

A Simplified Numerical Method for Assessing the Condensation Resistance of Windows

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ABSTRACT

Methods have been established for calculating heat transfer in windows whereby a one-dimensional analysis is used for the center-glass area and a two-dimensional numerical calculation is used to model conduction in the edge-glass and frame. The effect of fill gas motion cannot be seen because the fill gas is treated as an opaque solid. The fill gas cools the bottom edge of the indoor glazing, so the predicted minimum indoor glazing temperature will consistently be too high. A detailed two-dimensional simulation of the entire window can be used but requires substantial effort. A simplified method has been devised. The flow pattern of the fill gas in the entire cavity is found using a two-dimensional computational fluid dynamics (CFD) analysis of natural convection where the wall temperatures are established using the one-dimensional center-glass model. Velocities in the edge-glass and the temperature of the fill gas entering the edge-glass section are noted. These data are used in a two-dimensional edge-glass/frame analysis. This method is not complicated and results are obtained quickly. Temperature profiles agree with experimental data and detailed numerical simulation. Sample results in this paper demonstrate the effect of fill gas motion, edge-seal conductance, a low-emissivity (low-e) coating, and argon fill gas on minimum indoor surface temperature.

INTRODUCTION

Most modern windows contain a sealed, insulated glazing unit (IGU). The IGU consists of glazing layers (i.e., glazings) that are separated by an edge-seal. The edge-seal isolates the space between the glazings, thereby reducing the number of surfaces to be cleaned and creating an insulating cavity suitable for low-emissivity (low-e) coatings and/or low conductivity fill gases.

The edge-seal creates a thermal bridge at the perimeter of the IGU making this an area of increased thermal stress, high energy loss, and the site of condensation in winter. The conductive nature of the edge-seal has been accentuated by the remarkable reductions in the center-glass U-factor made available over the last decade. Until recently, few options were available to increase the thermal resistance of the edge-seal. A variety of edge-seals with significantly increased thermal resistance are now available, but none offer more thermal resistance than the center-glass portion of an IGU. The thermal resistance of the center-glass cavity (low-e, 1/2 in. argon, $R \approx 3.5 \text{ h-ft}^2 \text{ }^\circ\text{F/BTU}$) can only be approached by the best rigid insulating foam ($R \approx 2.5$ per 1/2 in.) (Wright and Sullivan 1989b; Wright et al. 1994).

The flow of fill gas within an IGU cavity contributes to the condensation problem at the bottom edge of the indoor glazing. In winter, fill gas flows upward near the indoor glazing and downward near the outdoor glazing. The descending gas becomes progressively colder. At the bottom of the cavity, this cold fill gas turns and approaches the indoor glazing where it starts its ascent. Thus, the bottom edge of the indoor glazing is cooled by the coldest fill gas.

Experimental results and detailed numerical simulation (Wright 1990; Wright and Sullivan 1995; deAbreu et al. 1996; Sullivan et al. 1996; Curcija and Goss 1994) support the idea that fill gas motion contributes to the bottom-edge condensation problem. Clearly, any model attempting to quantify local heat transfer rates in these regions or any model intended to determine the temperature distribution across the face of the glazing must account for both the natural convection of the fill gas and conduction within the edge-seal, glass, and frame components.

The methods currently in widespread use for estimating edge-glass heat loss (Frank 1987; ASHRAE 1997; EEL

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1995¹) do not account for fill gas convection. Therefore, they cannot be used to determine the minimum indoor pane temperature needed to evaluate the condensation resistance of a window. Local variations in surface temperature can be found using very detailed numerical methods (e.g., Wright and Sullivan 1995; Curcija and Goss 1994; deAbreu et al. 1996), but this approach is expensive in terms of operator time, CPU time, and required hardware.

The method presented here provides a means by which a numerical, conduction-only, two-dimensional frame and edge-glass analysis can be extended to account for fill gas motion. This extension is not complicated, and execution is no slower. Minimum indoor glazing temperatures can be predicted with no additional effort and in a reasonable amount of time using a desktop computer.

NUMERICAL ANALYSIS OF NATURAL CONVECTION

The control volume arrangement shown in Figure 1 is used to set up an analysis on a uniform staggered grid. An energy balance applied to this control volume, in terms of the temperatures at the four neighboring volumes and in the absence of energy sources (e.g., solar radiation), gives an expression for the temperature T_p .

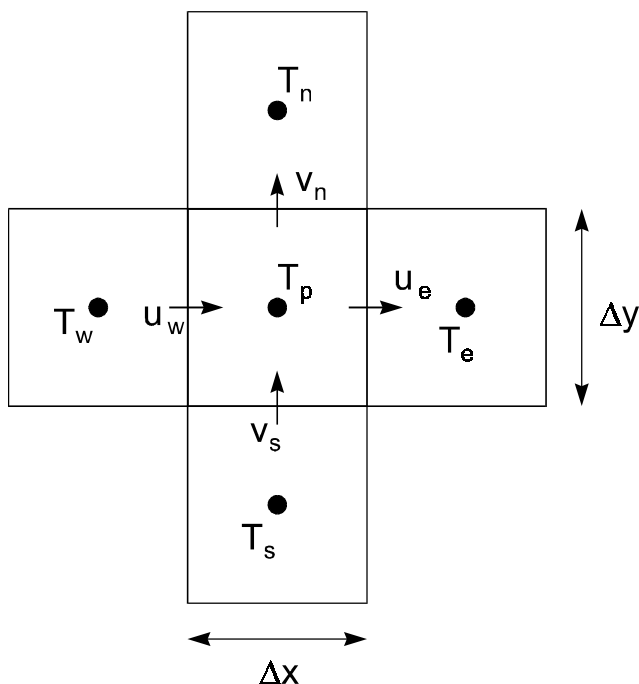


Figure 1 Control volume arrangement used for energy balance.

1. Earlier versions of the FRAME program could not account for fill gas motion. The most recent version of FRAME (EEL 1995) includes the model described here. It can be accessed by running FRAME 4.0 in "convection" mode.

$$a_p T_p = a_n T_n + a_s T_s + a_e T_e + a_w T_w \quad (1)$$

The coefficients (a_p, a_w , etc.) can be determined as a function of material properties, fluid velocities, control volume geometry, and the assumed temperature profile between the nodes. Many sets of these coefficients must be generated—one set for each control volume in the problem domain. Almost all of the CPU time needed to arrive at a solution is consumed in the solution of the coefficient matrices. Very little time is used to generate the coefficients.

Equation 1 shows that at any point, the temperature is determined as a weighted average of the temperatures at surrounding locations. In order to examine the effect of fluid motion, consider the coefficient associated with the west side of the control volume, a_w .

$$a_w = k \frac{\Delta y}{\Delta x} + \frac{1}{2} \rho \cdot u_w \cdot \Delta y \cdot C_p \quad (\text{central difference}) \quad (2)$$

where k , ρ , and C_p are the conductivity, density, and specific heat of the fluid, respectively. Similar expressions are used for a_n , a_s , and a_e . a_p is equal to the sum of the other four coefficients. See Patankar (1980) for more detail.

Equation 2 provides some useful information. If a conduction problem were formulated (i.e., all velocity components $u_w = u_e = v_n = v_s = 0$) using a square grid (i.e., $\Delta x = \Delta y$), T_p would be affected equally by all four neighboring temperatures. In this case, all four coefficients would be equal to $a_p/4$. However, if u_w, u_e, v_n , and v_s are positive, as shown in Figure 1, then a_w and a_s will be larger and a_e and a_n will be smaller. This makes sense because T_p will be strongly affected by the upstream temperatures T_w and T_s and only weakly by the temperatures at downstream locations.

The analysis of an entire window entails a variety of complications. In the glazing cavity, where convection takes place, four equations similar to Equation 1, corresponding to energy, x-momentum, y-momentum, and mass balances, must be solved simultaneously for the entire problem domain. In the solid sections, only conduction occurs and only the energy balance needs to be applied. The solution yields temperatures, two sets of velocity components, and the pressure field. Special attention must be taken to correctly account for changes in property values at surfaces where materials differ and at gas/solid interfaces. It is also necessary to include a model for radiant heat transfer in the window cavities.

A SIMPLIFIED APPROACH

Recognizing that the detailed analysis of a full window is a major undertaking, it is not surprising that conduction-only models (CSA 1993; NFRC 1991) are widely used to quantify frame and edge-glass heat transfer. Under this approach, the frame and edge-glass are isolated by assuming that the frame/wall and edge-glass/center-glass (2.5 in. from the sight line) interfaces are adiabatic. The complexity of dealing with natural convection is avoided by treating the fill gas as an opaque solid that is assigned an "effective conductivity." This effective conductivity is quantified by a one-dimensional center-

lass heat transfer solution that can be provided by software such as VISION (Wright and Sullivan 1992) or WINDOW (Finlayson et al. 1993). It has been demonstrated that this two-part analysis gives reliable estimates of overall window heat transfer.

A sample isotherm plot, generated by the FRAME program, is shown in Figure 2. It can be seen, by the near symmetry of the temperature distribution in the bottom of the glazing cavity, that the effect of fill gas motion has not been included in the analysis. A conduction analysis such as this can be readily extended to account for fill gas motion. It was shown in the previous section that a nonzero fluid velocity simply adds an extra term to the calculation of the various coefficients. The mechanics of solving for the temperature field remain unchanged, and no extra computational effort is required as long as the fill gas velocity field is already known.

A new capability has been included in the most recent version of the VISION software, VISION4, that allows it to estimate the fill gas velocity field. When a given glazing system is analyzed, the procedure starts in the conventional way by generating the one-dimensional center-glass heat transfer solution. Next, the known pane spacing, fill gas properties, and glazing surface temperatures are used to perform a two-dimensional numerical simulation of fill gas convection in the idealized case of a tall, vertical cavity with isothermal side walls and adiabatic ends (Wright and Sullivan 1994).

The wall temperatures of this idealized situation only differ notably from the real situation in the edge-glass section, which constitutes a small portion of the cavity. It is assumed that the velocity field is determined primarily by the balance of buoyant and viscous forces that exists through the center-

glass region and that the difference between this velocity field and the actual velocity field generated with the true wall temperatures can be neglected. This assumption can also be viewed in terms of the forces that act on the gas in the edge-glass section. Although it is understood that fill gas flow is driven by buoyancy, in general, it must be recognized that the flow in the edge-glass section will be strongly influenced by the momentum of the fill gas arriving from the center-glass section, and that inaccuracy in the edge-glass wall temperature will have little effect on the flow field. In other words, the edge-glass fill gas flow can be treated more like a forced convection problem than a natural convection problem, and simulation with isothermal walls will yield a good approximation of the edge-glass flow field.

Once VISION4 has determined a solution for the entire cavity, the velocity field for the edge-glass section of the cavity is stored on disk, along with the temperature profile across the edge-glass/center-glass interface and the properties of the fill gas. The edge-glass/center-glass temperature profile is needed because it is not appropriate to specify an adiabatic surface at this location when flow exists at the boundary. The temperature of the gas flowing into the edge-glass section must be known.

This entire process is repeated, once for each cavity in the glazing system, so that each disk file will contain data pertaining to one or more glazing cavities.

The most recent version of the FRAME program, FRAME 4.0, is capable of reading the VISION4 edge-glass velocity files. FRAME 4.0 can then use this information to generate a frame and edge-glass heat transfer solution that includes the effect of fill gas convection. Figure 3 shows an

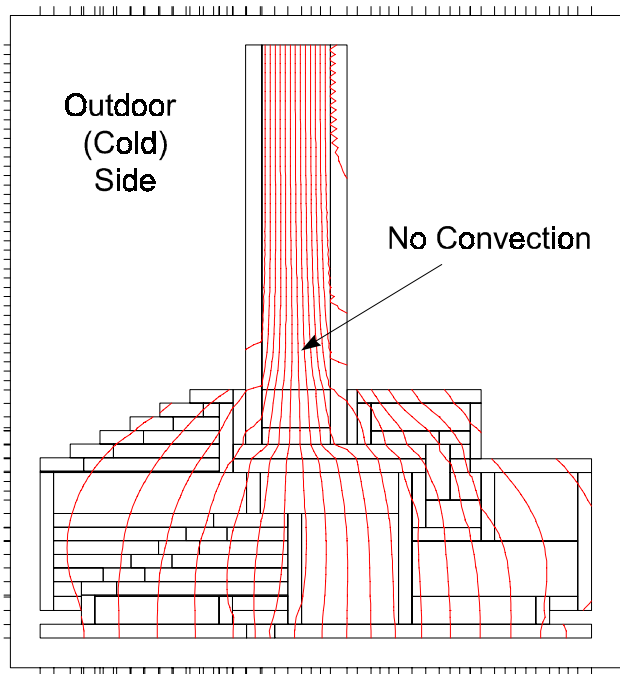


Figure 2 FRAME isotherm plot (conduction only).

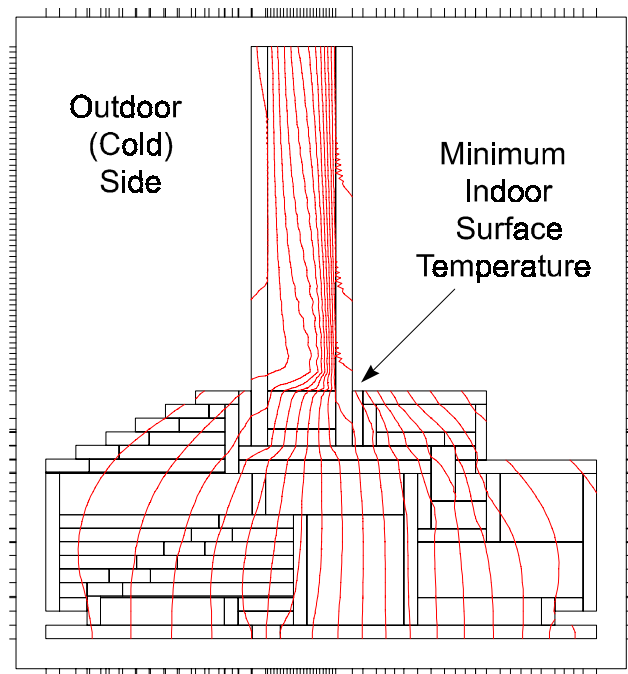


Figure 3 FRAME isotherm plot with fill gas convection.

isotherm output plot produced by FRAME 4.0. The only difference between this plot and the plot shown in Figure 2 is the effect of fill gas convection. This is readily evident because the temperature field in the bottom of the glazing cavity has been skewed toward the warm indoor glazing.

Note that the temperature field of the fill gas (Figure 3), as determined by FRAME 4.0, includes the effect of the more realistic, nonuniform wall (i.e., glazing and seal surface) temperatures. The temperature field generated by VISION4 is not stored and is not used in the FRAME 4.0 calculation. Therefore, small inaccuracies in the form of the velocity field generated by VISION4 can be expected to be of secondary importance.

SIMPLIFICATIONS

The implementation of the two-dimensional computational fluid dynamics (CFD) code in VISION4 includes three simplifications.

Aspect Ratio

The coefficient for convective heat transfer across a vertical, gas-filled, rectangular enclosure is known to be a function of the height-to-width aspect ratio, A , and the Rayleigh number, Ra (Wright and Sullivan 1989a).

$$Ra = \frac{\rho^2 l^3 g C_p \Delta T}{\mu k T_m} \quad (3)$$

where

- l = cavity width (pane spacing),
- ΔT = temperature difference between the vertical cavity walls,
- ρ , C_p , and μ = fill gas density, specific heat, and viscosity,
- T_m = mean temperature (absolute) of the fill gas, and
- g = acceleration due to gravity.

Accordingly, the velocity and temperature fields of the fill gas are also determined by Ra and A . A series of CFD runs was completed for the range of Ra of interest for IGU applications, $Ra \leq 12,000$, and for $10 \leq A \leq 100$. It was found that the flow/temperature fields were not affected by A for $A \geq 30$. Figure 4 illustrates this point. Figure 4 shows a plot of the velocity (vertical component, v) and temperature profiles at the center-glass/edge-glass interface. The temperature data have been converted to a nondimensional form using T_{WW} and T_{WE} , the west and east wall temperatures. The velocity has been shown as a fraction of the maximum vertical velocity component, v_{max} . Both are shown as a function of x/l , the fraction of the distance across the cavity from the west wall. Data are plotted at $Ra = 10,000$ for two different aspect ratios: $A = 30$ and $A = 100$. The $A = 30$ results are shown as data points that fall almost directly on the line that represents the $A = 100$ data.

VISION4 takes advantage of this result to save computer memory and execution time. All VISION4 CFD runs use $A = 30$, regardless of the specified cavity height.

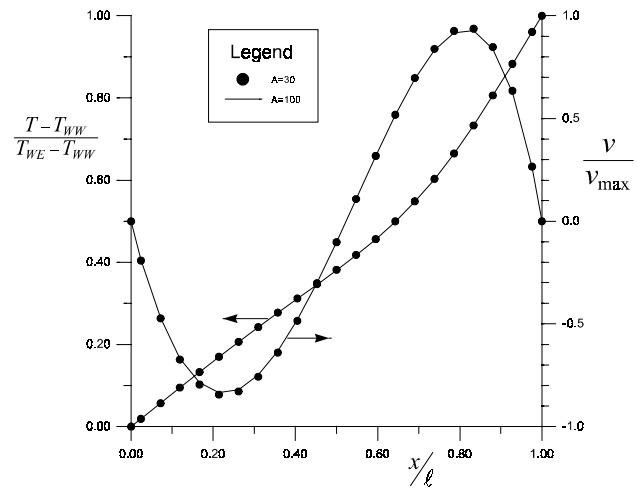


Figure 4 Comparison of velocity and temperature profiles at the center-glass/edge-glass interface for $A=30$ and $A=100$ ($Ra=10,000$).

Laminar Flow

The CFD model in VISION4 is based on the assumption that the fill gas flow is laminar and steady. This is true over the full range of Ra of interest in IGU analysis: typically $Ra < 10,000$. At higher values of Ra , the flow can become unsteady and eventually turbulent (Wright and Sullivan 1989a). This physical instability is also seen in the VISION4 CFD analysis; convergence slows progressively for Ra from 10,000 to 20,000 and simulations with $Ra > 20,000$ may result in floating point errors. This limitation does not detract from the value of the procedure because glazing systems that are associated with the potential for condensation problems will be double-glazed sealed units with a near-optimum pane spacing corresponding to Rayleigh numbers well below 10,000, regardless of fill gas type.

Secondary Cells

It is known that the fill gas flow in tall cavities will include a stationary cats-eye pattern of corotating secondary cells if the Rayleigh number is greater than about 5,700 (Bergholz 1978; Lee and Korpela 1983; Wright 1990; Wright and Sullivan 1989a, 1994, 1995; Curcija and Goss 1994). These cells are located within the core of the primary flow and do not extend to the edge-glass section of the glazing cavity.

Secondary cells are not generated by the VISION4 CFD procedure. There are three reasons for this. First, it is possible, but not practical, for VISION4 to model window cavity flows with secondary cells. The added computational effort increases the run time appreciably. Second, the presence of secondary cells in the center-glass section of the cavity creates a homogenizing action that increases the temperature of the fill gas entering the bottom edge-glass section. The increased temperature of the fill gas in this location will increase the minimum indoor pane temperature. Therefore, by choosing to

omit secondary cells, the resulting estimate of condensation resistance will correspond to a worst case situation. Third, even though the structure of the cells is not included in the fill gas flow, their effect is included because the wall temperatures are determined on the basis of a correlation for convective heat transfer in the glazing cavity that is based on heat transfer rates measured in the presence of secondary cells.

COMPARISON WITH MEASUREMENT AND DETAILED SIMULATION

Three studies provide comparisons between the results of the simplified method and fully detailed two-dimensional calculations and/or measured surface temperature profiles.

McGowan (1995) showed that thermocouple measurements of glass surface temperature could be predicted to within 1°C (1.8°F) in cases where the glass temperature was

not strongly influenced by a metal frame. He concluded that the simplified simulation gives reasonably accurate results.

deAbreu et al. (1996) compared the simplified method with a full two-dimensional numerical simulation called BRAVO by examining the vertical indoor (i.e., warm side) center-line surface temperature profiles of various IGUs mounted in a mask wall. Different edge-seals, pane spacings, double vs. triple glazing, and the presence of low-e coatings were considered. The plots shown in Figures 5 and 6, reproduced from deAbreu et al. (1996), pertain to the conventional double-glazed configuration (12.7 mm pane spacing, air fill gas). In both cases, the horizontal axis shows surface temperature and the vertical axis shows vertical distance from the bottom of the IGU. Figure 5 shows the effect of using an insulating foam spacer instead of an aluminum spacer bar. The edge-glass temperature is appreciably lower when an

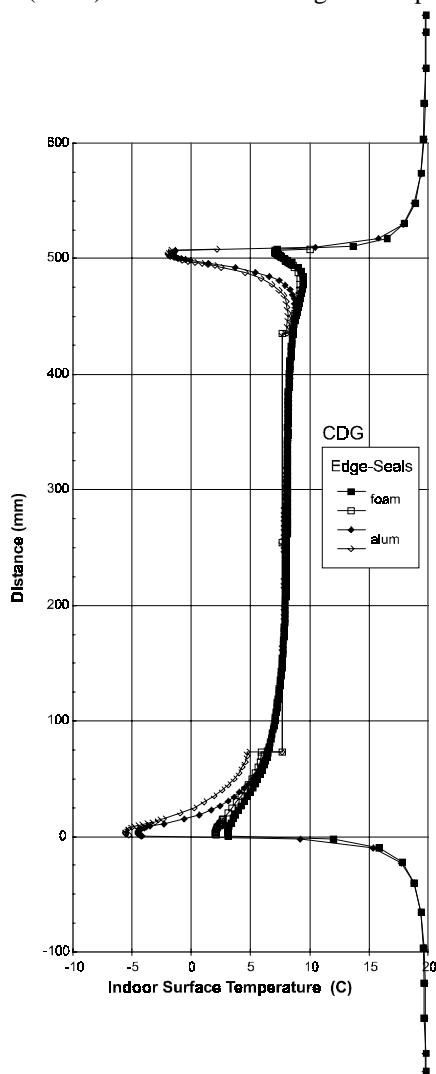


Figure 5 Effect of spacer material, foam vs. metal. BRAVO—closed symbols, VISION4/FROME 4.0—open symbols (reproduced from deAbreu et al. [1996]; pane spacing = 12.7 mm, fill gas = air.

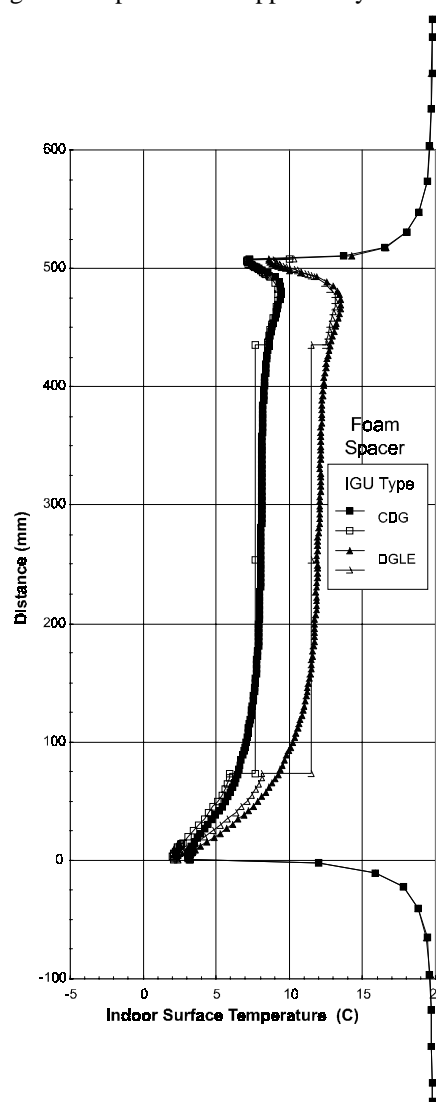


Figure 6 Effect of low-e coating. BRAVO—closed symbols, VISION4/FROME 4.0—open symbols (reproduced from deAbreu et al. [1996]; pane spacing = 12.7 mm, fill gas = air.

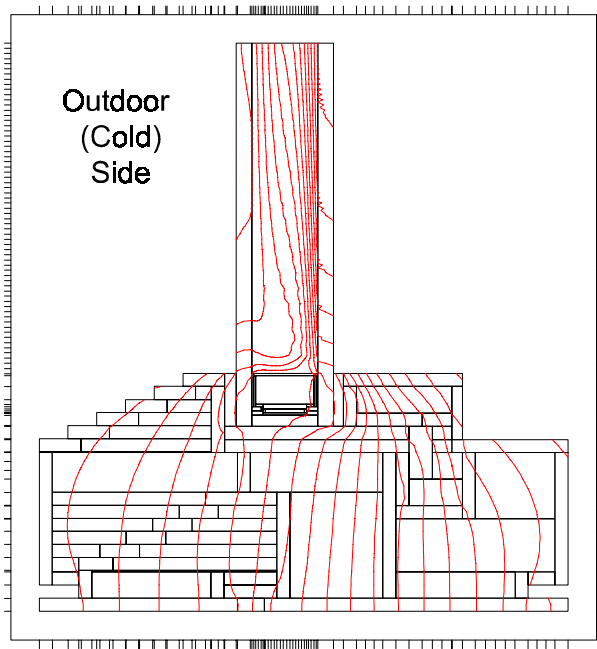


Figure 7 Double-glazed, low-e ($\epsilon=0.15$), 12.7 mm argon, vinyl frame, aluminum spacer (dual seal with butyl).

aluminum spacer is used. Figure 6 shows the effect of using a low-e coating. The low-e coating increases the center-glass temperature but has little influence on the minimum temperature at the edge.

In Figures 5 and 6, it is easy to pick out the results of the simplified method because of the discontinuity between the one-dimensional center-glass result and the two-dimensional edge-glass profile. These curves are plotted this way only for the purpose of showing that the simplified method has been used. In the regions of interest near the top and bottom edges of the IGUs, it can be seen that the simplified method closely matches the BRAVO results both quantitatively and qualitatively. It is shown that the fill gas motion cools the bottom but

not the top of the indoor glazing. The effect of conduction through the edge-seal, cooling both edges, can also be seen in Figures 5 and 6. deAbreu et al. (1996) concluded that the simplified method is a valuable tool for estimating indoor surface temperatures near the bottom edge of an IGU where condensation problems are most severe and that the minimum indoor glazing surface temperatures predicted by BRAVO could be reproduced to within 1°C (1.8°F).

The work of deAbreu et al. (1996) was performed as part of a larger study where two laboratories measured surface temperature profiles of similar IGUs using thermographic cameras (Griffith et al. 1996; Elmahdy 1996), and another simulation laboratory produced results numerically (Zhao et al. 1996). Sullivan et al. (1996) provide a comparison of the complete set of results and conclude that good agreement has been demonstrated between thermographic measurement and simulation results. The results of the simplified model shown in Figure 5 can be seen in Figures 8 and 9 of Sullivan et al. (1996), where favorable agreement with measured temperature profiles is also demonstrated.

SAMPLE RESULTS

VISION4/FAME 4.0 simulations were completed for six different IGUs mounted vertically in the same vinyl frame and exposed to the ASHRAE winter design condition (outdoor temperature = -17.8°C [0°F], indoor temperature = 21.1°C [70°F], wind speed = 6.8 m/s [15 mph], 100% cloud cover, and zero insolation). The IGUs were all double glazed with clear glass (nominal thickness = 3 mm [1/8 in.]) and 12.7 mm (1/2 in.) pane spacing. Three glazing system designs, conventional double-glazed (CDG), double-glazed low-e (DGLE), and double-glazed low-e with argon (DGLEA), were used in combination with highly conductive edge-seals (dual-seal aluminum/butyl) and insulating edge-seals (foam/butyl).

Figures 2 and 3 show frame/edge-glass cross sections with isotherms plotted at increments of 2°C (3.6°F) for the DGLEA unit with foam edge-seals. Figure 7 shows the corre-

TABLE 1
Minimum Indoor Glass Temperatures and Allowable Relative Humidity

	Aluminum Edge-Seal			Foam Edge-Seal		
	Minimum Temperature °C (°F)		Allowable Relative Humidity	Minimum Temperature °C (°F)		Allowable Relative Humidity
	No Fill Gas Motion	Fill Gas Motion		No Fill Gas Motion	Fill Gas Motion	
CDG	-1.2 (29.8)	-3.5* (25.7)	20%	4.7 (40.5)	1.5 (34.7)	27%
DGLE	-0.4 (31.3)	-3.2* (26.2)	20%	6.3 (43.3)	2.2 (36.0)	29%
DGLEA	-0.2 (31.6)	-2.5* (27.5)	21%	6.9 (44.4)	3.3 (37.9)	31%

* Frost point temperatures were estimated by extending the saturation vapor pressure curve for water below the freezing temperature. See page 119 of Iribarne and Godson (1981).

sponding plot for the DGLEA unit with aluminum edge-seals.

Minimum indoor glazing temperatures are listed in Table 1. Results are shown for simulations with fill gas motion and for simulations without fill gas motion. The values listed in Table 1 were sampled on the surface of the glass 0.001 mm (4×10^{-5} in.) above the indoor sight line.

Several interesting observations can be made on the basis of Table 1.

1. The calculated minimum indoor glass temperature is lower when the effect of fill gas motion is included. Fill gas motion lowers the minimum temperature by about 2.5°C (4.5°F) when aluminum edge-seals are used and by about 4°C (7.2°F) when foam edge-seals are used.
2. The use of foam edge-seals instead of aluminum edge-seals increases the minimum glass surface temperature by about 5°C to 6°C (9°F to 10.8°F), with greater benefit evident in IGUs with higher thermal resistance.
3. The use of a low-e coating increases the minimum indoor surface temperature by only a small amount. This increase is less than 1/2°C (0.9°F) in IGUs with aluminum edge-seals, and less than 1°C (1.8°F) when foam edge-seals are used.
4. The use of argon fill gas increases the minimum indoor surface temperature by a small amount, but slightly more than the use of low-e. The increase in minimum surface temperature caused by the use of argon is less than 1°C (1.8°F) in IGUs with aluminum edge-seals and just more than 1°C (1.8°F) when foam edge-seals are used.
5. Foam edge-seals allow for relative humidity (based on the minimum surface temperature and the given environment) in the 25% to 30% range, but aluminum edge-seals offer a lower allowable relative humidity of about 20%. In fact, the minimum surface temperatures predicted for IGUs with aluminum edge-seals were all below the freezing point, suggesting that frost or ice can be expected.

CONCLUSIONS

A method has been presented whereby a conduction-based two-dimensional frame and edge-glass numerical analysis can be extended to account for convective fill gas motion. The resulting glazing temperature profiles are useful for stress analysis and for evaluating condensation resistance. The method requires one initial CFD calculation to determine the fill gas flow pattern but adds very little complexity to the two-dimensional frame and edge-glass analysis. The frame and edge-glass calculation runs no more slowly than it would have in dealing with a conduction-only problem, and it can still be run on a desktop computer.

Results from initial test runs using this method as implemented in VISION4 and FRAME 4.0 are in good agreement with hot-box thermocouple results, detailed two-dimensional simulations, and temperature profiles measured using thermography.

Simulation results for various double-glazed IGUs in a vinyl frame indicate that edge-seal conductance and fill gas motion strongly influence the minimum indoor glass surface temperature, while the presence of a low-e coating or argon fill gas have a much weaker influence.

ACKNOWLEDGMENTS

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