#4933

Including Furnace Flue Leakage in a Simple Air Infiltration Model

I S Walker and D J Wilson

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

Introduction

Although there are many simple infiltration models already available none of them have an appropriate method of dealing with what is often the single largest leak in a building; a furnace or fireplace flue. Flues are different from the distributed leakage used in simple infiltration models. Flues represent 10% to 30% of the total building leakage all of which is concentrated at one location above the ceiling height. The flue top is often unsheltered when the rest of the house is sheltered from wind. Because the flue is filled with room air most of the time this leads to an increased stack effect. The pressure-flow exponent, n, for a furnace flue is about 0.5 rather than the value 0.6 to 0.8 typical of the rest of the building leaks.

The Alberta Infiltration Model, AIM-2, gives improved estimates by incorporating the $Q = C\Delta P^n$ characteristic into the model from first principles, treating the flue as a separate leakage site with its own wind shelter, and locating the flue outlet above the roof, rather than grouping the flue leakage with the ceiling leaks as in other models.

Describing the Leakage Distribution

A power law pressure-flow relationship for a building envelope is assumed

$$Q - C_{total}\Delta P^n \qquad (1)$$

Measurements on several test houses in the present study demonstrated that a single value for C_{total} and n accurately describe building leakage flows over a wide pressure range, from less than 1 Pa to over 50 Pa.

Sherman (1980) introduced the idea of using leakage distribution parameters X and R to describe the building envelope flow rates in terms of stack and wind factors, f_s and f_w. In AIM-2 we followed this approach, adding an additional flue fraction parameter, Y.

$$R = \frac{C_{(ceiling)} + C_{(floor)}}{C_{total}} \qquad \text{"ceiling-floor sum"} \quad (2)$$

$$X = \frac{C_{(ceiling)} + C_{(floor)}}{C_{total}} \qquad \text{"ceiling-floor difference"} \quad (3)$$

$$Y = \frac{C_{flue}}{C_{total}} \qquad \text{"flue fraction"} \quad (4)$$

Stack and wind effects in AIM-2 are combined as if their independant pressure differences add linearly, and an additive correction term is introduced to account for the interaction of the wind and stack effects in producing the internal pressure, see Walker and Wilson (1990). Model validation, discussed later, used data sets from the Alberta Home Heating Research Facility chosen to be dominated by wind or stack effects, so that this correction term was negligible. In this way, AIM-2 could be tested against independent infiltration measurements without assuming any empirical constants other than the pressure coefficients available from existing wind tunnel data sets.

Comparison of AIM-2 with Other Infiltration Models

The two models that most closely resemble the Alberta Infiltration Model (AIM-2) use variable leakage distribution. They are Sherman's orifice flow model from Sherman and Grimsrud (1980), often referred to as the LBL model, and a variable flow exponent (VFE) model, adapted by Reardon (1989) from Yuill's (1985) extension of Sherman's model to power law leakage. One of the other models chosen for comparison, Shaw (1985), is based on empirical fitting and superposition of the stack and wind pressure terms to measured data. The fourth model, Warren and Webb (1980) does not specify leakage distribution variation. The significant differences between AIM-2 and the LBL and VFE models are:

- The attic space above the ceiling is assumed in the LBL and VFE models to have a zero pressure coefficient. The attic pressure coefficient in AIM-2 is taken to be a weighted average of the pressure coefficients on the eave and end wall vents, and the roof surface vents. The eave vents are assumed to have the same pressure as the wall above which they are located.
- There is no furnace flue in the LBL or VFE model. In these models any furnace flue leakage is simply added to the ceiling leakage, and sees the attic pressure. In AIM-2 the furnace flue is incorporated as a separate leakage site, at the flue exit height above the roof. The flue is assumed to be filled with

indoor air at room temperature, and exposed at its top to a pressure set by wind flow around the rain cap.

- The floor leakage in Sherman's LBL model and in VFE was located above a crawlspace that was assumed to have a zero pressure coefficient. In AIM-2 the crawlspace pressure is taken as the average of the four outside wall pressures from wind effect. AIM-2 also deals with a house with a full basement or a slab-on-grade, where "floor" leakage is the crack around the floor plate resting on the foundation, plus cracks, holes and other leakage sites in the concrete foundation above grade. These floor level leakage sites are uniformly distributed around the perimeter of the house, and exposed to the same pressure as each of the walls on which they are located.
- The LBL model assumes orifice flow with n = 0.5 in $Q = C\Delta P^n$ of each leak. Both VFE and AIM-2 assume a single value of n in the range 0.5 to 1.0 for leakage through the floor, walls, and ceiling. The flue is assumed to have a value of n = 0.5.
- Both LBL and VFE assume that wind flow, Q_w, and stack flow Q_s, combine in quadrature as a sum of squares. AIM-2 assumes the flows add as a pressure sum plus an interaction term that accounts empirically for a wind-induced shift of the neutral pressure level.

AIM-2 Stack Effect

The stack factor, f_s, is defined by

$$Q_s = C_{total}\, fs\, P_s^n \qquad (5)$$

where, in terms of the ceiling height, H, of the building, the stack effect reference pressure is

$$P_s = \rho_o\, g\, H \left(\frac{T_i - T_o}{T_i}\right) \qquad (6)$$

with subscript "o" indicating outdoor and "i" indicating indoor conditions.

The stack factor f_s was determined by a numerical solution of the non-linear inflow-outflow balance equations, and is approximated in AIM-2 by

$$f_s = \left(\frac{1 + nR}{n + 1}\right)\left(\frac{1}{2} - \frac{1}{2}M^{5/4}\right)^{n+1} + F \qquad (7)$$

The functional form of this approximation was selected to produce the correct behaviour of f_s for ceiling-floor difference ratio limits of X = 0 and X = ±1, and at the limits R = 0 where all leakage is concentrated in the walls, and R = 1 where all the leaks are in the floor and ceiling. The factors M and F are defined by

$$M = \frac{(X + (2n + 1)\,Y)^2}{2-R} \quad \text{for} \quad \frac{(X + (2n + 1)Y)^2}{2-R} \le 1 \qquad (8)$$

with a limiting value of

$$M = 1.0 \quad \text{for} \quad \frac{(X + (2n + 1)\,Y)^2}{2-R} > 1 \qquad (9)$$

The additive flue function F is,

$$F = nY\,(\beta_f - 1)^{\frac{(3n-1)}{3}}\left(1 - \frac{3\,(X_c - X)^2 R^{1-n}}{2(\beta_f + 1)}\right) \qquad (10)$$

where β_f is the ratio of flue height to ceiling height above floor level, and

$$X_c = R + \frac{2(1-R-Y)}{n+1} - 2Y(\beta_f - 1)^n \qquad (11)$$

The variable X_c is the critical value of the ceiling-floor difference fraction X at which the neutral level passes through the ceiling in the exact numerical solution. For $X > X_c$ the neutral level will be above the ceiling, and attic air will flow in through the ceiling. For $X < X_c$ room air will exfiltrate through the ceiling. This critical value of X_c is useful in determining whether moist indoor air will exfiltrate through the ceiling and condense in attic insulation in winter. The role of the flue in reducing ceiling exfiltration is evident from the contribution of the flue leakage factor, Y, in (11).

The stack factor is shown in Figure 1 for typical values of n = 2/3, β_f = 1.5 for a house with no flue, Y = 0, and for a flue with 20% of the total leakage area, Y = 0.2. It is apparent that treating the flue as a separate leakage site with a stack height above the ceiling has a significant effect on the stack factor f_s.

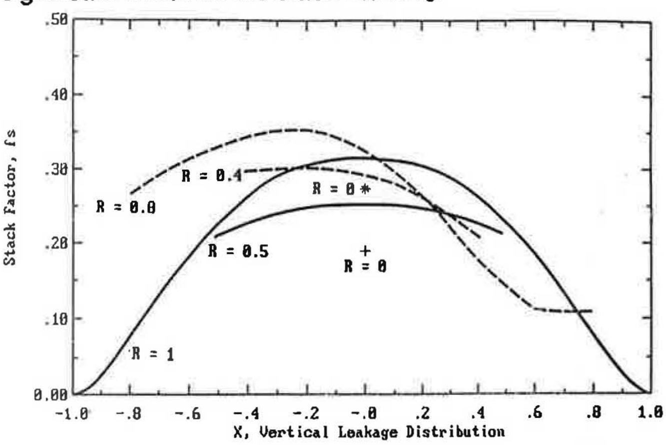

*Figure 1: AIM-2 (Equation 7) for Stack Factor, fs, with no Flue Leakage (Y=0) solid line and +, and with 20% of Leakage in the Flue (Y=0.2) and ß=1.5 dashed line and *.*

AIM-2 Wind Effect

The wind induced infiltration rate Q_w is defined in terms of wind factor f_w by

$$Q_w = C_{total}\, f_w\, P_w^n \qquad (12)$$

where the reference wind pressure is expressed in terms of the unobstructed windspeed (with no local shelter) at eaves height, and an overall shelter coefficient, S_w,

$$P_w = \rho_o \frac{(S_w U_e)^2}{2} \qquad (13)$$

The exact numerical solution for f_w, and its approximating function in AIM-2 depend on the set of wind pressure coefficients used. Using the pressure coefficients from Akins (1979), the approximating function for wind factor for slab-on-grade or basement construction types is

$$f_w = 0.19(2-n)\left(1-\left(\frac{X+R}{2}\right)^{1.5-Y}\right) - \frac{Y}{4}(S-2YS^4) \qquad (14)$$

where $S = \dfrac{X+R+2Y}{2}$

This form for f_w was chosen to produce the correct behaviour for the limiting values of all leakage concentrated in either walls, floor or ceiling, and for $X = 0$ where the floor and ceiling leakage are equal. Surprisingly, the flue height β_f does not appear in (14), because the exact solution indicated that the dependence on β_f is felt very weakly through the change in windspeed at the flue top.

For a house with a crawl space, the pressure inside the crawl space may be approximated by the average of the four walls which change the dependence of f_w on X and R. Approximating functions for this type of construction are discussed by Walker and Wilson (1990).

The wind factor calculated from equation (14) is shown in Figure 2 for $n = 2/3$, $Y = 0.2$, and for no flue, $y = 0$. This shows that there is little difference between considering the flue leakage as a hole in the ceiling, venting into the attic, or as a separate leakage site with its own flue cap pressure coefficient above the roof. The major advantage of the separate flue leakage site is to allow it to have a different wind shelter than the rest of the building.

The exact numerical solution for f_w, used the wind pressure coefficient data set of Akins (1979), with wind normal to the upwind wall, and all walls of the same length. Three other wind tunnel data sets, ASHRAE (1989), AIVC (1986) and Wiren (1984), for wall and roof pressure coefficients were also used to find numerical solutions for f_w. These other sets of pressure coefficients produced wind factors that are functionally similar, but with a difference in magnitude. The two extreme results are for the Wiren and ASHRAE data sets, that produce values of f_w 10-20% larger and 10-20% smaller than Akins data set.

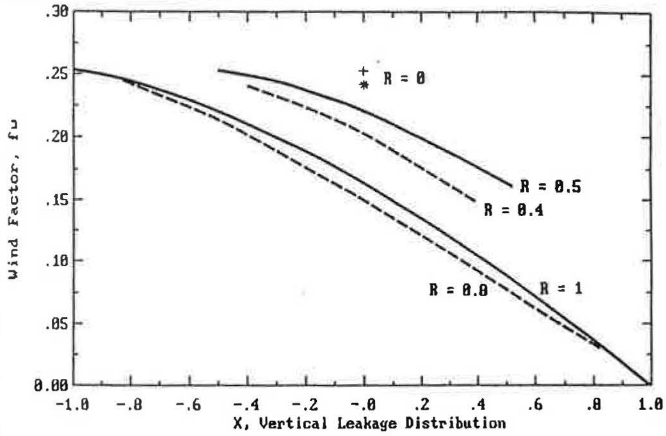

*Figure 2: AIM-2(Equation 14) for Wind Factor, f_w, with no Flue Leakage ($Y=0$) solid line and +, and with 20% of Leakage in the Flue ($Y=0.2$) and $\beta_f = 1.5$ dashed line and **

Shelter Coefficients

Local shielding by nearby buildings trees and obstructions is very difficult to estimate by simply inspecting the building site, and uncertainty in estimating the local shelter coefficient S_w in (13) is often the major source of error in estimating wind driven air infiltration rates.

In AIM-2, the shelter coefficient S_{wo} for the building walls is combined with a different coefficient S_{wflue} for the top of the flue

$$S_w = S_{wo}(1-Y) + S_{wflue}(1.5Y) \qquad (15)$$

$S_{wflue} = 1.0$ for an unsheltered flue, which protrudes above surrounding obstacles, and $S_{wflue} = S_{wo}$ for a flue top which has the same wind shelter as the building walls. The factor 1.5 is an empirical adjustment found by comparing AIM-2 to an exact numerical solution for each leakage site with its own shelter and pressure coefficient.

Comparison of AIM-2 with Measured Infiltration

AIM-2 has been validated by comparing its predictions to air infiltration measurements in two houses at the Alberta Home Heating Research Facility. Continuous infiltration measurements were carried out in the test houses using a constant concentration SF_6 tracer gas injection system in each house described by Wilson and Dale (1985). Envelope leakage characteristics were measured in the two houses using fan pressurization over the range from 1 Pa to 75 Pa.

House Number	Flue Configuration	Flow Coefficient $m^3/s\ Pa^n$	Exponent n	Leakage area A_o at 4 Pa cm^2
4	closed	0.007	0.7	65
4	open with 7.5 cm dia orifice	0.010	0.66	93
5	open 15 cm dia. flue	0.020	0.58	158

Table 1: House leakage characteristics

The single storey houses are of wood frame construction with polyethylene vapour barriers and full concrete basements. Details of the house construction are given in Wilson and Dale (1985).

For house 4 with the flue blocked it was estimated that 50% of the leakage is in the walls and 25% in the floor and 25% in the ceiling. For house 4 with a 7.5 cm diameter orifice in a 15 cm diameter flue it was estimated that 40% of the leakage was in the flue, 30% in the walls, 15% in the floor and 15% in the ceiling. For house 5 with a 15 cm diameter flue 60% of the leakage was estimated to be in the flue, 30% in the walls, 5% in the floor and 5% in the ceiling.

The predictions of AIM-2 and these four models, are compared to measured data in Figures 3 and 4 for unsheltered conditions (north and south winds) in house 5 with a 15 cm diameter flue, and for house 4 with the flue blocked. These results show that AIM-2 has the best overall performance for houses with furnace flues, mainly because the furnace flue is treated as a separate leakage site with its own wind pressure coefficient.

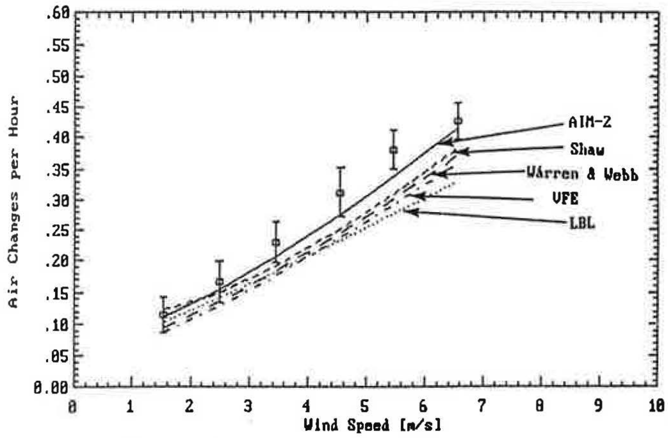

Figure 3:Comparison of ventilation models with measured data for unshielded windspeed dependance (North and South winds) in house #5 with an open 15 cm diameter flue with $\Delta T \geq 10°C$ and $U \geq 1.5$ m/s (279 hours)

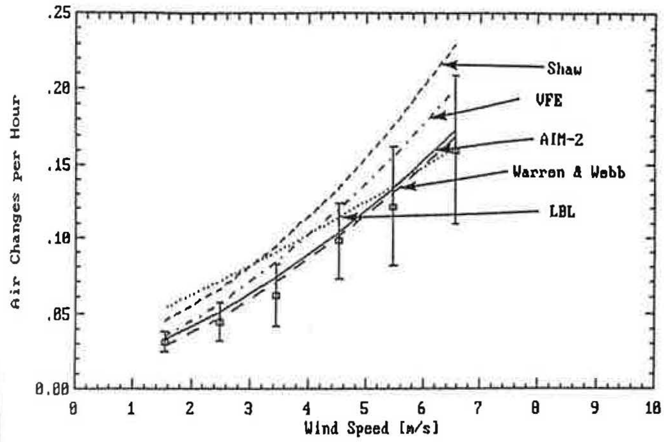

Figure 4: Comparison of ventilation models with measured data for unshielded windspeed dependence (North and South winds) in house #4 with blocked flue, and $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s (285 hours)

Figure 5 compares the windspeed dependence of the models for house 5 with an open 15 cm diameter flue where the house is heavily sheltered by a row of adjacent test houses (east and west winds). All the models except AIM-2 underpredict the wind effect infiltration rate Q_w significantly because they are unable to account for unshielded flue leakage on a shielded building. The same data that were binned for Figure 5 are shown individually in Figure 5b. This shows the amount of scatter present in the measured hourly data and the need for data binning for clearer model comparisons. Figure 6 illustrates the superior performance of AIM-2 in predicting stack effect flow Q_s for house 4 with a 7.5 cm diameter restriction orifice in the flue.

In conclusion, AIM-2 with separate flue leakage has shown a significant advantage over existing simple air infiltration models. Current efforts to improve AIM-2 are focused on developing accurate methods for estimating wind shelter from surrounding structures.

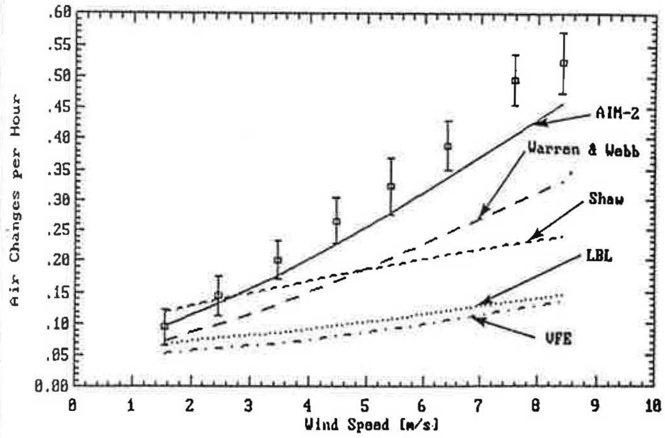

Figure 5: Comparison of ventilation models with measured data for shielded windspeed dependence (East and West winds) in house #5 with an open 15 cm diameter flue with $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s (461 hours)

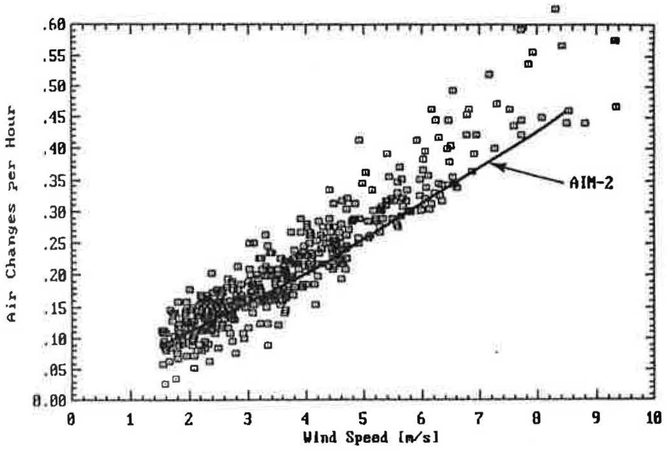

Figure 5b: Comparison of AIM-2 with unbinned measured data for shielded windspeed dependence (East and West winds) in house #5 with an open 15 cm diameter flue with $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s. 461 hours of unbinned data.

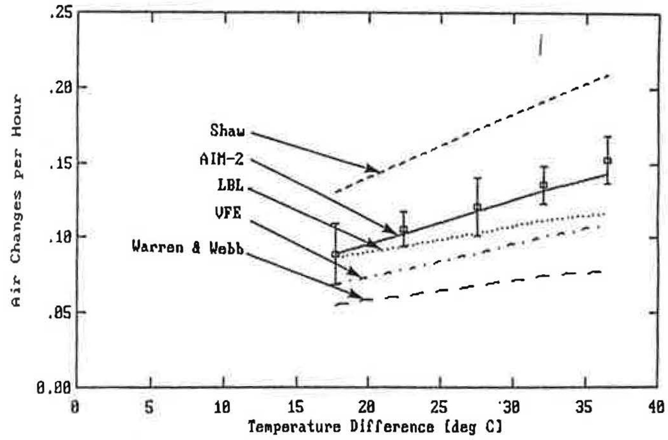

Figure 6: Comparison of ventilation models to measured data for DT dependence in house #4 with an open 7.5 cm diameter orifice in the flue, with $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s. $R=0.3$, $X=0$, $Y=0.4$, and $B_f=1.5$ (102 hours).

References

AIVC (1986) "Air Infiltration Calculation Techniques - An Applications Guide" Air Infiltration and Ventilation Centre, Bracknell, UK.

ASHRAE (1989) "Air Flow Around Buildings", Chapter 14, Handbook of Fundamentals.

Akins, R. E., Peterka, J. A. and Cermak, J.E. (1979) "Averaged Pressure Coefficients for Rectangular Buildings", Wind Engineering Vol. 1, Proc. 5th Int. Conf. pp. 369-380.

Hayson, J.C. and Swinton, M.C. (1987) "The Influence of Termination Configuration on the Flow Performance of Flues", Canada Mortgage and Housing Research Report.

Irwin, J.S. (1979) "A Theoretical Variation of the Wind Profile Power Law Exponent as a Function of Surface Roughness and Stability", Atmospheric Environment 13, pp. 191-194.

Reardon, J.T. (1989) "Air Infiltration Modelling Study", Report #CR5446.3, Energy Mines and Resources Canada, National Research Council of Canada.

Shaw, C.Y. (1985) "Methods for Estimating Air Change Rates and Sizing Mechanical Ventilation Systems for Houses", Building Research Note 237, Division of Building Research, National Research Council of Canada.

Sherman, M.H. and Grimsrud, D.T. (1980) "Measurement of Infiltration Using Fan Pressurization and Weather Data", Lawrence Berkeley Laboratory, Report #LBL-10852.

Walker, I.S. and Wilson D.J. (1990) "The Alberta Infiltration Model: AIM-2", University of Alberta, Dept. of Mechanical Engineering, Technical Report No. 71.

Warren, P.R., and Webb, B.C. (1980) "The Relationship Between Tracer Gas and Pressurization Techniques in Dwellings", Proc. First Air Infiltration Center Conference, pp. 245-276.

Wilson, D.J., and Dale, J.D., (1985) "Measurement of Wind Shelter Effects on Air Infiltration", Proceedings of Conference on Thermal Performance of the Exterior Envelopes of Buildings, Clearwater Beach, Florida, Dec. 2-5, 1985.

Wiren, B.G. (1984) "Wind Pressure Distributions and Ventilation Losses for a Single-Family House as Influenced by Surrounding Buildings - A Wind Tunnel Study", Proc. Air Infiltration Centre Wind Pressure Workshop, Brussels, 1984.

Yuill, G.K. (1985) "Investigation of Sources of Error and Their Effects on the Accuracy of the Minimum Natural Infiltration Procedure", Report for Saskatchewan Research Council, Canada.