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Measurements of Window Air Leakage at Cold Temperatures and Impact on Annual Energy Performance of a House

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ABSTRACT

This study was initiated to determine the extent of cold temperature air leakage from operable windows available in today's marketplace and the impact that this has on the energy consumption of a house. During the heating season, changes in the window's leakage characteristics, as a result of thermal and pressure effects, were to be included.

At two laboratories, air-leakage tests down to −30°C were performed on 35 windows, enough to reach some general conclusions about performance.

The majority of windows met or exceeded the highest levels of air leakage performance of Canadian window standards at normal temperatures, and many did very well even at the lowest temperatures tested. Increased leakage at cold temperatures was attributed to design more than frame material; vertical sliders (including tilt-in) exhibited the worst performance under all conditions.

Data were used to quantify the impact on the annual energy performance of a house. The Canadian Standards Association's (CSA) window performance indicator for houses, the CSA Energy Rating (ER) number (CSA 1993), was evaluated for the case of variable air infiltration with outdoor climate. Results were encouraging; for the majority of windows the impact on the rating was negligible, as long as leakage was not excessive at normal temperatures. For others, lessons were learned about materials and designs that could be used to improve product performance at extreme temperatures.

INTRODUCTION

Excessive window air leakage during the heating season can result in three undesirable consequences for a homeowner: reduced comfort from cold drafts, increased demand on the house heating system, which may not be capable of meeting load requirements, and increased energy consumption. This study attempts to characterize real-world leakage for a range of production windows and quantify the influence on the energy consumption of a house. It is presumed that proper installation practice for both operable and fixed windows will eliminate other site-specific leakage associated with windows.

The impact of windows on house energy performance can be shown to result from three window energy fluxes: solar energy entering interior spaces, thermal energy transmitted through the window to or from the interior, and mass transfer of air to or from the inside through (or past) window parts. Although the latter component is usually considerably less than the first two, for well constructed and installed windows, it has not been easy to estimate, and its contribution in severe conditions, such as in cold climates, needed to be evaluated.

Annual energy performance estimates for fenestration are part of Canadian Standards Association (CSA) standards in Canada and National Fenestration Rating Council (NFRC) standards in the U.S. These in turn are referenced by building energy codes to set minimum levels of energy performance (Henry 1995). The standards attempt to account for infiltration effects through all weather conditions experienced during the heating season; however, window leakage data generally have been available only for specific test conditions, usually 20°C and one specific pressure difference. Similarly, energy simulation programs, whether performing hourly calculations or applying a bin approach, simplify window air leakage calculations, often only applying wind and stack effects to estimated overall house leakage.

Some manufacturers in Canada claimed that their products were not fairly rated by the CSA Energy Rating (ER) number since their products maintained low air leakage under winter conditions while competitors' products distorted and

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leaked excessively. Testing was needed to see if these claims were justified and if there was a significant impact on the established ER numbers.

THE TESTING PROGRAMS

To date, the majority of window air-leakage data has been collected in tests following ASTM E283, which specifies a test method for ideal conditions, for instance, 20°C on both sides of the specimen. Results have been shown to be quite reproducible and have been useful to compare products, albeit under ambient conditions for which air leakage usually is not of concern. Since it has been well known that temperature gradients can cause shrinkage and distortion of window components, leakage characteristics under more extreme summer and winter conditions would be more useful.

In 1991, a new standard, ASTM E1424-91, was put forward to determine rate of air leakage through building envelope components as a function of temperature and pressure differentials. Calibration requirements for test equipment, however, are still under development. The only previous reported work on window air leakage at any temperature other than standard conditions was that carried out by Kehrli in 1989. He tested a few windows at low temperatures following a cycle of both low and elevated temperatures. Results suggested some very real air leakage problems with the few windows tested but failed to identify causes or quantify energy impacts.

As support to CSA standards development, the government of Canada commissioned two separate studies, one at a commercial testing laboratory in Montreal and the other at the National Research Council (NRC), to look into changes in window air leakage as a result of both temperature and pressure differentials. These projects were initiated to test representative windows from the marketplace to determine the extent of the problems and to make recommendations with respect to the ASTM interim standard for testing under such conditions. If warranted, additional test requirements could be added to CSA standards to better account for air leakage in annual window energy performance estimates.

The test method evaluated and used (in a modified form) in both cases was ASTM E1424-91. Changes to the procedure were validated by means of inter-laboratory comparisons with a few selected windows.

Windows Tested

In all, five windows were tested at NRC and 30 at the commercial testing laboratory. These were representative of the broad range of operable window types sold in Canada: casement, vertical sliding, horizontal sliding, tilt-turn, and awning. They were off-the-shelf units obtained from local suppliers. Frames and sashes were constructed of aluminum, vinyl, fiberglass, wood, and wood with vinyl cladding. A varied assortment of hardware (individual locks, multi-point locks, snubbers, etc.) and weather stripping was used on the products. A brief description of each is contained in the table of results. Windows were mounted in testing surround panels according to manufacturers' normal instructions for mounting in walls.

Tests at NRC

Windows were mounted in a surround panel with the weather side facing an environmental chamber capable of providing temperature and pressure differences with the room side of up to 40 K and up to 1500 Pa (Elmahdy 1995). An air-leakage apparatus was installed on the room side along with instrumentation in accordance with ASTM E1424-91. Details of the test apparatus and test procedure are described in the reference.

Five windows were tested at room-side temperature of 20°C and weather-side temperatures of 20°C, –5°C, and –20°C and six pressure differentials: 0, 50, 75, 100, 200, and 300 Pa.

Generally, all windows showed increasing leakage with increased temperature and pressure differential. Tests showed the greatest increase with pressure differential but went far beyond average pressures experienced in houses during heating seasons. Two of the casement windows actually showed slightly decreased leakage at greater temperature differential, possibly a result of members closing with shrinkage. Although no trends could be identified with window type (casement, vertical slider, horizontal slider, etc.) or frame material, it was noted that measurements on one particular window were accurately repeatable after a period of time. Air-leakage measurements per unit crack length, at 75 Pa pressure differential, are included in Table 1.

Tests at Commercial Laboratory

Windows were mounted in a mask wall between two chambers, one maintained at 20°C, the other at the test condition temperatures (NRCan 1995). Laminar flowmeters were used to measure leakage rate from the "inside" chamber at a set ΔP. A schematic of the test setup is shown in Figure 1. Further details of instrumentation, window mounting, and test procedures are contained in the reference.

Air leakage measurements per unit length of crack are listed in Table 1 for the 22 windows at $\Delta P = 75$ pascals and three outdoor temperatures ($T = -30$°C, 0°C, and 20°C). These values span the normal range of conditions expected during the heating season in Canada. Additional data were also obtained at an elevated temperature of 50°C and at $\Delta P = 300$ pascals but are not included here. Subsequent to the initial test, additional data were reported (CSA 1996) and are included in Table 1 as A-I: 23 to A-I: 30.

Careful observation during testing revealed the following information:

- Exterior lock-side corners of casement windows warped at cold temperatures by as much as 3.5 mm in relation to the frame. The magnitude was as much a function of design (number and location of locking points, profile rigidity, etc.) as sash material (wood, aluminum, vinyl, etc.)

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TABLE 1
Summary of Air Leakage Test Results for 35 Windows

Sample	Type	Material	Hardware	Measured Infiltration per Unit Crack Length ($m^3/h{\cdot}m$) at Indoor Air 20°C and ΔP = 75 Pa for Outdoor Air (°C) –30	0	20	Infiltration Heat Loss/yr (MJ/m) New/Old	Change in ER
A-I: 1	Casement	f: wood/PVC clad	2 locks	1.10	0.65	0.45(A3)	6.1/3.8	–0.4
		s: PVC	1 snubber					–0.1
A-I: 2	Casement	all wood	2 locks	0.25	0.25	0.20 (A3)	2.1/1.7	
			1 snubber					
A-I: 3	Casement	f: wood/PVC clad	2 locks	0.45	0.21	0.18 (A3)	2.1/1.5	–0.1
		s: PVC	1 snubber					
A-I: 4	Casement	all PVC	2 locks	0.18	0.07	0.06 (A3)	0.7/0.5	0.0
			1 snubber					
A-I: 5	Casement	all PVC	mp locking (3)	0.12	0.12	0.06 (A3)	1.0/0.5	–0.1
			1 snubber					
A-I: 6	Casement	all PVC	3 locks	0.23	0.21	0.16 (A3)	1.8/1.3	–0.1
			2 snubbers					
A-I: 7	Casement	all PVC	mp locking (3)	2.84	0.90	0.59 (A2)	10.3/5.0	–0.6
			1 snubber					
A-I: 8	Casement	all PVC	mp locking (3)	1.35	0.28	0.27 (A3)	3.8/2.3	–0.2
			2 snubbers					
A-I: 9	Casement	same as A-I: 8 with a larger bulb weatherstrip		0.83	0.27	0.24 (A3)	3.1/2.0	–0.2
A-I: 10	Casement	same as A-I: 8 but	2 locks	0.58	0.52	0.47 (A3)	4.4/3.9	–0.1
			2 snubbers					
A-I: 11	Casement	aluminum	mp locking (2)	2.72	1.07	0.82 (A2)	11.3/6.9	–0.7
A-I: 12	Casement	aluminum	2 locks	0.45	0.37	0.34 (A3)	3.2/2.9	–0.1
A-I: 13	Casement	aluminum	mp locking (3)	0.78	0.39	0.25 (A3)	3.8/2.1	–0.2
			3 snubbers					
A-I: 14	Casement	f: alum/wood/PVC		1.09	0.72	0.58 (A2)	6.6/4.9	–0.3
		s: alum/PVC						–0.1
A-I: 15	Tilt-turn	PVC	5 locks	0.58	0.40	0.37 (A3)	3.6/3.1	–0.1
A-I: 16	Awning	wood	2 locks	0.43	0.41	0.37 (A3)	3.5/3.1	–0.1
A-I: 17	Hor sliding	aluminum	4 moving sashes	0.63	0.55 (A3)		5.3/4.6	–0.1
A-I: 18	Hor Sliding	PVC	1 moving sash	3.23	2.59	1.89 (A1)	22.6/15.9	–1.1
A-I: 19	Hor Sliding	PVC	1 moving sash	1.17	1.06	1.01 (A2)	9.1/8.5	–0.1
A-I: 20	Vert Sliding	wood/PVC clad	2 tilt-in sashes	0.62	0.58	0.46 (A3)	4.9/3.9	–0.2
A-I: 21	Vert Sliding	PVC	1 moving sash	1.62	1.93	2.85	20.0/23.9	1.1
A-I: 22	Vert Sliding	PVC	1 tilt-in sash	9.19	5.83	3.69	53.6/31.0	–3.1
A-I: 23	Vert Sliding	PVC	1 moving sash	0.74	0.58	0.54 (A3)	5.1/4.5	–0.1
A-I: 24	Hor Sliding	PVC	1 moving sash	1.11	1.02	0.57 (A2)	8.7/6.2	–0.4

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TABLE 1 (Continued)
Summary of Air Leakage Test Results for 35 Windows

Sample	Type	Material	Hardware	Measured Infiltration per Unit Crack Length ($m^3/h{\cdot}m$) at Indoor Air 20°C and ΔP = 75 Pa for Outdoor Air (°C)			Infiltration Heat Loss/yr (MJ/m)	
				−30	0	20	New/Old	Change in ER
A-I: 25	Casement	PVC	mp locking (3)	0.72	0.51	0.46 (A3)	4.6/3.9	−0.2
			1 snubber					
A-I: 26	Casement	f: Wood/PVC clad	2 locks	2.66	1.02	0.57 (A2)	10.9/4.8	−0.7
		s: PVC						
A-I: 27	Casement	Wood/Aum clad	2 locks	1.66	1.63	1.56 (A2)	13.7/13.1	−0.2
A-I: 28	Casement	PVC	mp locking (3)	0.90	0.41	0.34 (A3)	4.1/2.9	−0.2
			2 snubbers					
A-I: 29	Casement	PVC	2 locks	0.37	0.08	0.05 (A3)	1.1/0.4	−0.1
			1 snubber					
A-I: 30	Casement	PVC	2 locks	0.22	0.11	0.06 (A3)	1.1/0.5	−0.1
			1 snubber					
				for Outdoor Air (°C)				
				−30	0	20		
NRC: 1	Casement	aluminum one of two units operable		0.63	0.61	0.58 (A2)	5.1/4.9	−0.1
NRC: 2	Casement	fiberglass		0.17	0.18	0.18 (A3)	1.5/1.5	0.0
NRC: 3	Casement	wood		0.48	0.48	0.40 (A3)	3.9/3.4	−0.1
NRC: 4	VertSlider	aluminum		6.05	6.34	6.03	52.1/50.6	−0.3
NRC: 5	Vert Slider	PVC		1.92	1.80	1.30 (A2)	15.5/10.9	−0.6

- With double-hung windows, contraction of the sash with respect to the frame sometimes resulted in loss of contact between weather strips and the adjacent members. Windows with tilt-in sash had particularly bad performance at low-temperatures.
- With respect to the horizontal sliders, tilt-turn, and awning windows tested, little differential movement was noticed.

The test results were even more revealing:

- Virtually all windows demonstrated increased air leakage at low temperatures. For 75 pascal ΔP, the worst had five times the air leakage at −30°C as at 20°C.
- Increases at low temperature depended moderately on window type. Casement increases seemed to be greater than other types.
- Variation in infiltration rate for a given product cannot be linked to the type of frame and sash material (PVC, aluminum, wood, etc.) but rather to overall product design. Changes in weather stripping and hardware design and location can radically change performance.

The Canadian window performance standard CAN/CSA-A440-M90 provides for rating of operable windows in three categories when tested at the specified 20°C and ΔP = 75 Pa:

A1: less than 2.79 ($m^3/h{\cdot}m$)

A2: less than 1.65 ($m^3/h{\cdot}m$)

A3: less than 0.55 ($m^3/h{\cdot}m$)

Most windows were very good by this standard, falling into the best category (A3). A few were rated A2, and two PVC sliders were rated A1. Although the standard does not apply to tests at other than 20°C, it is useful to consider the same categories at lower temperatures. Almost all windows increased air leakage at cold temperatures, some substantially, but nearly half remain in the same category even at −30°C. Others moved down a category, and two products would not meet the minimum level.

The ASTM E-1424-91 standard proved effective to evaluate operable window performance at low temperatures. To minimize costs of testing windows at many temperatures, energy performance standards could be changed to call for two tests, one at 20°C as required now and another at a winter design temperature (e.g., 2.5% January temperature), or, alter-

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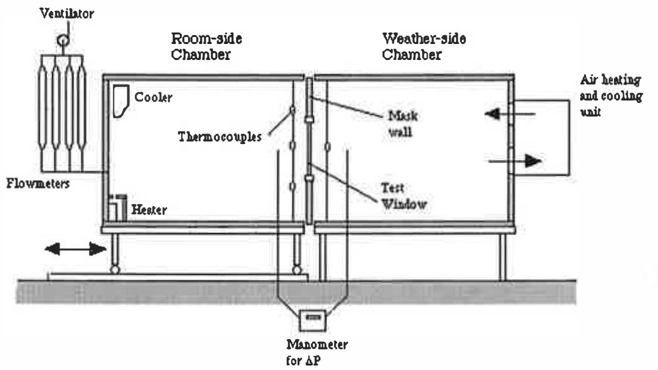

Figure 1 *Test facility in Montreal for determining window air leakage at cold temperatures.*

natively, just a single test but at some more representative heating season temperature such as –5°C.

IMPACT ON ANNUAL ENERGY RATING

Both the CSA and NFRC annual energy rating systems for windows include terms for air leakage losses. Both currently use estimates based on measurements made with ASTM E283, in other words, at 20°C and no ΔT across the unit.

In CSA A440.2, the window ER number is calculated from

$$ER = 72.2\ SHGC - 21.9\ U_w - 0.54\ (L_{75}/Aw) \qquad (1)$$

where

ER = window energy rating, W/m^2;
SHGC = window solar heat gain coefficient, dimensionless;
U_w = overall window U-factor, W/m^2·°C;
L_{75} = window air leakage rate at 75 Pa, m^3/h;
Aw = total window area, m^2.

The last term, the air-leakage term, uses a measured quantity, L_{75}, determined according to CSA A440 (ASTM E283 test). The coefficient in this term, 0.54, as well as coefficients for other terms in the ER equation, were determined by a process of modeling a standard two-story house in many Canadian and northern U.S. locations over a typical heating season. Until now, for lack of better data and because this term is small compared to the other two terms in the ER equation, air leakage data measured only at 20°C have been used.

A different approach is taken to determining a fenestration heating rating (FHR) in NFRC 900, but contributions come from solar gain, transmission loss, and air leakage as in CSA A440.2, with the latter evaluated again in a simplified manner.

It is not sufficient to obtain air leakage at some design temperature, for instance –25°C, and use this in the air leakage term, since during the heating season, climatic conditions are probably only at this temperature for a few hours, if at all. Rather, the combined effects of wind and temperature (stack effect) on pressure together with variations in outside temperature, during all of the hours of the heating season, should be evaluated.

Data obtained from measurements of typical window characteristics for air leakage under a range of pressure and temperature differentials could be used in hour-by-hour energy simulations to evaluate the impact on rating numbers. Windows with specific low-temperature air-leakage characteristics could be modeled in a particular climate, over a complete heating season, to determine the effect on energy consumption.

Such a study was undertaken for CANMET as part of a CSA study (NRCan 1996). To simplify calculations, binned weather data were used with the ENERPASS energy simulation computer program to model a typical house in a number of Canadian cities. The house characteristics were the same as, and the process similar to, those used to develop the ER equation, which is the basis for the current CSA standard for window annual energy performance.

Five windows from the commercial testing laboratory study were evaluated. These were selected from among casement and slider types representative of average and high air-leakage rates at 20°C and 75 Pa. Measured data taken at –20°C, 0°C, and 20°C were used to produce profiles as shown in Figure 2.

For each window, its air leakage characteristics as a function of outdoor temperature and pressure difference (due to wind and stack effects) for a specific location are calculated for the bin hours during the heating season. In Figure 3, results are shown for one example (Montreal weather and window A-I: 18), which includes comparison with infiltration estimation based on 20°C measurements only. Note that roughness in the curve is simply a result of temperatures being recorded in bins and the finite number of hours recorded. Finally, infiltration rates are summed for the hours at each temperature difference to determine annual infiltration heat loss. The impact of the air infiltration at other temperatures was approximated by using an average outside air temperature of –5°C and an average pressure difference of 3.4 Pa during

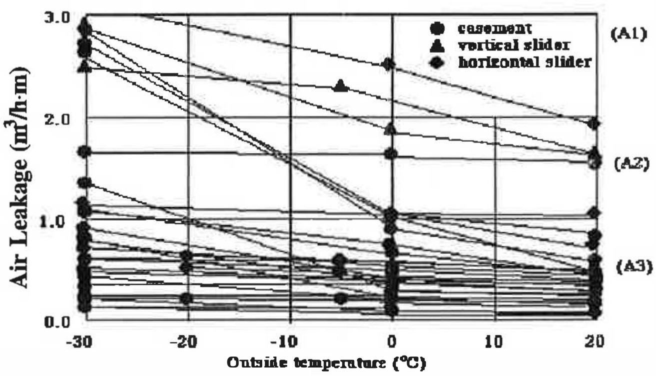

Figure 2 *Measured window air infiltration at low temperatures (m^3/h·m).*

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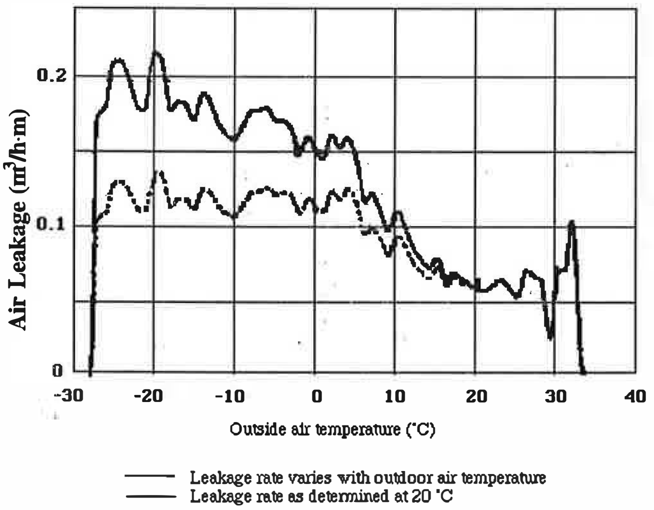

Figure 3 *Window air infiltration as a function of outside air temperature ($m^3/h{\cdot}m$) (window A-I: 18 in Montreal).*

4693 heating hours to calculate a new annual infiltration rate. Air leakage based on crack length is converted to total window values by using the crack length for each window type as defined by the specified sizes of the A440.2 standard. Comparison with infiltration rates based on 20°C measurement is shown in the second to last column of Table 1.

Finally, the impact on the ER number is calculated by substitution into the ER equation.The impact is listed for each window in the last column of Table 1. Note that, with the exception of A-I: 22 and A-I: 23, all windows decrease ER number by less than 1.0. Many decrease by as little as 0.1. This amount is not significant when comparing products. The exceptions were one window that actually slightly decreased leakage at lower temperatures and the other a tilt-in vertical slider that did not meet minimum CSA air-leakage requirements at any temperature.

Annual energy ratings currently do not take into account performance changes as a result of use or aging. In the same way, investigations described in this paper have not considered changes in the window product as a result of temperature cycling, as would occur from day to night in winter or season to season. Previous studies (NRCan 1991; NRCan 1993) covered pressure and motion cycling, and it is expected that temperature cycling would have no greater impact.

CONCLUSIONS

The results of this investigation fully support the use of the existing window ER system, and additional low-temperature tests are not warranted. Thirty-five samples of windows representative of a broad range of operable types, frame/sash materials, design, and hardware were tested for air leakage at the usual temperature of 20°C and at various temperatures down to –30°C. The results may be summarized as follows:

1. The ASTM E-1424-91 standard proved effective to evaluate operable window performance at low temperatures. It could be used to get more information about window air leakage characteristics for annual energy performance estimation.
2. Two-thirds of the windows met the highest level (A3) of the CSA A440 standard for air leakage. Of those that did not, most fell into the next category, while three did not even meet minimum requirements. Worst were vertical sliders, PVC, and aluminum.
3. At lower temperatures, most windows exhibited increased air leakage, although many only very slightly. At the lowest temperatures, nearly half remained in the same category, while others increased more dramatically, and four did not meet minimum CSA levels. Changes seem to be affected by window design more than materials, and there seems no justification to claims that one window material is better than others at low temperatures.
4. An estimate of the impact of increased air leakage at low temperatures on annual energy performance was carried out. For the vast majority of windows, the ER number was reduced by less than one. Anomalies for two windows that also were very poor performers at normal temperatures could be explained by design details.

The air leakage term in the ER calculation is normally small but needs to be retained, however, in order to account for poor performance of the few very leaky windows.

Durability issues relating to energy performance were not investigated, but other studies have suggested similar increases in air leakage as a result of pressure and motion cycling.

Further work may be warranted to investigate design details that affect air leakage and changes with temperature so that products can be improved. Nevertheless, most products in today's marketplace are excellent, and air leakage does not appear to be reducing energy efficiency significantly at any temperature. Specifiers and consumers, however, would be well advised to demand tested products to avoid getting the odd "lemon" in the marketplace.

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