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AIM-2

THE ALBERTA AIR INFILTRATION MODEL

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Nomenclature

A_o	Equivalent leakage area
β	Dimensionless Flue Height
β_f	Dimensionless Flue Height
β_o	Dimensionless neutral level height
B_1	Interaction coefficient for combining wind and stack effect
C	Building leakage coefficient
C_c	Ceiling leakage
C_f	Floor leakage
C_{flue}	Flue leakage
C_w	Wall leakage
ΔP	Pressure difference
ΔP_{ref}	Reference pressure difference for effective leakage area
ΔT	Indoor-Outdoor temperature difference
F	Factor used to determine stack flow factor, f_s
f_s	Stack flow factor
$f_{s,LBL}$	LBL stack flow factor
f_w	Wind flow factor
g	Gravitational acceleration
H	Building eave height
H_f	Height of flue top
M	Factor used to determine stack flow factor, f_s
n	Building leakage exponent
p_m	Windspeed exponent at met. station
p_s	Windspeed exponent at building site
P_s	Stack effect reference pressure
P_w	Wind effect reference pressure

Q	Total flow through building envelope
Q_s	Flow due to stack effect
Q_w	Flow due to wind effect
$Q_{w,\ sheltered}$	Flow due to wind effect for a sheltered building
$Q_{w,unsheltered}$	Flow due to wind effect for an unsheltered building
R	Ceiling-floor leakage sum
R^*	Parameter used to determine f_{wc}
ρ_o	Outdoor air density
S	Factor used to determine wind flow factor, f_w
S_w	Local wind shelter coefficient
S_{wo}	Shelter coefficient for building walls
S_{wflue}	Shelter coefficient for top of flue
T_i	Indoor temperature
T_o	Outdoor temperature
U	Windspeed
U_e	Unobstructed windspeed at eaves height at the building site
U_{met}	Windspeed recorded at met. station
$U_{sheltered}$	Effective sheltered windspeed
$U_{unsheltered}$	Effective unsheltered windspeed
X	Ceiling-floor leakage difference
X_c	Critical value of X at which the neutral level passes through the ceiling
X_{crit}	Critical value of X for wind flow factor with a crawl space, f_{wc}
X_s	Shifted X value for wind flow factor with a crawl space, f_{wc}
X^*	Parameter used to determine f_{wc}
Y	Fraction of building leakage in the flue

Y^*	Parameter used to determine f_{wc}
z	Height above grade level
z_m	Height at which met. station wind is measured
z_o	Terrain roughness scaling length

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Summary

This report presents the relevant equations needed for a complete single zone air infiltration model (AIM-2), and validates the model by comparing its predictions to measured infiltration rates in test houses. The pressure-flow relationship for the building envelope is described using a power law whose coefficients are determined by fan pressurization testing. Unlike other simple models the furnace flue is treated as a separate leakage site.

Wind and stack effects are determined separately, then superposed as a sum of pressures, with a correction term that accounts for the interaction of wind and stack induced pressure. This wind and stack effect interaction term includes the only empirical constant in AIM-2 determined by fitting to measured data.

The predictions of AIM-2 have been compared to those of four other simple models, and to infiltration data measured in two houses at the Alberta Home Heating Research Facility (AHHRF). The results indicate that treating the furnace flue as a separate leakage site significantly improves model predictions. Because the flue leakage is at a different height for stack effect AIM-2's predictions have about 5% error and the other model errors range from about 20% to 50%. The flue top has its own wind pressure coefficient, and is allowed to have different shelter than the rest of the building. For a sheltered building with a flue AIM-2's error is about 16% with the other models ranging from about 40% to 90%. For an unsheltered building with a flue AIM-2 has an error of about 12% with the other models ranging from about 20% to 26%. These errors are the approximate sum of the bias and scatter in each case. The measurements also show that the orifice flow assumption used in some models is a significant source of error, and the power law pressure-flow relationship, used in AIM-2, is more appropriate as it reduces the scatter error for a house with no flue from 18% for an orifice flow model to 3% for AIM-2.

The two major sources of uncertainty in applying AIM-2 are the estimation of local wind shelter and leakage distribution. Building shelter is difficult to estimate due to the complexity of local air flow around buildings. The table of shelter values for AIM-2 defines shelter coarsely and any finer selections of shelter would be difficult to justify. The leakage distribution between walls, floor, ceiling and flue was estimated by visual inspection. It is shown that errors in estimating this leakage distribution can cause significant errors in predicting air infiltration.

Introduction

The pressure differences that cause air infiltration are generated by the natural effects of wind (wind effect) and indoor-outdoor temperature difference (stack effect). In a real building the pressure acting across a specific leakage site is a combination of all three effects. An air infiltration flow model is used to find the total ventilation rate for a building from weather data, using the building's leakage distribution, pressure-flow and wind shelter characteristics.

The purpose of this report is to present the relevant equations needed for a complete single zone model, and then validate the model by comparing its predictions to measured ventilation rates in real buildings. This report will not go into great detail about equation derivations and justification of assumptions, or provide an extensive literature review.

In order to develop a simple model for estimating air infiltration it is necessary to examine separately the flowrate through each leak resulting from stack and wind effects. To determine the total building infiltration rate the building leakage flow pressure characteristic must be known. Fan pressurization tests used to find this flow characteristic have shown that the assumption of orifice flow used in the most popular infiltration models is unrealistic. A better way of describing the pressure-flow relationship for a building envelope is the power law

$$Q = C\Delta P^{n} \qquad (1)$$

where C and n are found from least squares fitting to pressurization test results. For orifice flow $n=1/2$, but for a typical residential building $n=2/3$. Measurements by the authors on several test houses have demonstrated that a single value for C and n accurately describe building leakage flows over a wide pressure range, from less than 1 Pa to over 50

Pa. Typical wind and stack effect pressures lie in the range from 1 Pa to 10 Pa.

The experimentally determined C and n are used in separate relationships to find stack and wind induced flow rates. The Alberta Infiltration Model, Version 2 (AIM-2) gives improved estimates for total building ventilation rates of single zone houses with furnace flues. This improvement is obtained by incorporating the $Q = C\Delta P^n$ characteristic into the model from first principles, and by treating the flue as a separate leakage site with its own wind shelter, locating the flue outlet above the house (depending on the actual flue height) rather than grouping the flue leakage with the other building leaks, as in other models.

Describing the Leakage Distribution

Pioneering work by Sherman (1980) introduced the idea of using a set of quantitative parameters to describe the leakage distribution of the building envelope, and to determine the stack-driven and wind-driven flow rates in terms of stack and wind factors, f_s and f_w. These two factors contain all the information about how the leakage distribution affects the total building infiltration. The leakage distribution is specified in terms of the ratio parameters R, X and Y, calculated from the leakage coefficients of each of the following components.

C_{flue} = leakage of flue at elevation $z = H_f$ above floor level

C_c = leakage of ceiling at elevation $z = H$ above floor level

C_f = leakage of floor level leaks, at $z = 0$

C_w = leakage of walls, (Each of the four walls is assumed to have the same uniformly distributed leakage)

Assuming that the exponent n in (1) is the same for all leakage sites, the total leakage coefficient C is

$$C = C_c + C_f + C_w + C_{flue} \quad (2)$$

Leakage distribution parameters are defined using the format suggested by Sherman (1980), with the addition of a separate flue fraction for AIM-2.

$$R = \frac{C_c + C_f}{C} \quad \text{"ceiling-floor sum"} \quad (3)$$

$$X = \frac{C_c - C_f}{C} \quad \text{"ceiling-floor difference"} \quad (4)$$

$$Y = \frac{C_{flue}}{C} \quad \text{"flue fraction"} \quad (5)$$

Superposition of Wind and Stack Effects

In real infiltration the stack and wind effects are not independent, because wind and stack pressures act simultaneously across each leak. The magnitude of this pressure difference depends on the internal pressure of the building, which is set by the requirement that total mass inflow must equal the total mass outflow. The variation in stack induced pressure difference with height above the floor gives rise to a location on the building envelope where there is no pressure difference between indoors and outdoors. This neutral pressure level depends on the leakage distribution, and can be calculated for the case of stack induced infiltration with no wind. When wind pressures are present the neutral level shifts (and is different for each wall) in order to keep the total inflow and outflow equal. The internal pressure then depends on both the wind and stack pressures, and wind and stack flowrates cannot simply be added, but instead must be superposed in some way that accounts for this interaction.

The superposition technique used in AIM-2 adds the two flows non-linearly, as if their pressure differences added, and introduces an extra term to account for the interaction of the wind and stack effects in producing the internal pressure. The AIM-2 model uses a simple first-order neutral pressure level shift that produces the superposition

$$Q = \left(Q_s^{\frac{1}{n}} + Q_w^{\frac{1}{n}} + B_1 (Q_s Q_w)^{\frac{1}{2n}}\right)^n \tag{6}$$

where Q_s = Flow due to stack effect

Q_w = Flow due to wind effect

Q = Total flow due to combined wind and stack effects

B_1 = Interaction coefficient, assumed constant

It is easy to show that the interaction term causes the largest percentage effect on Q when wind and stack flows Q_w and Q_s are equal. The constant B_1 was determined empirically using direct measurements of air infiltration. Analysis of data from several houses at the Alberta Home Heating Research Facility for periods where Q_s and Q_w were approximately equal suggests that a reasonable estimate for B_1 is

$$B_1 \simeq -\frac{1}{3}$$

from which we see that wind and stack effect interaction reduces the total infiltration rate from the level predicted by a simple sum of pressures superposition. This is the only constant in AIM-2 that was determined by fits to measured data. The other empirical inputs to AIM-2 are the set of wind pressure coefficients from Akins (1979) wind tunnel experiments, the flue cap pressure coefficient from Hayson and Swinton (1987), and our estimates of wind shelter coefficients. 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 interaction term in (6) involving the empirical coefficient B_1 was negligible. In this way, AIM-2 could be tested against independent infiltration measurements that played no part in its development.

Comparison of AIM-2 With Other Flow 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 fom Sherman and Grimsrud (1980) (often referred to as the LBL model), and the "Variable n" model, refined by Reardon (1989) from Yuill's (1985) extension of Sherman's model to power law leakage $Q = C\Delta P^n$. The other models chosen for comparison; Shaw (1985) and Warren and Webb (1980), use empirical coefficients that do not change from house to house. All the models make the implicit assumption that each of the four walls has the same leakage. The significant differences between AIM-2 and Sherman's and Yuill's models are summarized below:

1. The attic space above the ceiling was assumed in Sherman's LBL Model (and in Yuill's extension) to have a zero pressure coefficient. The attic pressure coefficient in AIM-2 is assumed 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 they are

adjacent to. The eave vents above each wall are assumed to have the same size, and the roof vents to have a size equal to the sum of the eaves.

2. The floor leakage in Sherman's LBL model (and in Yuill's power law extension) was located above a crawl space which 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 assumed to be uniformly distributed around the perimeter of the house near ground level, and to be exposed to the same pressure as each of the walls on which they are located.

3. There is no furnace flue in Sherman's LBL model, or Yuill's power law extension. 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 a normalized height β_f above the floor. (The ceiling of the upper story is at $\beta = 1.0$, the floor at $\beta = 0$) 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.

4. Sherman's LBL model assumes orifice flow with $n = 0.5$ in $Q = C\Delta P^n$ of each leak. Both Yuill's extension and the Alberta Infiltration Model AIM-2 assume a single value of n in the range 0.5 to 1.0. (orifice flow to fully developed laminar flow) The same value of n is assumed to apply to each leakage site, floor, walls, and ceiling. The flue is assumed to have a value of $n = 0.5$ in developing exact numerical solutions for the wind and stack factors. Because these factors are then applied to the single average exponent n for the whole house, f_s and f_w depend on n in their flue terms. The empirical approximating functions in (21) to (26) reflect this combined n and Y dependence.

5. Both Sherman and Yuill assume that wind flow, Q_w, and stack flow Q_s, combine in quadrature as a sum of squares. The Alberta Infiltration Model AIM-2 includes the interaction term in (6) which accounts empirically for a wind-induced shift of the neutral pressure level.

The effect of these different assumptions in AIM-2 is easiest to assess by first looking at a house without a flue.

AIM-2 Stack Effect-No Flue

The flow induced by stack effect is assumed to have the functional form

$$Q_s = C f_s P_s^n \tag{7}$$

where

C = total building leakage coefficient in $C\Delta P^n$, $m^3/s\ Pa^n$

$$P_s = \text{stack effect reference pressure} = \rho_o\, g\, H \left(\frac{T_i - T_o}{T_i} \right),\ \text{Pa} \tag{8}$$

g = gravitational acceleration $\simeq 9.8\ m/s^2$

ρ_o = outdoor air density, kg/m^3

f_s = stack flow factor

H = building eave height (ceiling height of the uppermost story), m

T_i = Indoor Temperature, °K

T_o = Outdoor Temperature, °K

An exact numerical solution was found for f_s by balancing inflows and outflows. For all n values the exact equation for the stack factor (which requires a numerical solution) with no flue, is the same as Yuill's (1985). AIM-2 uses an approximating function instead of the exact solution for stack factor. The functional form of this approximation was selected to produce the correct behavior of f_s at the limits where all leakage is concentrated in the walls ($R = 0$), in the floor and ceiling ($R = 1$), and for the ceiling-floor difference ratio limits of $X = 0$ and $X = \pm 1$. The functional form is

$$f_s = \left(\frac{1 + nR}{n+1} \right) \left(\frac{1}{2} - \frac{1}{2} \left(\frac{X^2}{2-R} \right)^{5/4} \right)^{n+1} \tag{9}$$

Values of f_s from equation (9) are shown graphically in Figure 1, with $n = 2/3$. Note that f_s for $R = 0$ is a single point at $X = 0$. When $n = 0.5$ the exact numerical solution for the stack flow Q_s is the same as Sherman's LBL model. However, the approximating function recommended by AIM-2 is somewhat different than Sherman's approximation. Sherman's stack factor $f_{s,LBL}$ is defined by

$$Q_s = A_o f_{s,LBL} \left(\frac{P_s}{\rho_o} \right)^{0.5} \tag{10}$$

where A_o = leakage area of the house at reference pressure ΔP_{ref}. Setting $n = 0.5$ in equation (7) and equating to (10) yields

$$\left(\frac{1}{\rho_o} \right)^{0.5} A_o f_{s,LBL} = C \, f_s$$

At a reference pressure ΔP_{ref} the leakage area A_o and flow coefficient C are related by

$$A_o = C \left(\frac{\rho_o}{2} \right)^{0.5} (\Delta P_{ref})^{n-0.5} \tag{11}$$

so our definition of the stack factor f_s is related to the LBL value by

$$f_s = 2^{-0.5} f_{s,LBL} \tag{12}$$

Using (12), Sherman and Grimsrud's (1980) approximating function for orifice flow may be written in the form

$$f_{s,LBL} = \left(\frac{1 + 0.5R}{1.5} \right) \left(\frac{1}{2} - \frac{1}{2} \left(\frac{X^2}{(2-R)^2} \right) \right)^{3/2} \tag{13}$$

We believe (9) with $n = 0.5$ is a more accurate approximation than the LBL function in (13).

AIM-2 Wind Effect-No Flue

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

$$Q_w = C\, f_w\, P_w^{\ n} \qquad (14)$$

where C has already been defined, and the reference wind pressure is

$$P_w = \rho_o \frac{(S_w U_e)^2}{2} \qquad (15)$$

U_e = unobstructed wind speed (with no local shelter) at eaves height at the building site

f_w = wind factor

S_w = local wind shelter coefficient

To derive an exact numerical solution for f_w, the wind pressure coefficient data set of Akins (1979) was used, with wind normal to the upwind wall, and all walls of the same length (square floor plan). The approximating function developed for AIM-2 to fit the exact numerical solution is

$$f_w = 0.19(2-n) \left[1 - \left(\frac{X+R}{2} \right)^{3/2} \right] \qquad (16)$$

Both the LBL and AIM-2 models make the implicit assumption that f_w does not change significantly with wind direction. This assumption was checked by using wind direction dependent pressure coefficients from Akins (1979) and found to introduce a variability of about ± 10%. 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 produce wind factors that are functionally similar, but with a difference in magnitude. The two extreme results are from Wiren's and ASHRAE's data sets, and these produce values of f_w that are respectively 10-20% larger and 10-20% smaller compared to the values of f_w found using Akins data set.

It is interesting to compare the wind factor f_w in (16) with Sherman and Grimsrud's approximation

$$Q_w = A_o f_{w,LBL} \left(\frac{2\,P_w}{\rho_o} \right)^{0.5} \tag{17}$$

Equating this to (14) with $S_w = 1.0$ for no shielding yields, for $n = 0.5$

$$\left(\frac{2}{\rho_o} \right)^{0.5} A_o f_{w,LBL} = C\, f_w$$

Then, using (11) with $n = 0.5$ we see

$$f_{w,LBL} = f_w \tag{18}$$

Using (18), Sherman's approximating function is, for no shielding (i.e. using the largest value for his generalized shielding coefficient)

$$f_{w,LBL} = 0.324\ (1 - R)^{1/3} \tag{19}$$

For all leaks in the walls, $R = 0$ and $X = 0$ and $n = 0.5$, (16) predicts $f_w = 0.285$, about 10% less than Sherman's value in (19). The assumptions for floor level and attic pressure coefficients in Sherman's LBL model make (19) independent of the difference factor X between ceiling and floor level leakage. In AIM-2, there is a strong dependence of f_w on X in (16) caused by our assumptions for attic and floor level pressures. This is shown graphically in Fig. 2, with $n = 2/3$.

AIM-2 Stack Effect-With Flue

With a flue, the model becomes more complicated because both the size and height of the flue are variables in a non-linear flow network. Numerical solutions to the exact flow balance equation were approximated by algebraic functions for use in AIM-2. In addition to the distributed leakage of the building envelope expressed in terms of R, X and Y, we require the normalized height β_f of the flue,

$$\beta_f = \frac{H_f}{H} \tag{20}$$

Where: H_f = Height of flue top

H = Building eave height

In both the exact numerical solution, and the approximating functions developed for AIM-2, the flue is assumed to be filled with air at indoor room temperature. The air flow induced during combustion when the flue is hot is neglected.

The stack factor f_s in (7) was found by a numerical solution of the non-linear inflow-outflow balance equations, and is approximated in AIM-2 by the function

$$f_s = \left(\frac{1 + nR}{n+1} \right) \left(\frac{1}{2} - \frac{1}{2} M^{5/4} \right)^{n+1} + F \tag{21}$$

where

$$M = \frac{(X + (2n+1)Y)^2}{2-R} \qquad \text{for} \quad \frac{(X + (2n+1)Y)^2}{2-R} \leq 1 \tag{22}$$

with a limiting value of

$$M = 1.0 \qquad \text{for} \quad \frac{(X + (2n+1)Y)^2}{2-R} > 1 \tag{23}$$

The additive flue function F is,

$$F = nY(\beta_f - 1)^{\frac{3n-1}{3}} \left[1 - \frac{3(X_c - X)^2 R^{1-n}}{2(\beta_f + 1)} \right] \tag{24}$$

where

$$X_c = R + \frac{2(1-R-Y)}{n+1} - 2Y(\beta_f - 1)^n \tag{25}$$

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 cause ice to form in attic insulation in winter. The role of the flue in reducing ceiling exfiltration is evident from the contribution of the Y factor in (25).

The functions in (21) to (25) reduce to (9) when Y = 0. The stack factor calculated using equation (21) is shown in Fig. 3 for typical values of n = 2/3, β_f = 1.5 and Y = 0.2. 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, as can be seen by comparing Fig. 1 and 3.

AIM-2 Wind Effect - With Flue

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 recommended approximating function for wind factor is

$$f_w = 0.19(2-n)\left\{1 - \left(\frac{X+R}{2}\right)^{3/2-Y}\right\} - \frac{Y}{4}\,(S - 2YS^4) \tag{26}$$

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

The functional form for f_w was chosen to produce the correct behavior 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. The flue height β_f does not appear in (26), because, in the exact solution the dependence on β_f is felt very weakly through the change in windspeed at the flue top. When Y = 0 (26) reduces to (16), the relationship for f_w, with no flue. The wind factor calculated from equation (26) is shown in Fig. 4 for n = 2/3, Y = 0.2. Comparing Fig. 2 with no flue to Fig. 4 with a flue, we see that there is little effect on wind factor f_w of 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. We will show later that 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.

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. Using this assumption to find wind factor yields a different empirical approximation, f_{wc}, for a house with a crawl space,

$$f_{wc} = 0.19(2-n)\ X^{*}R^{*}Y^{*} \qquad (26a)$$

where

$$R^{*} = 1 - R\left(\frac{n}{2} + 0.2\right)$$

$$Y^{*} = \left(1 - \frac{Y}{4}\right)$$

$$X^{*} = 1 - \left(\left(\frac{X - X_s}{2 - R}\right)^{2}\right)^{0.75}$$

where

$$X_s = \left(\frac{(1-R)}{5}\right) - 1.5Y$$

There is a critical value of the floor-ceiling difference fraction, X_{crit}, above which f_w does not change with X,

$$X_{crit} = 1 - 2Y$$

If $X > X_{crit}$ then use $X = X_{crit}$

For the case where all the leaks are in the walls, R = 0 and the wind factor for a house with a crawl space is $f_{wc} = 0.276$, which is 15% below Sherman's estimate (19) and 3% less than for a house with no crawl space (26).

Adjusting Windspeed for Local Terrain

Surrounding buildings, vegetation and terrain produce two types of wind shelter. Very near the building local obstructions caused by trees and neighboring structures located within two house heights provide direct shielding. This important source of wind shielding will be dealt with later by a shelter coefficient. A second type of shelter is provided by the overall terrain roughness that extends several kilometers upwind of the buildings. This roughness will change the shape of the wind velocity profile. Because windspeed is measured at an airport meteorological tower at a height z_m, usually in open flat terrain, some adjustment is required to estimate the wind speed at eaves height H in the local building terrain (neglecting specific nearby obstructions). One simple method of accounting for these differences in measuring heights (z_m and H) and in terrain roughness is to use a power law profile $U \propto z^p$ for mean windspeed with height above ground. Irwin (1979) gives values of the exponent p for varying terrain roughness and atmospheric stability classes. Then, if we assume that the windspeed at the surface influenced boundary layer height $z \simeq 600$ m is the same above the airport and the building site, the wind speed at eaves height H is

$$U_e = \left(\frac{600}{z_m}\right)^{p_m} \left(\frac{H}{600}\right)^{p_s} U_{met} \tag{27}$$

where

z_m = height at which met. station wind is measured, m.

H = building eaves height above ground

p_m = windspeed exponent at met station

p_s = wind speed exponent at building site

U_e = unobstructed windspeed at building eaves height

U_{met} = windspeed recorded at met. station

The eave height can be estimated from

$$H = 0.5 + 2.5\ N \tag{28}$$

where H is in meters, and N is the number of stories. To simplify the process of estimating wind effects we will reduce Irwin's six stability classes to two by assuming that met. tower windspeeds greater than 3 m/s occur in neutral stability (class D) and less than 3 m/s are in stable conditions (class E). Table 1 gives values of p for three different levels of terrain roughness, defined quantitatively by their roughness scaling lengths z_o. (This roughness scaling length is derived from the log-law velocity variation, and is typically about 3% of the largest roughness element height). For airport met. tower locations the "mixed woods and fields" terrain Class 2 is often a reasonable approximation.

Table 1 Windspeed Power Law Exponent p for Adjusting Meteorological Tower Windspeeds to Local Building Sites Irwin (1979)

Terrain Class	Terrain Roughness	U_{met}>3 m/s neutral stability Class D	U_{met}<3 m/s stable Class E
1	Open Flat Terrain Rural Grassland z_o = 1 cm	0.12	0.34
2	Suburban Detached Housing Mixed Woods and Fields z_o = 10 cm	0.16	0.32
3	Dense Urban Housing with Multi Story Buildings Heavy Forests z_o = 100 cm	0.27	0.38
4	High Rise Urban Centers z_o = 300 cm	0.37	0.47

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 (14) 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, combined with a different coefficient S_{wflue} for the top of the flue stack gives an improved estimate of the total local shielding. A simple linear combination is used in AIM-2,

$$S_w = S_{wo}(1 - Y) + S_{wflue}(1.5Y) \tag{29}$$

where the factor 1.5 is an empirical adjustment found by comparing AIM-2 to an exact numerical solution using local leaks, each with their own pressure coefficients. $S_{wflue} = 1.0$ 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. With no flue, $Y = 0$ and $S_w = S_{wo}$.

Due to the difficulty in accurately estimating the effects of local wind shielding, the proposed values in Table 2 give only a rough approximation for the shelter coefficient. This table uses the shielding class description suggested by Sherman and Grimsrud (1980), with the addition of a new class of "complete shielding". However, it is important to note that although the terrain classes are the same, the values for S_{wo} suggested in AIM-2 are not the same as Sherman and Grimsrud's "generalized shielding coefficient" used in the LBL and variable n models.

TABLE 2. Estimates of Shelter Coefficient S_{wo} for No Flue

Shelter Coefficient S_{wo}	Description
1.00	No obstructions or local shielding
0.90	Light local shielding with few obstructions within two house heights
0.70	Heavy shielding, many large obstructions within two house heights
0.50	Very heavy shielding, many large obstructions within one house height
0.30	Complete shielding, with large buildings immediately adjacent

In general, the local shelter coefficient S_w will be a function of wind direction. Using a single shelter coefficient for a building will yield inaccurate results if the building is not equally sheltered for all wind directions. In applying AIM-2 we recommend that the shelter coefficient be estimated for each side of the building, and the average value for the upwind walls be used for each hourly wind speed and direction.

Validation of AIM-2 and Comparison with Other Models

AIM-2 has been validated by comparing its predictions to air infiltration measurements in two houses at the Alberta Home Heating Research Facility. The home heating research facility consists of six unoccupied test houses that have been continuously monitored since 1981 for building energy uses and air infiltration rates. The test houses are located on an agriculture research farm about 10 km south of the city of

Edmonton, and are situated in a closely spaced east-west line with about 2.8 m separation between their side walls. False end walls, with a height of 3.0 m but without roof gable peaks, were constructed beside the end houses (houses 1 and 6) to provide equivalent wind shelter and solar shading. Construction details are given in Table 3 for houses 4 and 5 used in the validation study reported here.

The flat exposed site is surrounded by rural farmland, whose fields are planted with forage and cereal crops in summer, becoming snow-covered stubble in winter. Windbreaks of deciduous trees cross the landscape at intervals of a few kilometers, with one such windbreak located about 240 m to the north of the line of houses. The houses are totally exposed to south and east winds. Several single-story farm buildings, located about 50 m to 100 m to the west, provide some shelter from west to northwest winds.

Micrometeorological towers are located midway along the row of houses on both the north and south sides of the line of houses. The wind speed and direction at a 10 m height are measured with low friction cup anemometers and vanes on both towers. The tower windspeed accounts for local terrain effects, including the shelter from farm buildings and local windbreaks. These on-site measurements require only a correction for tower to eaves height, so that $p_m = p_s = 0.16$ was used in (27), with $H = 3$ m and $z_m = 10$ m.

Continuous infiltration measurements were carried out in the six test houses using a constant concentration SF_6 tracer gas injection system in each house. Two independent infrared analyzers sampled three houses in sequence through a manifold controlled by solenoid valves, as described in Wilson and Dale (1985). It is important to note that the measured data were not used to adjust any model coefficients, except to find a suitable value for B_1. The validation carried out here used data sets with stack and wind dominated extremes, so that determining B_1 from the measured data had a negligible effect on model validation.

Envelope leakage characteristics were measured in the two houses using a fan pressurization test over the range from 1 Pa to 75 Pa, from which C, n and the ΔP_{ref} = 4 Pa leakage area A_o can be found:

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

The leakage distribution was estimated by inspection at the test facility. 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 15cm 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 differences between measured infiltration rates and those predicted by AIM-2 can be characterized by two statistical quantities:

bias and scatter. The bias can be thought of as the error in the magnitude of the proportionality constants of the model equations, and the scatter as the errors (and omissions of relevant variables) in the functional form of the equation. The bias indicates the average error that would be obtained over a long time period for all windspeeds and temperature differences, and is found from the variation between the calculated values and the mean measured value in each of the windspeed ranges shown in Figures 5 through 8. The measured data was averaged in bins 1 m/s wide. For each bin the mean is shown by a square symbol and one standard deviation by error bars. The scatter indicates the error that occurs for a single windspeed and temperature difference rather than long time averaged mean values, and is found by subtracting the bias from the calculated values and then averaging the absolute error for each windspeed range bin. The other models included for comparison are:

- The LBL (USA) model (Sherman and Grimsrud (1980))
- The IRC/NRC (Canada) Variable n extension of the LBL model from Yuill (1985) and Reardon (1989)
- The NRC (Canada) model of Shaw (1985)
- The BRE (U.K.) model of Warren and Webb (1980)

The predictions of AIM-2 and these four models, are compared to measured data in Table 4 for unsheltered North and South wind direction conditions 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 and without furnace flues because the furnace flue is treated as a separate leakage site with its own wind pressure and wind shelter coefficients. The same data used to calculate bias and scatter in Table 2 are shown graphically in Figures 5 and 6.

Figure 7 compares the windspeed dependence of the models for house 5 with an open 15 cm diameter flue where the house is heavily sheltered in East and West winds. The shelter in this case is from the neighboring houses in the row, where the gap between the houses is approximately three metres (about one half of the house height). Warren and Webb's and Shaw's models have relationships for sheltered or unsheltered buildings, but with no variation in the degree of shelter. For these two models the sheltered building relationships were used. The LBL and IRC/NRC variable n models both use the same table of values for shelter that is originally from LBL, and the shelter coefficient that most closely matches the shelter condition for this case was chosen.

For AIM-2, $S_W = 1.0$ was used for unsheltered conditions, and "very heavy shielding" $S_W = 0.5$ was used for the sheltered case, see Table 2. In AIM-2 the shelter coefficient S_W appears directly as a windspeed multiplier, and is the ratio of an effective sheltered windspeed, $U_{sheltered}$ to the unsheltered windspeed, $U_{unsheltered}$. An equivalent value of S_W may be found for each model using (29).

$$S_w = \frac{U_{sheltered}}{U_{unsheltered}} = \left(\frac{Q_{w,sheltered}}{Q_{w,unsheltered}} \right)^{1/2n} \tag{29}$$

Substituting the appropriate equations for flowrate, with their different shelter coefficients, and assuming a typical value of $n = 2/3$, values of effective S_W for each model are summarized in Table 5, and range from 0.32 for the LBL model to a physically unrealistic value of 1.5 for Shaw's model at a windspeed of 1 m/s.

All the models except AIM-2 underpredict the wind effect infiltration rate Q_W significantly because they cannot have unshielded flue leakage with a shielded building. A summary of the bias and scatter for each model is given in Table 6.

Figure 8 illustrates the temperature difference dependence of the models for house 4 with a 7.5 cm diameter restriction orifice in the flue. A summary of the bias and scatter for each model is given in Table 7. As before, AIM-2 gives the best overall agreement, because it allows the flue leakage to be above the ceiling height for stack effect.

In almost all cases the LBL model has the greatest scatter. This is because its assumption of orifice flow for the building envelope produces an incorrect variation in ventilation rate with windspeed and temperature difference.

Another significant source of error, common to all ventilation models, lies in trying to predict ventilation rates based on weather data measured at a site remote from the building under study. This is a common practice since most meteorological data that is generally available is measured at airports in flat unobstructed terrain. The wind speed must be corrected for differences between the measurement site and the building due to changes in terrain and localized shelter effects. The procedure used in AIM-2 uses simple methods to correct the windspeed to account for local shelter and differences between typical rural and urban terrain and makes no attempt to correct the wind direction which may be altered by both natural and man made structures (river valleys, hills, high rise towers, etc.). For the test results presented here, all the meteorological data was measured on site and these difficulties were not encountered.

Effect of Changing Leakage Distribution on Model Predictions

To test the effect of leakage distribution, four different values for the parameters R and X were chosen with Y (the fraction of leakage in the flue) and β_f (the nondimensional flue height) unchanged. The resulting model predictions were compared to data where stack effect dominates, taken in house 4 with a 7.5 cm diameter orifice in the flue. The sum of ceiling and floor leakage R was varied from zero to 0.4, and X (the difference between ceiling and floor leakage) was varied from -0.1 to +0.2. The fraction of flue leakage, Y, was constant at 0.4, and the nondimensional flue height, β_f, was 1.5. Shaw's and Warren and Webb's models do not have leakage distribution parameters, and their predictions do not change for these different cases.

The models compared in this section are AIM-2, LBL and the Variable n model. The case of R=0.3, and X=0 is used as a basis for comparison. The results show that the scatter is not significantly changed by the leakage distribution parameters, as one would expect, because R, X, Y and β_f do not change the functional forms of the equations predicting the flowrates. Instead, these parameters change the lead constants, the stack and wind factors, f_s and f_w, and will affect only the bias.

- For R = 0.2 and X = -0.1, the models increase their predicted values by less than 8%, so that AIM-2 now overpredicts by 5.1% rather than underpredicting by 3.4%, and the underpredictions of the LBL and Variable n models are less by a similar amount.
- For R = 0 and X = 0, with all the non-flue leakage in the walls (not a typical leakage distribution), the model predictions are changed by less than 6%, a relatively small amount with AIM-2 underpredicting less, and LBL and the Variable n model underpredicting more.

- The third distribution uses R = 0.4 and X = +0.2. Unlike putting all the leakage in the walls this does not seem an unlikely leakage distribution, yet it yields predictions reduced by about 20% for all three models.

These tests show that correctly estimating leakage distribution can be an important factor in predicting ventilation rates. However, it also shows that it is possible for an atypical leakage distribution to produce reasonable results.

Conclusions

- Including the furnace flue as a separate leakage site allows AIM-2 to account for the effect of the flue on natural ventilation rates much better than the other models tested here.
- Using a power law pressure-flow relationship for the building envelope ensures that AIM-2 has the correct variation with changes in windspeed and indoor-outdoor temperature differences.
- Model predictions are highly dependent on estimates of wind shelter that can be difficult to quantify. Table 2 shows that different estimates of this factor can vary the predicted ventilation rate by a factor of two.
- Models that use leakage distribution parameters R, X and Y are sensitive to the choice of these parameters. Typical variability in estimating these parameters can change the predicted infiltration rates by up to 20%.

Finally, the use of on-site meteorological towers removed the need for transferring wind data from an airport location to the site. The uncertainty associated with the process should be examined in future studies.

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List of Figures

Table 3 Construction Details of Houses Tested at AHHRF

House #4

Floor Area: 6250 x 6860 mm

Wall Height: 2440 mm

Basement Height: 2440 mm, 1830 mm Below Grade

Walls: 9.5 mm Prestained Rough Tex Plywood
50 mm Rigid Insulation
50 mm x 100 mm studs with fiberglass batt insulation
0.228 mm polyethylene Vapour Barrier
13 mm Painted Gypsum Wallboard

Windows: North : None
South : 2 - 2870 x 910 mm double glazed sealed
East : 1090 x 1065 mm double glazed opening
West : None

Ceiling: 9.5 mm plywood sheathing
0.228 mm polyethylene Vapour Barrier
13 mm Gypsum Wallboard

Door: 910 x 2030 mm insulated metal

House #5

Floor Area: 6250 x 6860 mm

Wall Height: 2440 mm

Basement Height: 2440 mm, 1830 mm Below Grade

Walls: 9.5 mm Prestained Rough Tex Plywood
50 mm x 100 mm studs with fiberglass batt insulation
0.152 mm polyethylene Vapour Barrier
13 mm Painted Gypsum Wallboard

Windows: North : 990 x 1950 mm double glazed sealed
South : None
East : 1000 x 1950 mm double glazed opening
West : 1000 x 1950 mm double glazed opening

Ceiling: 9.5 mm plywood sheathing
0.152 mm polyethylene Vapour Barrier
13 mm Gypsum Wallboard

Door: 910 x 2030 mm insulated metal

Table 4 Model Errors for Binned Averages of Wind Dominated Ventilation for Unsheltered Buildings at AHHRF*

	House #4 Flue Closed		House #5 15 cm Flue Open	
Model	Bias	Scatter	Bias	Scatter
AIM-2	10% (0.008)	3% (0.002)	-8% (-0.022)	4% (0.011)
LBL (Sherman)	34% (0.018)	18% (0.016)	-20% (-0.061)	6% (0.016)
Variable n (Yuill)	25% (0.022)	4% (0.003)	-22% (-0.059)	3% (0.009)
Shaw	45% (0.038)	2% (0.002)	-12% (-0.038)	8% (0.017)
Warren and Webb	4% (0.005)	5% (0.003)	-19% (-0.051)	2% (0.009)

* - Values in brackets are in Air Changes per Hour, ACH.

Table 5 Equivalent Shelter Coefficients for simple ventilation models for East and West winds

Model	Wall Shelter Coefficient, Sw	Flue Shelter Coefficient, Swf
AIM-2	0.5	1.0
Variable n	0.32	0.32
LBL	0.32	0.32
Warren and Webb	0.70	0.70
Shaw U=1 m/s	1.5	1.5
Shaw U=5 m/s	0.5	0.5

Table 6 Model Errors for Binned Averages of Wind Dominated Ventilation for a Sheltered Building at AHHRF*

	House #5 15 cm Flue Open	
Model	Bias	Scatter
AIM-2	-12% (-0.041)	4% (0.011)
LBL (Sherman)	-60% (-0.199)	28% (0.078)
Variable n (Yuill)	-66% (-0.215)	23% (0.063)
Shaw	-29% (-0.122)	30% (0.084)
Warren and Webb	-35% (-0.112)	6% (0.014)

* - Values in brackets are in Air Changes per Hour, ACH.

Table 7 Model Errors for Binned Averages of Stack Dominated Ventilation at AHHRF*

	House #4 7.5 cm Flue Open	
Model	Bias	Scatter
AIM-2	-3.4% (-0.005)	1.5% (0.002)
LBL (Sherman)	-14.1% (-0.019)	6.9% (0.008)
Variable n (Yuill)	-26.1% (-0.032)	1.7% (0.002)
Shaw	42.6% (0.051)	1.9% (0.002)
Warren and Webb	-44.2% (-0.054)	5.1% (0.006)

* - Values in brackets are in Air Changes per Hour, ACH.

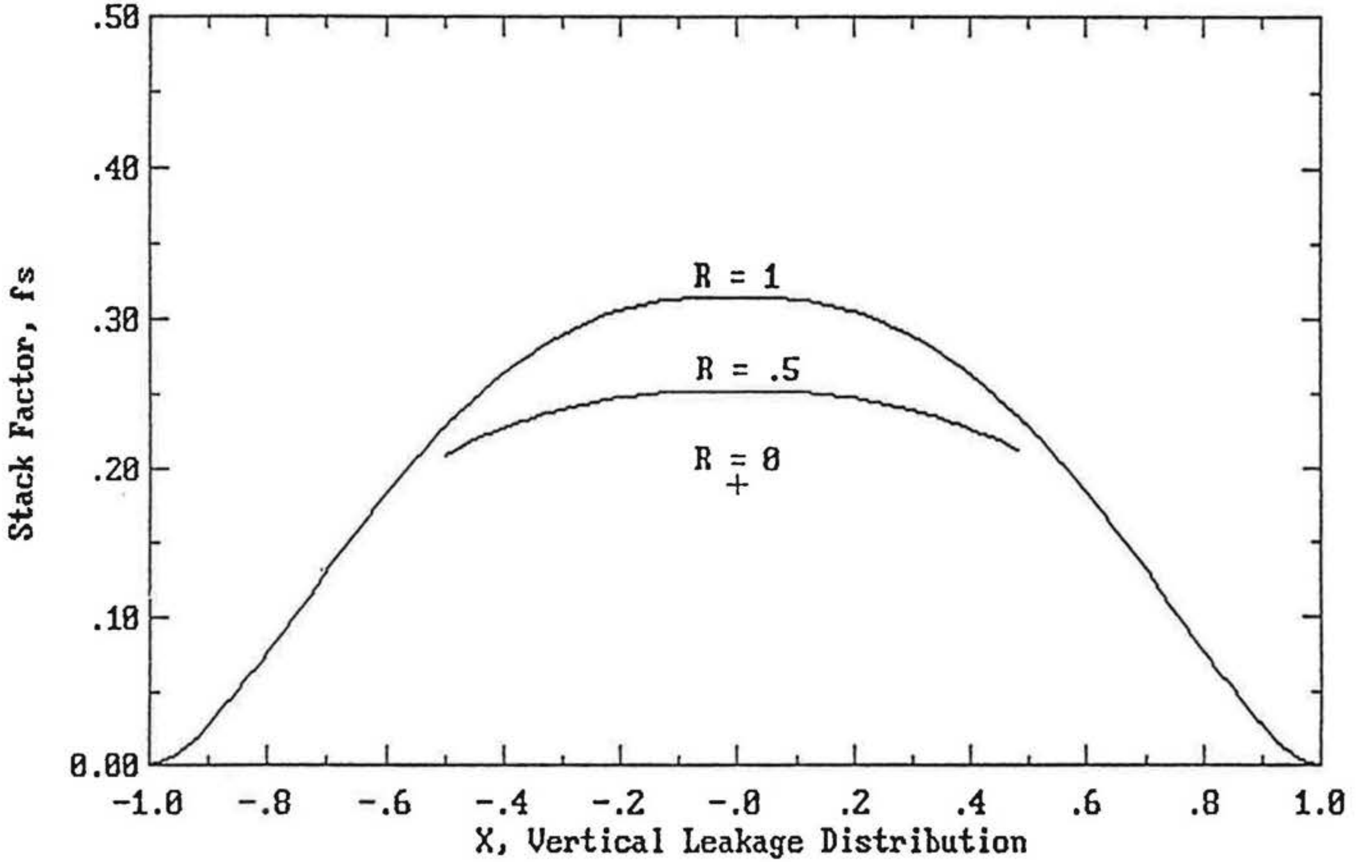

Figure 1 AIM-2 function (Equation 9) for Stack Factor, f_s, with no Flue Leakage (Y=0)

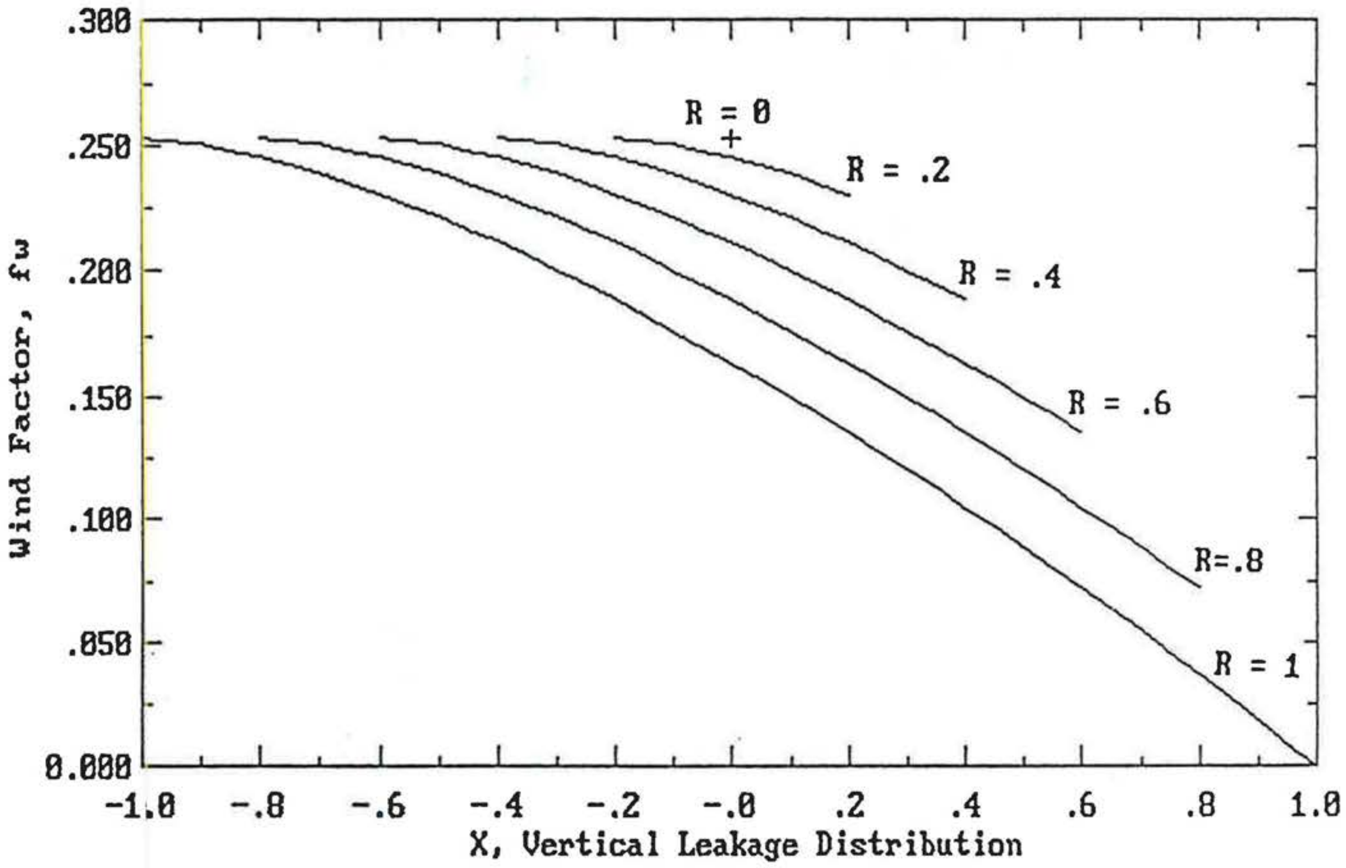

Figure 2 AIM-2 (Equation 16) for Wind Factor, F_W, with no Flue Leakage (Y=0)

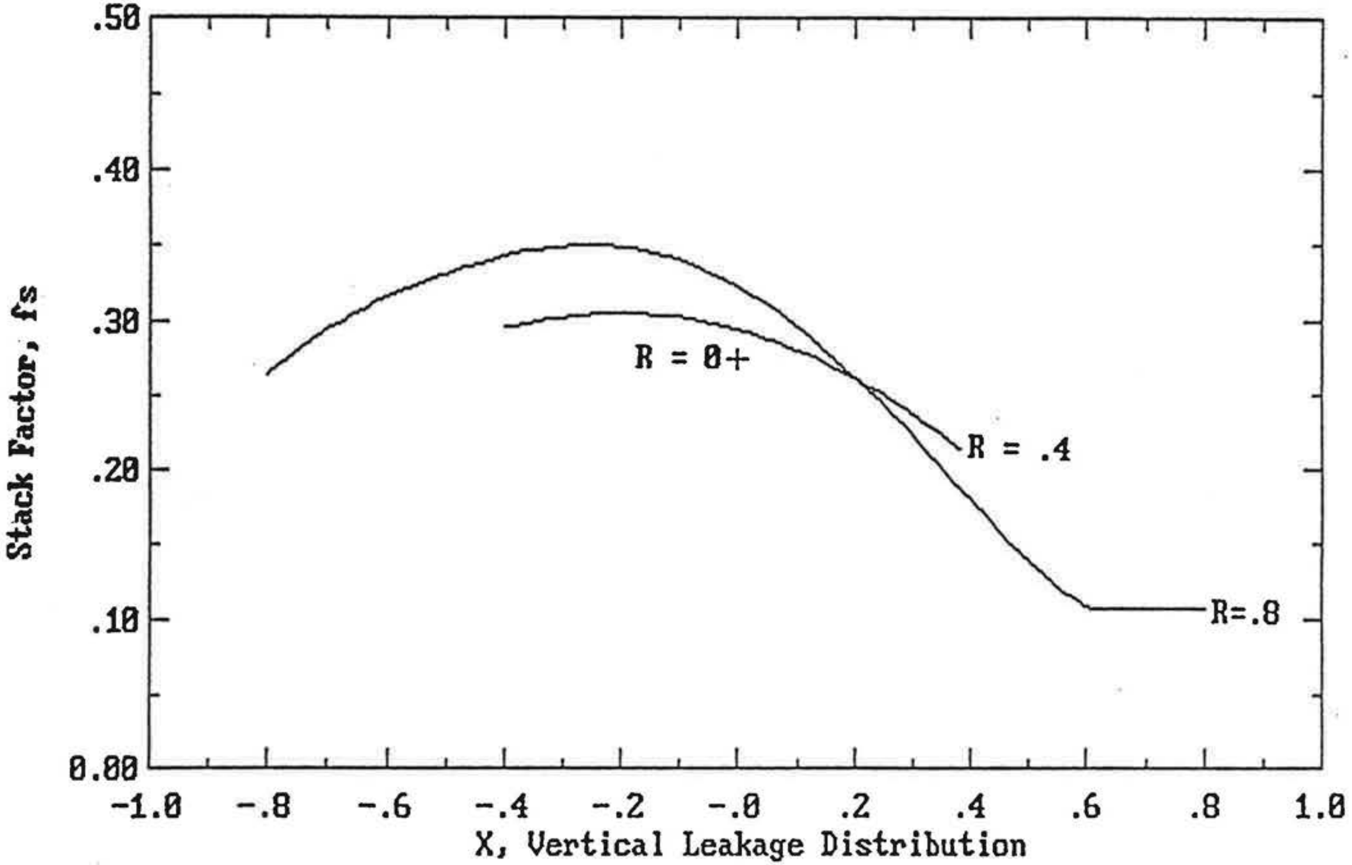

Figure 3 AIM-2 (Equation 21) for Stack Factor, f_s, with 20% of Leakage in the Flue (Y=0.2), and β_f=1.5

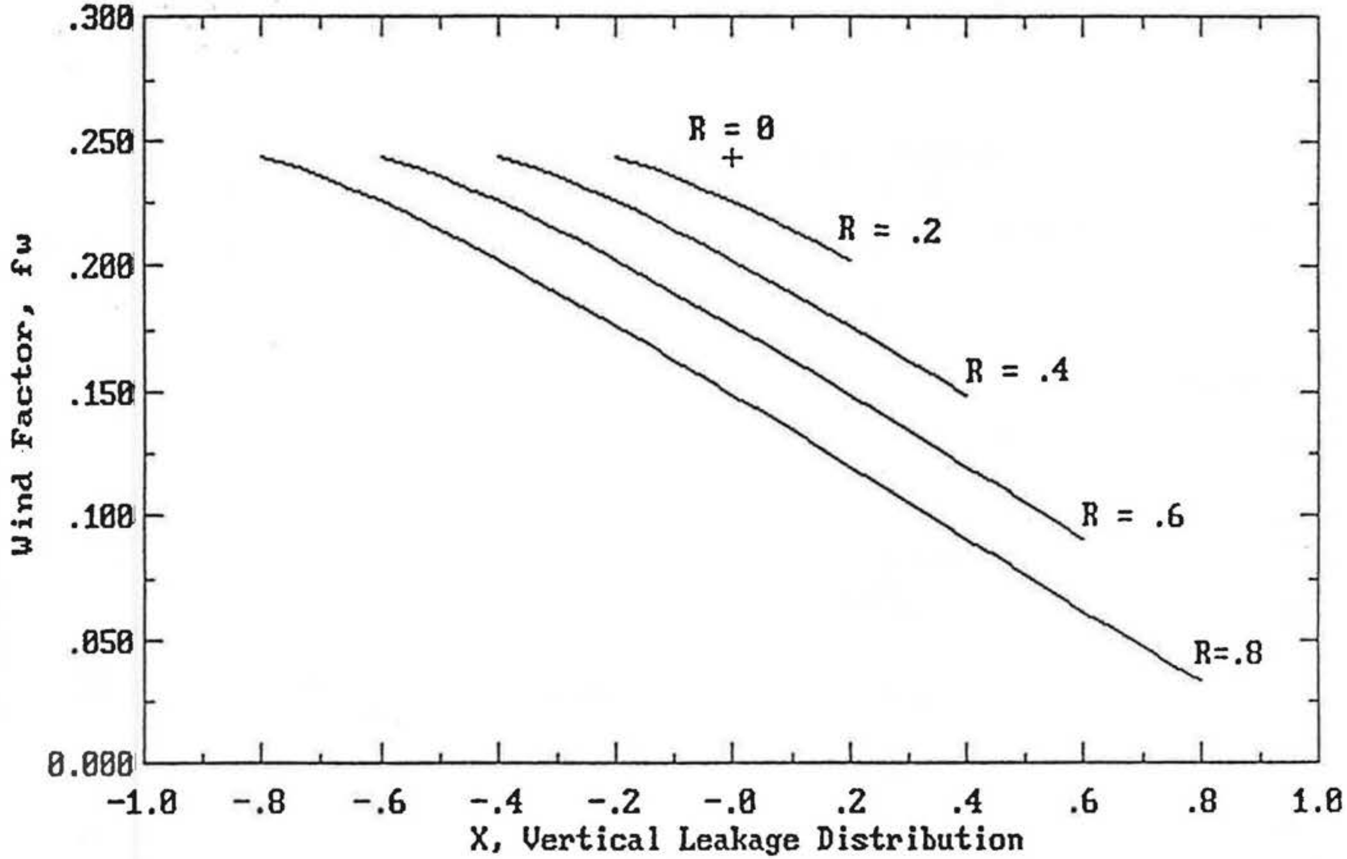

Figure 4 AIM-2 (Equation 26) for Wind Factor, f_w, with 20% of Leakage in the Flue (Y=0.2), and β_f=1.5

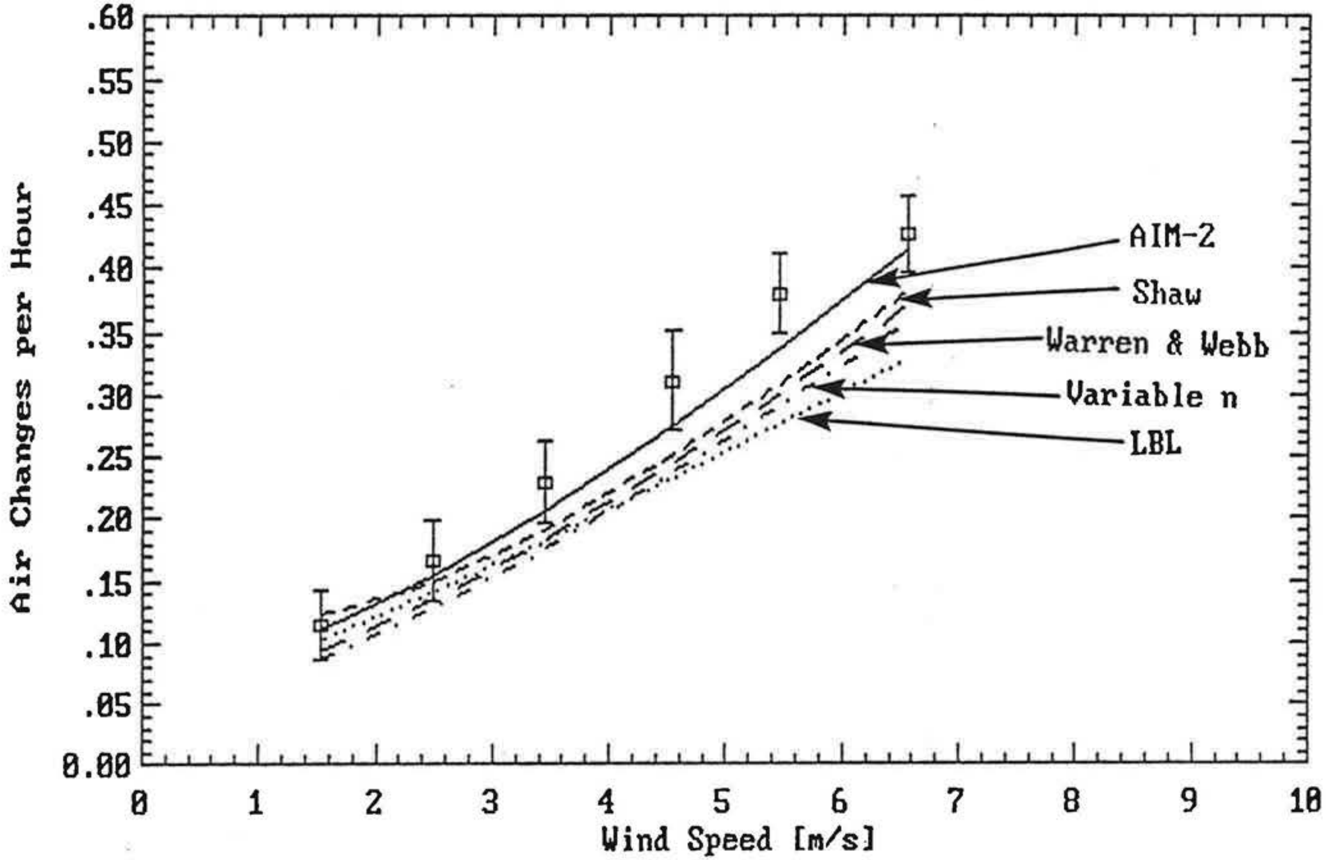

Fig. 5 Comparison of Ventilation Models with measured data for Unshielded Windspeed dependance (North and South Winds) in House #5 with an open 15cm diameter flue with $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s (279 hours)

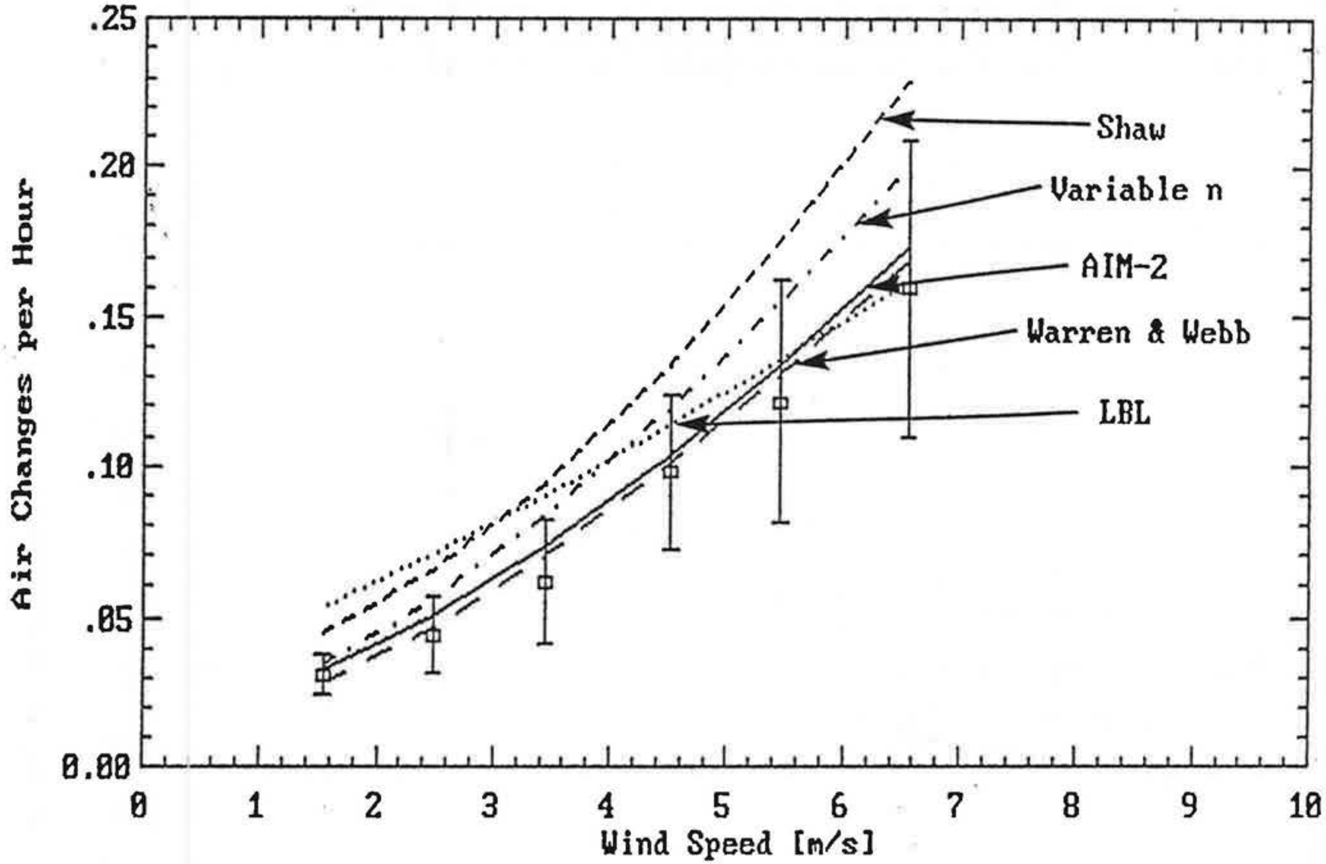

Fig. 6 Comparison of Ventilation Models with measured data for Unshielded Windspeed dependance (North and South Winds) in House #4 with blocked flue, and $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s (285 hours)

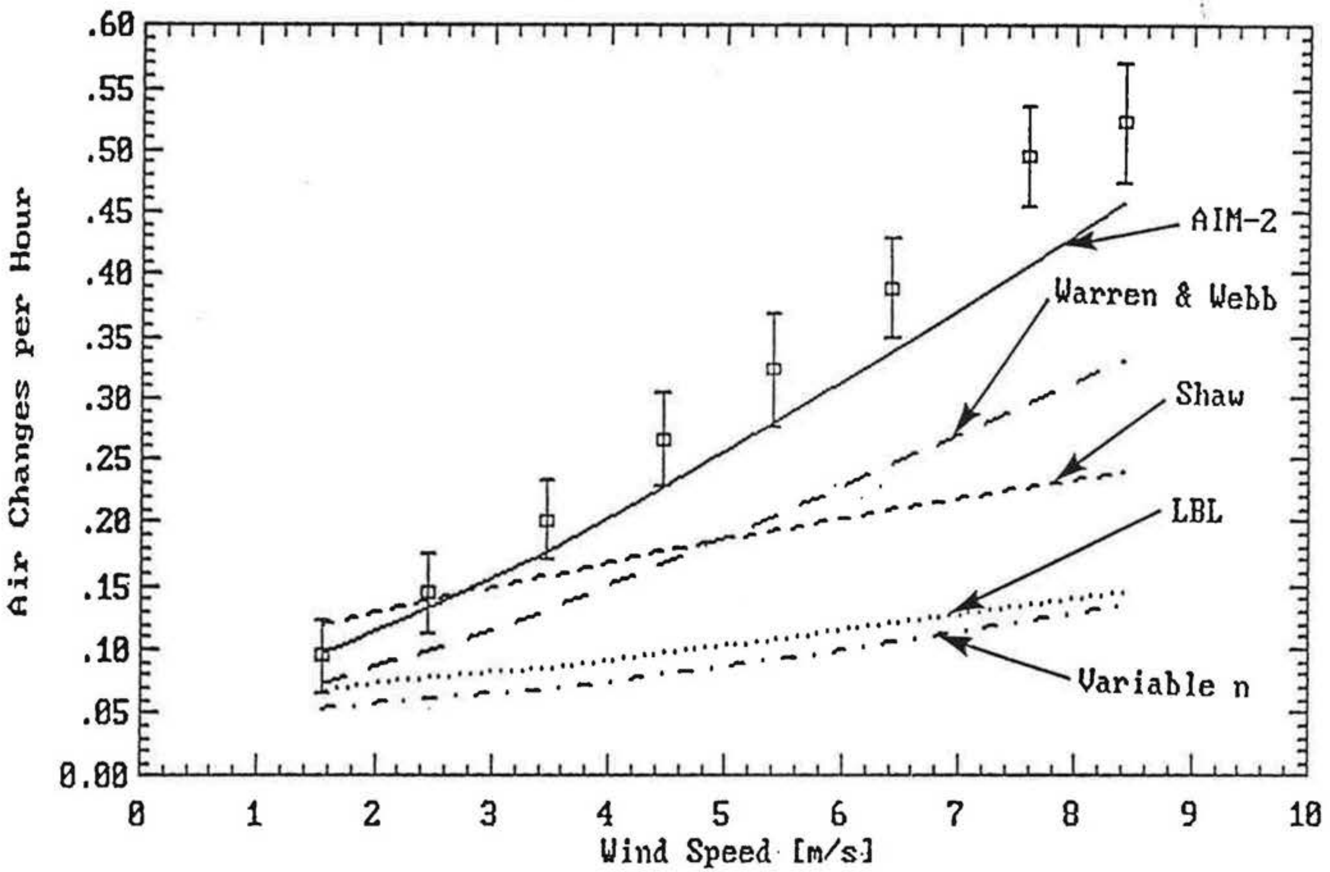

Fig. 7 Comparison of Ventilation Models with measured data for Shielded Windspeed dependance (East and West Winds) in House #5 with an open 15cm diameter flue with $\Delta T \leq 10°C$ and $U \geq 1.5$ m/s (461 hours)

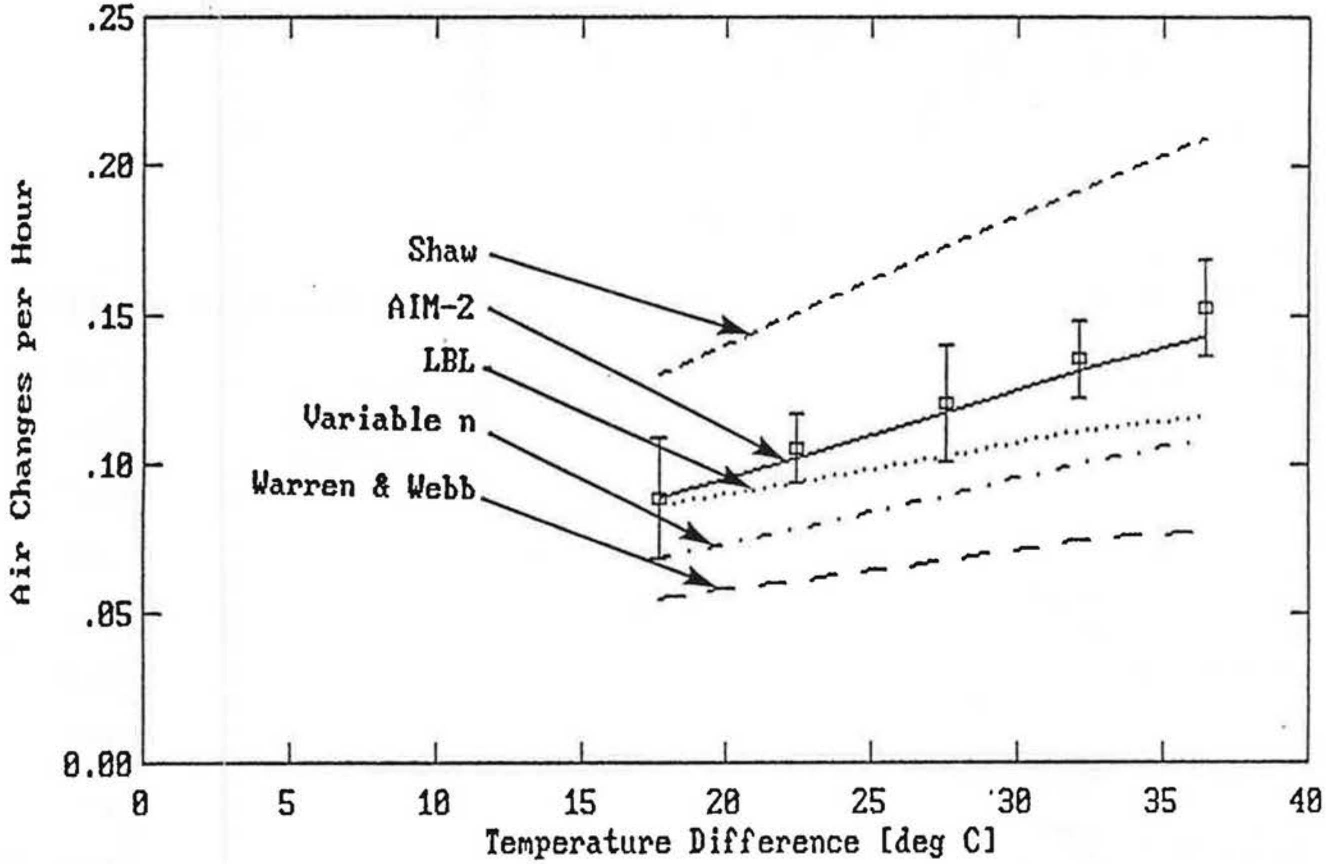

Fig. 8 Comparison of Ventilation Models to measured data for ΔT dependance in House #4 with an open 7.5cm diameter orifice in the flue, with $\Delta T \geq 10°C$ and $U \leq 1.5$ m/s. R=0.3, X=0, Y=0.4, and $\beta_f=1.5$ (102 hours)