (including air cavity division rules) and the reference (*CFD, fluid flow* simulations) is 8.5 percent. This result was obtained for the frame with the lowest U-factor. Comparing the *FEM, 5-mm-rule, DetRad* (ISO 15099 convection coefficient and view-factor based radiation) to *CFD, fluid flow* cases, we find the differences to be 1.3, 2.9, 2.1, and 1.3 percent for the respective frames. Thus, increasing the accuracy in the model (by using convection correlation and view-factor radiation rather than convection and radiation correlations) decreases the differences between the results from CFD and FEM simulations for frames S1, S3, and S4. For S2, however, the difference increases slightly (from 1.2 to 2.9)[1]. This indicates that more accurate and detailed radiation models produce better results for irregular cavities.

Table 5 also shows that there are only minor differences between using five or seven mm as the breakpoint to determine when frame cavities should be subdivided for modeling purposes. For most of the frames, a seven-mm rule seems to produce more accurate results than a five-mm rule. A previous study that investigated convection effects in horizontal frame cavities concludes that seven mm is an appropriate break point and should apply to any constrictions in cavity volume, even in triangular cavities (Gustavsen et al. 2005).

Temperature Comparisons

In this section, we compare temperatures for selected simulations and frame locations. Accurate temperature information is important for determining the likelihood of condensation in a window product.

To check the similarities in temperatures among the various simulation techniques, we noted the temperature of two points on each of the four frames. For frames S1, S2, and S4, the selected locations were: the lowest point on the interior face of the frame and the point connecting the frame with the glazing/panel on the interior side. For frame S3, the points connecting the frame with the top and bottom panel on the interior side were selected. The results are shown in Table 5. The same labels as used above for the U-values are used to name the various simulated models. As above, frame S4 was simulated with temperature differences across the frame of 20 ºC and 38.89 ºC; the latter results for frame S4 are marked with an asterisk. We find that agreement among the four models is quite good. The largest difference is a maximum difference of 1.1 °C, for the PVC frame (S1).

[1] On further investigation of this frame (S2-6) it was discovered that the cavity directly underneath the foam glazing insert has the highest cavity heat flow. The aspect ratio of this cavity is 0.6 which can lead to errors in the convective heat transfer in the cavity as described in Gustavsen (2001). The geometry of this cavity may also lead to an error in the assignment of the temperatures in the cavity walls as described in Gustavsen et al. (2005). For this cavity, a sensitivity study showed a 2.6 percent difference in the Nusselt numbers between the FEM detailed radiation and ISO 15099 radiation correlation. (As will be presented in a following section, this same frame was simulated with convection disabled (S2-8 and S2-9 in Table 6) and this shows that the results from the FEM detailed radiation model matches closely with the CFD DTRM radiation simulation.)

Table 5
Temperatures of Two Selected Points on the Simulated Frames

Description	CFD, fluid flow *T* [°C]	FEM, no division *T* [°C]	FEM, 5-mm-rule *T* [°C]	FEM, 5-mm-rule, DetRad *T* [°C]
S1 - Bottom interior point	16.3	16.6	16.7	16.6
S1 – Frame/glazing interior point	4.9	4.1	4.1	3.8
S2 - Bottom interior point	15.2	15.2	15.2	15.1
S2 – Frame/glazing interior point	16.1	16.0	16.0	15.9
S3 – Top of lower glazing/frame interior point	12.9	12.5	12.6	12.7
S3 – Bottom of upper frame/glazing interior point	13.5	13.1	13.1	13.2
S4 - Bottom interior point	17.8	17.9	17.9	17.9
S4 – Frame/glazing interior point	18.1	18.1	18.2	18.2
S4* - Bottom interior point	16.9	16.9	17.0	17.0
S4* – Frame/glazing interior point	17.6	17.3	17.5	17.5

Accuracy of ISO 15099 Radiation Model

Previous studies related to heat transfer in window frames have focused on the accuracy of the convection heat-transfer correlations in ISO 15099 (Gustavsen et al. 2001b, 2005). Above, we assess the accuracy of the combined convection and radiation correlations. In this section, we investigate the accuracy of the radiation correlations prescribed in ISO 15099. For this investigation, the various frames were simulated without the effect of convection. That is, the air was motionless in all cavities (which means that the air cavities had a Nusselt number of 1). The air properties used both for the CFD and FEM simulations are equal to the properties listed in Table 2 for the respective mean temperatures. The following simulations were performed:

- *CFD, no convection, DTRM radiation* denotes the simulations with the CFD code where calculation of fluid flow was disabled. Thus, the air cavities of the window frames contain unmoving air. Radiation is included by the Discrete Transfer Radiation Model (DTRM), which relies on a ray-tracing technique to calculate surface-to-surface radiation.
- *FEM, no convection, DetRad* denotes simulations with the FEM program. The air cavities were divided in a way such that the Nusselt number was 1 for all. A detailed view-factor-based algorithm was used to account for thermal radiation.
- *FEM, no convection, ISORad* represents cases that were simulated with the thermal radiation model prescribed in ISO 15099. The air cavities were treated as for the FEM case above.

The results are displayed in Table 6. In addition to the cases described above, the *CFD, fluid flow* results from Table 5 are listed in Table 6 for easy comparison.

Table 6
Thermal Transmittance (U-factor) for the Various Frames Simulated with no Convection (Unmoving Air) in Air Cavities

Case	Description	ΔT [K]	U_f [W/m^{2}K]	ΔU ref. case 7 [W/m^{2}K]	% exceeding case 7
S1-1	CFD, fluid flow	38.89	1.583	-	-
S1-7	CFD, no convection, DTRM radiation	38.89	1.523	0	0
S1-8	FEM, no convection, DetRad	38.89	1.519	-0.004	-0.25
S1-9	FEM, no convection, ISORad	38.89	1.425	-0.098	-6.43
S2-1	CFD, fluid flow	20.0	2.189	-	-
S2-7	CFD, no convection, DTRM radiation	20.0	1.828	0	0
S2-8	FEM, no convection, DetRad	20.0	1.832	0.004	0.20
S2-9	FEM, no convection, ISORad	20.0	1.814	-0.014	-0.76
S3-1	CFD, fluid flow	20.0	7.555	-	-
S3-7	CFD, no convection, DTRM radiation	20.0	7.530	0	0
S3-8	FEM, no convection, DetRad	20.0	7.580	0.049	0.65
S3-9	FEM, no convection, ISORad	20.0	7.957	0.426	5.66
S4-1	CFD, fluid flow	20.0	1.040	0	0
S4-7	CFD, no convection, DTRM radiation	20.0	0.984	0	0
S4-8	FEM, no convection, DetRad	20.0	0.999	0.015	1.52
S4-9	FEM, no convection, ISORad	20.0	0.904	-0.080	-8.13

The table shows that there is very good agreement between the CFD code results using the DTRM radiation model and the FEM program using the view-factor model. The ISO 15099 radiation model does not compare that well with the other results, except for frame S2, which has mostly rectangular cavities; this is the type of frame for which the ISO 15099 radiation model was developed. There are two possible reasons for the poor ISO 15099 results for the other window frames: 1) this radiation correlation is not suited for irregular shaped cavities; or 2) the method used for converting irregular frame cavities to rectangular frame cavities and the corresponding assignment of surface temperatures to the walls of the rectangular cavity does not work.

THE FUTURE OF WINDOW AND FRAME U-FACTOR CALCULATIONS

As computer performance has improved, the use of more sophisticated computer tools like Computational Fluid Dynamics (CFD) programs has grown, making it possible to simulate in detail various building physical problems like natural convection in air cavities of building structures, convection and moisture transfer in porous materials, driving rain, and snowdrifts around buildings. CFD programs typically include detailed radiation heat-transfer models (ray-tracing or view-factor based). This paper investigates whether CFD tools are preferable to traditional conduction heat-transfer tools for performing heat-flow simulations in windows. The answer to this question depends on many variables; we offer some considerations to address in formulating an answer.

Important topics to consider are the accuracy of currently used procedures and international standards as well as the user threshold/friendliness of CFD programs compared to ease of use of current programs. This paper addresses the first issue: the accuracy of current procedures for calculating horizontal frame U-factors. Based on our study of a small number of window frames, this paper concludes that the deviations between the current calculation standards (ISO 15099) and the CFD simulations are not large; however, the differences increase with decreasing frame U-value. Thus, as the insulating value of a frame gets better, more accurate models or CFD tools seem to be required. When CFD codes are used, it is not necessary to treat air cavities as solids and use convection and radiation cavity models.

Any decision about whether current cavity models are accurate enough will also need to take into account the differences among models in treating vertical frame sections (only horizontal sections were studied in this paper). Vertical frame studies require three-dimensional CFD simulations to capture the natural convection effects in the air cavities. Larger discrepancies among the models may be found in studies of vertical frame sections.

The necessity of simulating three-dimensional frame jambs to capture the natural convection effect in a CFD program also influences the user threshold. In a conduction simulation code, both horizontal and vertical frame members are simulated in two dimensions but with separate convection correlations for each case. The necessary three-dimensional CFD simulations for jamb sections will become easier to perform as the pre-processing tools for CFD codes get better. Today it is possible to extrude a two-dimensional representation of a frame to get a three-dimensional frame. Still, there is a need for more insight into the physics of the problem when CFD codes are used. The user needs to know whether the flow is laminar or turbulent, and, if there is turbulent flow, which model is the best. The choice of discretization schemes may also influence the solution. There may also be difficulties with making some problems converge toward a stationary solution (because, for example, a stationary solution may not be possible). This may be true for tall vertical air cavities found in glazing, and in air cavities where the heat flow direction is vertical. Thus, smarter CFD codes are needed if we are to achieve the user friendliness and relatively low threshold of the current conduction codes. For specific problems such as window frames, it should be possible to develop these codes.

To some extent the movement from traditional conduction codes to CFD tools has already begun, mostly for simpler geometries, projects seeking new correlations that can be used in simpler conduction programs, and projects in which researchers have time and resources to explore the possibilities of CFD codes. Because results from CFD tools give more details about the physical processes taking place than do results from conduction tools, the use of CFD tools may lead to better window design (for example, see the stream contour plots for two of the frames investigated in this paper, in Figure 4). Nonetheless, practitioners and consultants generally use conduction tools, probably because these tools require less setup and simulation time than CFD codes. As window frames improve and the need for more accurate models grows, CFD codes will likely be used increasingly.

CONCLUSIONS

This paper describes conduction and Computational Fluid Dynamics (CFD) simulations that were carried out to study heat transfer rates for four horizontal window frames with complex internal cavities. Vertical jamb sections were not studied in this paper because they require three-dimensional simulations; these sections should be the subject of future research. The simulations show that traditional software programs, simulating only conduction and using the equivalent conductivities prescribed in ISO 15099 to model radiation and natural convection in the air cavities, give results that compare reasonably with CFD simulations. The results from the two types of models vary most for more insulating frames (i.e., frames with a low U-factor). Some of the results suggest that the natural convection and radiation correlations prescribed in ISO 15099 should be improved. Specifically, the simulation results show that utilization of a ray-tracing or view-factor-based radiation model instead of the ISO 15099 radiation model to calculate radiation heat transfer through the air cavities substantially increases the accuracy of these results. In fact, using a view-factor based radiation model may be more important for increasing the accuracy of the results (for horizontal profiles) than from using a CFD model.

This paper shows that CFD simulations of heat transfer in window frames give valuable information about how air flows in window frame air cavities that can help engineers design improved window frames. As CFD codes become “smarter” with respect to automatic selection of models and discretization schemes, CFD codes will likely replace traditional conduction models. Currently, however, the required simulation time appears to be too long and the user threshold for CFD appears to be too high for CFD tools to be used in day-to-day simulations.

ACKNOWLEDGMENTS

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FIGURE CAPTION SHEET

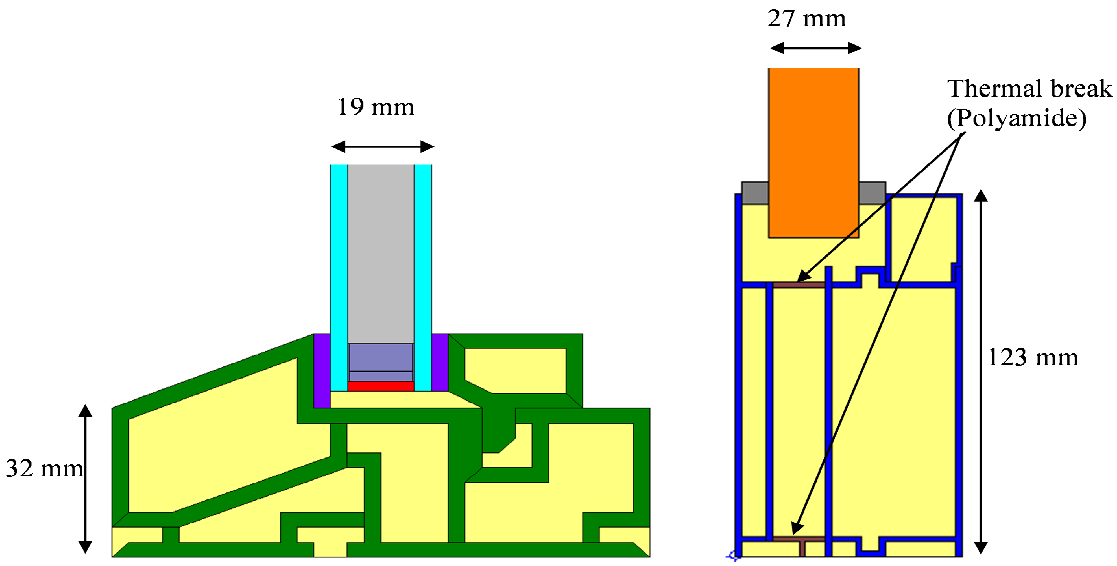

Figure 1. Cross section of window frames; To the left, a PVC window frame (S1) and to the right, an aluminum window frame (S2)

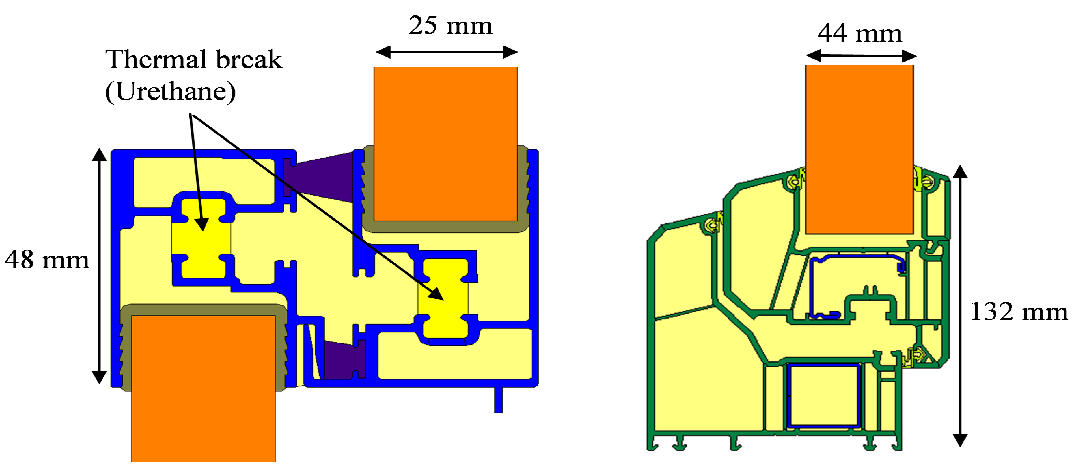

Figure 2. Cross section of aluminum frame, S3 (left) and PVC frame, S4 (right)

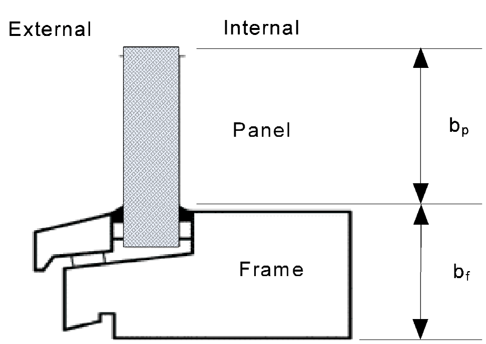

Figure 3. Definition of frame and insert panel length

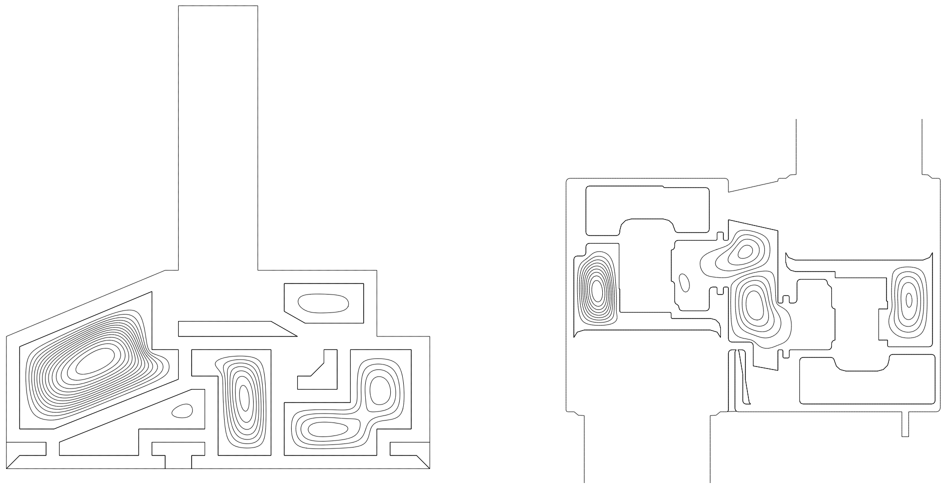

Figure 4. Example of velocity contours for frame S1 (left) and frame S3 (right)