Implementing the Results of Ventilation Research
16th AIVC Conference, Palm Springs, USA
19-22 September, 1995

A Simple Calculation Method for Attic Ventilation Rates

I S Walker*, T W Forest**, D J Wilson**

* Energy Performance of Buildings Group, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, USA
** Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada

Synopsis

The ventilation of an attic is critical in estimating heating and cooling loads for buildings because the air temperature in the attic is highly sensitive to ventilation rate. In addition, attic ventilation is an important parameter for determining moisture accumulation in attic spaces that can lead to structural damage and reduced insulation effectiveness. Historically, attic venting has been a common method for controlling attic temperature and moisture, but there have been no calculation techniques available to determine attic ventilation rates. Current practice is to use rules of thumb for estimating attic vent areas.

Simple algebraic relationships are developed here, using functions fitted to an exact numerical solution for air flow through attic envelopes. This algebraic model (AVENT) was developed to be easy to use as diagnostic or design tool. Key factors included in the model are: climate (wind and stack effect), wind shelter, leakage distribution and total attic leakage.

This paper validates the model predictions by comparing to measured data from two attics at the Alberta Home Heating Research Facility (AHHRF). Average errors for the model are about 15% compared to the measured ventilation rates.

1 Introduction

The impact of attic venting on energy use and moisture control is well known. For example, in hot climates attic ventilation is used to cool the attic to reduce heating loads due to solar gain on the roof, and in cold climates attic venting is used to alleviate moisture problems. Methods for predicting attic ventilation rates are not well developed. For example, analyses of heat and moisture transport in attics by Gorman [1] and Peavy [2] used a single fixed value and simple empirical data correlations respectively. Other studies by Walker and Forest [3] have introduced a method for calculating attic ventilation rates using a numerical procedure to balance the flow equations through localised and attic envelope leaks. Walker and Forest's model works well for research level investigations, but is difficult to implement by other researchers or designers as a design or diagnostic tool.

The objective of this paper is to present a simple model that can be used to predict attic ventilation rates based on attic leakage, leakage distribution and weather conditions. Using this model for attic ventilation, building designers will be able to better optimise building performance. For example, the attic leakage may be placed at different locations (e.g. soffit, roof ridge or gable end vents) to find the effect on ventilation rate. To this end, the model developed here includes the effects of total attic venting, distribution of the attic vents and weather conditions.

2 Outline of AVENT model

The model is a set of algebraic equations that have been empirically fitted to the exact numerical solution of the flow equations for attic leaks. This is a procedure that has been used successfully by the authors for ventilation calculations for houses (see Walker and Wilson [4]). Because of the similarity of the model development procedure and the use of the same leakage and weather parameters, the empirical equations for attic ventilation have the same form as those in a house ventilation model, AIM2, developed previously by Walker and Wilson [4]. The differences will be discussed later in this paper.

The total attic leakage (determined by fan pressurization or combining vent sizes) is distributed at different locations on the attic envelope (e.g., the soffits). The leaks are separated because they are at different heights, which affects the stack effect, or because they have different surface pressure coefficients. The wind and stack induced pressures across each leak are calculated for each leakage site and the leakage coefficient and the pressures for each leak are combined to calculate flows using a power law pressure-flow relationship.

A mass balance is then performed on the sum of all leakage flows through the attic envelope. This involves a numerical solution of the non-linear pressure-flow equations. This mass balance is then used to determine empirical coefficients, stack factor, f_s, and wind factor, f_w, to multiply leakage distribution parameters and wind and stack induced pressures to determine the ventilation rate. The wind and stack effects are treated separately and then superposed to calculate the total ventilation rate.

3 Leakage Distribution

The leakage distribution determines where on the attic envelope leaks are located, and determines the stack and wind pressures they experience. The leaks are characterised by two parameters: C [m^3/sPa^n], the leakage coefficient and n, the pressure exponent that are used in the pressure-flow relationship $Q=C\Delta P^n$. For simplicity it is assumed that the same leakage exponent, n, can be applied to all the attic leaks. Using a single exponent means that the total attic leakage coefficient, C_{total}, is just the simple sum of all the separate leaks for the attic:

$$C_{total} = C_{floor} + C_{ridge} + C_{soffits} + C_{gables} + C_{pitched} \tag{1}$$

where

C_{floor} - the attic floor, the same as the ceiling of the house

C_{ridge} - the roof ridge vents

$C_{soffits}$ - the soffits under the eaves

C_{gables} - the gable end vents

$C_{pitched}$ - the pitched roof surfaces. This includes the background leakage and any vents on these surfaces (e.g., mushroom cap vents).

For stack effect calculations, the five leakage sites are differentiated by their height. The floor and gable leakage is at the bottom of the attic, the ridge vents are at the top and the pitched surface and gable end leaks are assumed to be distributed evenly with height. The information about leakage height is condensed into two parameters R and X given by Equations 2 and 3, and first suggested by Sherman and Grimsrud [5]. For an attic these are, for stack effect:

$$R_s = \frac{C_{floor} + C_{soffit} + C_{ridge}}{C_{total}} \tag{2}$$

$$X_s = \frac{C_{floor} + C_{soffit} - C_{ridge}}{C_{total}} \tag{3}$$

For wind effect, C_{floor} is exposed to the house interior pressure due to wind. Because attic floor (i.e., house ceiling) leakage rates are usually much smaller than the flow through soffit or eave vents, only a very rough approximation is required to estimate floor leakage. With this in mind, the house interior pressure is assumed to be the average of the pressure coefficients on the four walls of the house. C_{ridge} is assumed to have the same average pressure coefficient as the pitched roof surfaces. C_{soffit} and C_{gable} have the same pressure coefficients as the walls beneath them. This different grouping of leakage sites for wind effect means that R and X have to be redefined for wind effect by the following equations.

$$R_w = \frac{C_{floor} + C_{ridge}}{C_{total}} \tag{4}$$

$$X_w = \frac{C_{floor} - C_{ridge}}{C_{total}} \tag{5}$$

4 Wind Pressure Coefficients

The wind pressure coefficients for the attic floor, gable end vents and soffits are assumed to be the same as the wall beneath them. The pressure coefficients for these surfaces were taken from the wind tunnel measurements of Akins et al. [6]. This pressure coefficient data set was chosen because it presented results for many wind directions. Because Akins et. al. did not measure pressure coefficients on a range of pitched roof surfaces, the pitched roof pressure coefficients are taken from wind tunnel tests by Wiren [7]. For wind normal to the upwind side of the building, the upwind face has a Cp=0.65, the sides have Cp=–0.65 and the downwind face has Cp=–0.3. These coefficients are for an unsheltered building. Adjustments to these pressure coefficients for houses sheltering each other in a row have been discussed by Walker and Wilson [8]. An harmonic trigonometric function was developed by Walker and Wilson to interpolate between these normal values to fit the angular variation in pressure coefficients shown by Akins et. al. This function has been successfully applied to pressure coefficients for calculating attic ventilation by Walker and Forest [3] and Forest and Berg [9] using an exact numerical attic ventilation model.

For the rest of the attic leaks, the wind pressure coefficients taken from Wiren [7] are shown in Table 1.

Table 1. Roof pressure coefficients from Wiren [7].

Roof Pitch, degrees from horizontal	Upwind face	Downwind face
<10	-0.8	-0.4
10 to 30	-0.4	-0.4
>30	+0.3	-0.5

5 Stack Effect

The flow induced by stack effect, Q_s[m³/s], is assumed to have the power law form

$$Q_s = C_{total} f_s \Delta P_s^n \tag{6}$$

where f_s = stack flow factor and ΔP_s = stack effect reference pressure [Pa] given by

$$\Delta P_s = \rho_{out} g (H_p - H_e) \left(\frac{|T_a - T_{out}|}{T_a} \right) \tag{7}$$

where ρ_{out} = outdoor air density, [kg/m³]

g = gravitational acceleration [m/s²]

H_p = roof peak height above grade [m]

H_e = height of eaves or soffits above grade [m]

T_a = attic air temperature [K]

T_{out} = outdoor temperature [K].

The stack factor, f_s, was found by using a numerical solution to the attic flow equations to calculate the stack driven ventilation rate flowrate, Q_s. This was substituted into Equation 6, which was then solved for f_s. Q_s and f_s were calculated over a wide range of R_s, X_s and flow exponent, n. The algebraic approximation for stack factor was developed to give the same dependence of f_s on these parameters as the exact numerical solution. This approximation is given by Equation 8. The functional form of this approximation was selected to produce the correct limits of f_s when all leakage is concentrated in the pitched roof surfaces (i.e., no soffit or gable vents and $R_s = 0$), in the floor, eaves and roof ridge ($R_s = 1$), and for the ceiling-floor difference ratio limits of $X_s = 0$ and $X_s = +/- 1$.

$$f_s = \left(\frac{1 + nR_s}{n+1} \right) \left(\frac{1}{2} - \frac{1}{2} \left(\frac{X_s^2}{2 - R_s} \right)^{\frac{5}{4}} \right)^{n+1} \tag{8}$$

Equation 8 is the same as stack factor for a house with no furnace flue in AIM2, except that the leakage distribution coefficient definitions have changed to suit attic leakage locations. The stack factor calculated using Equation 8 is shown in Figure 1 together with the exact numerical stack factor. Figure 1 shows that the difference between exact and approximate f_s is typically a few percent, and that the stack factor (and therefore ventilation rate) is highly dependent on leakage distribution.

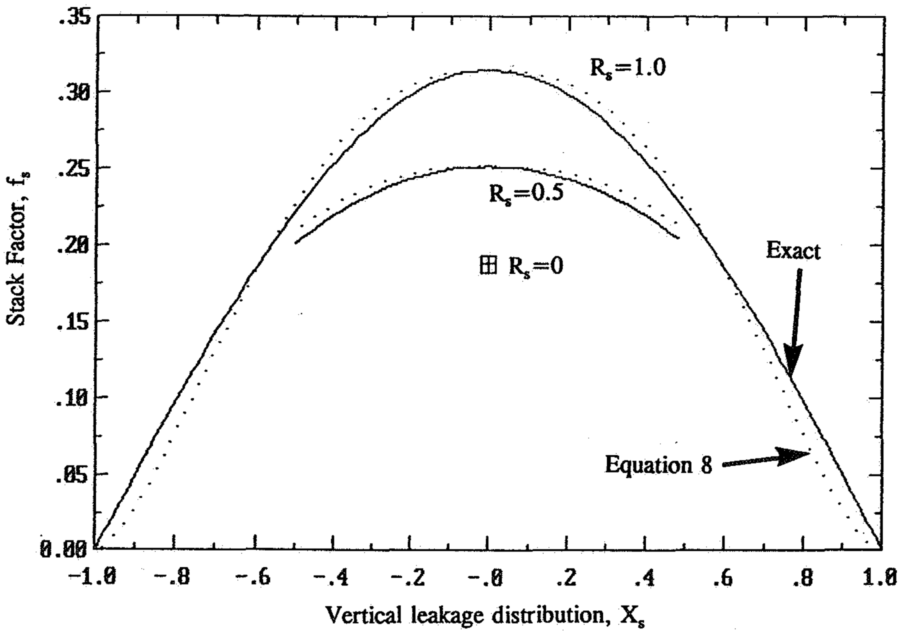

Figure 1. Comparison of stack factor, f_s, from exact numerical calculations and empirical approximation.

6 Wind Effect

The wind induced infiltration rate, Q_w[m³/s] is defined in terms of wind factor f_w by

$$Q_w = C_{total}\ f_w\ \Delta P_w^n \tag{9}$$

The reference wind pressure, ΔP_w is given by

$$\Delta P_w = \frac{\rho_{out}(S_w U)^2}{2} \tag{10}$$

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

S_w = local wind shelter coefficient.

S_w is 1.0 for an unsheltered attic and 0 for a completely sheltered attic. Values of S_w must be estimated for the building location. Methods for estimating S_w are outlined by Walker and Wilson [8], including an interpolation method for calculating S_w for any wind direction.

The wind factor, f_w, was found by using the exact numerical solution to determine Q_w. This value for Q_w was then substituted into Equation 9, which was solved for f_w. As with the stack factor calculations, the approximating function for f_w was found by calculating f_w over a wide range of leakage parameters and finding functional forms that would reproduce the same characteristic dependence on these parameters. The wind factor, f_w, is given by

$$f_w = 0.15(2-n)\,X^* R^* \tag{11}$$

where

$$R^* = 1 - R_s\left(\frac{n}{2} + 0.2\right) \tag{12}$$

$$X^* = 1 - \left(\left(\frac{X_s - \left(\frac{1-R_s}{5}\right)}{2-R_s}\right)^2\right)^{0.75} \tag{13}$$

The main difference between the above relationship for f_w and that given by Walker and Wilson [4] for houses is the change in lead coefficient to **0.15** (from 0.19). This change is due to different pressure coefficients used for the attic. The value 0.15 is for roofs with pitches between 10 and 30 degrees (which covers most roofs). The change of pressure coefficients with roof pitch given by Table 1 changes this lead coefficient by typically less than 5%, except at extreme leakage distributions (i.e. no soffits, gable vents or floor leakage) where the change is about 25%. For simplicity a single value for this lead coefficient is adopted that covers a wide range of roof configurations.

Figure 2 compares the exact numerical and approximate value for f_w. This figure shows that typical differences between the exact and approximate f_w are about +/-5%. This figure also illustrates the strong dependence of f_w (and therefore ventilation rate) on leakage distribution.

The effect of wind angle on wind factor depends on how the pressure coefficients change with wind angle. Walker and Wilson [8] have discussed how wind pressure coefficients change with wind direction, and how to interpolate between normal pressure coefficients to determine pressure coefficients at intermediate wind angles. However, calculations using pressure coefficients measured by Akins et al. [6] for several wind directions have shown that large changes in pressure coefficient do not translate into large changes in f_w with wind angle. These calculations indicated that f_w has about a +/-15% variation with wind angle for an exposed attic. Calculations were also performed for an attic on a house sheltered by its neighbours, with reduced side wall pressure coefficients when the wind blows along the row of houses. These calculations had about the same variability and mean value over all wind directions as the exposed house. Because the change in f_w with wind angle is extremely complex and is not a dominant parameter it is neglected for simplicity. Its effect can be estimated in a particular situation by varying the lead coefficient in f_w from 0.13 to 0.17.

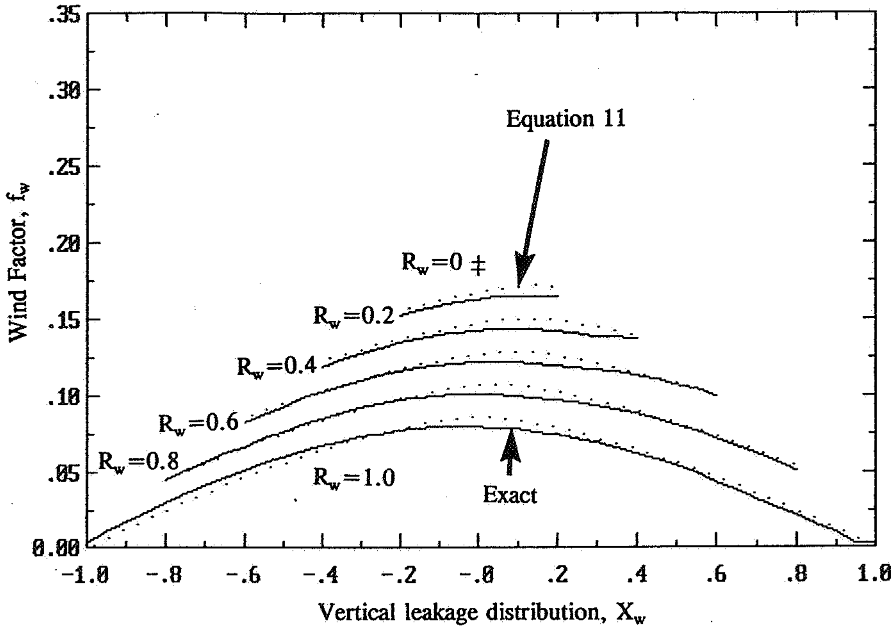

Figure 2. Comparison of wind factor, f_w, from exact numerical calculations and empirical approximation.

7 Combining Stack and Wind effects

The stack and wind driven ventilation rates given by Equations 6 and 9 must be combined to determine the total ventilation rate. This attic model, AVENT, uses the same superposition technique used before by the authors for calculating house ventilation rates. A detailed analysis of this and other superposition techniques is given by Walker and Wilson [10]. The superposition method used here is based on simple pressure addition for wind and stack effects and a simple first order interaction term:

$$Q=\left(Q_s^{\frac{1}{n}}+Q_w^{\frac{1}{n}}+B_1(Q_sQ_w)^{\frac{1}{2n}}\right)^n \tag{14}$$

where Q = total flow due to combined wind and stack effects [m^3/s]

B_1 = interaction coefficient, assumed constant.

Analysis of data from the AHHRF test houses in many leakage configurations by the authors for periods where Q_s and Q_w were approximately equal suggests that a reasonable estimate for the interaction coefficient is B_1 =-0.33

8 Measurements and Model Verification

The measurements used to verify the model predictions were made at the Alberta Home Heating Research Facility (AHHRF). Two attics were monitored that had different leakage (by about a factor of four) and different leakage distributions. The two attics are labeled Attic 5 and Attic 6. Attic 5 is relatively tight in construction with few vents with a flow coefficient (C) of 0.044 [m^3/sPa^n] and exponent (n) of 0.71 and attic 6 has soffit vents and mushroom cap vents resulting in a much leakier construction with $C = 0.232$ [m^3/sPa^n] and $n = 0.6$. The ventilation rates were measured using a constant concentration tracer gas system. Attic temperatures and ambient weather conditions were also monitored. The measurements are described in greater detail by Walker and Forest [11].

A total of 3758 hourly averaged ventilation rate measurements were made in attic 5 and 3522 in attic 6. These measurements were made over a year so as to capture a large range of weather conditions. Analysis of these measurements showed that attic ventilation is a weak function of ambient temperature because the attics are not tall (2 m at the peak) and the temperature differences are smaller than for houses because the attics are unheated. This small height and temperature difference means that stack effect pressures are small and there is little stack effect ventilation. For this reason, the figures comparing measured and predicted ventilation rates will concentrate on wind effect. In addition, ventilation rates were normalised by attic volume to express them in air changes per hour (ACH).

The above relationships, in Equations 6 through 14, were used to predict attic ventilation rates for the two attics based on their total leakage, leakage distribution estimates and measured weather conditions for every hour of measurements. Figures 3 and 4 compare the measurements and model predictions for attics 5 and 6 respectively. For clarity in these figures, the measured ventilation rates were binned for every 1 m/s of windspeed. The average is shown by a square and the bars represent the standard deviation of the measured data within each bin. The predicted ventilation rates were also binned and averaged every 1 m/s and the averages are shown connected by a solid line in these figures.

Figures 3 and 4 show that the model predictions are close to the measurements on average with a mean difference of 13% for attic 5 and 15% for attic 6. The figures also show the large range of measured data for each windspeed bin. Some of this is due to having a range of windspeeds (and temperatures) within each bin, but is dominated by variations due to wind shelter (because the test houses are in an east-west row they shelter each other for east and west winds and are exposed for north and south winds). This shelter variation introduces a variation of approximately a factor of two in wind driven ventilation rates. Note that our model is able to account for this shelter variation using the shelter factor, S_w in Equation 10. Additional variation is the result of averaging measured values over an hour. Analysis by Walker and Forest [11] found that after accounting for given windspeed and wind direction there is still a standard deviation of about 30% in measured ventilation rates. For this reason it was essential to have the large data sets used here to evaluate the model predictions.

The above differences between measurements and model are averaged over the whole data set and indicate the precision of the model when applied to long time averages that would be typical when estimating energy losses for attics. The average absolute difference (which does not cancel positive and negative differences) is about 33% for attic 5 and 40% for attic 6. This is a typical difference between model and measurements for an individual hour. Given the hourly variation in measured ventilation rates and the simplicity of the model these average and absolute errors seem reasonable for design estimates.

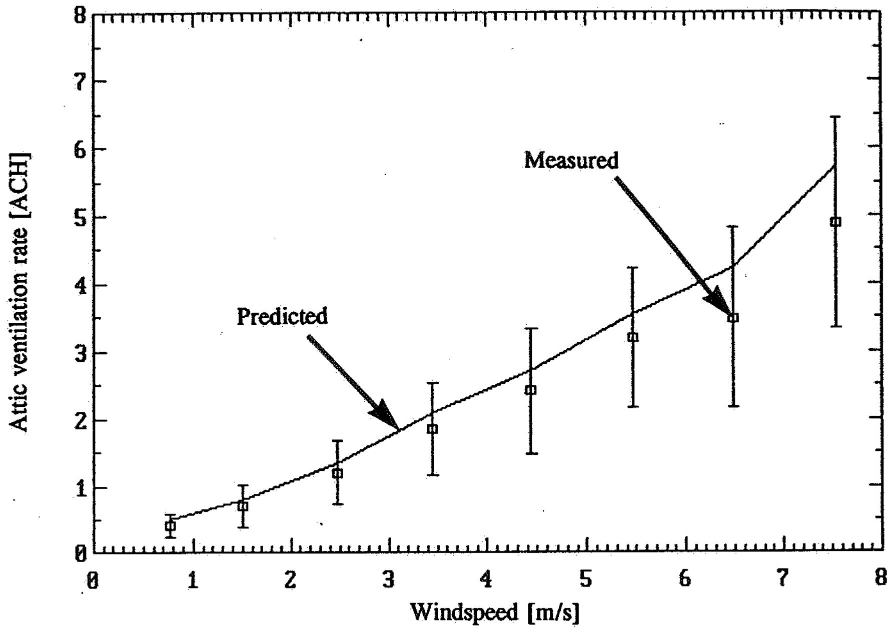

Figure 3. Measured and predicted attic ventilation rates for attic 5 at AHHRF (3758 hours). Bars represent one standard deviation of measured data.

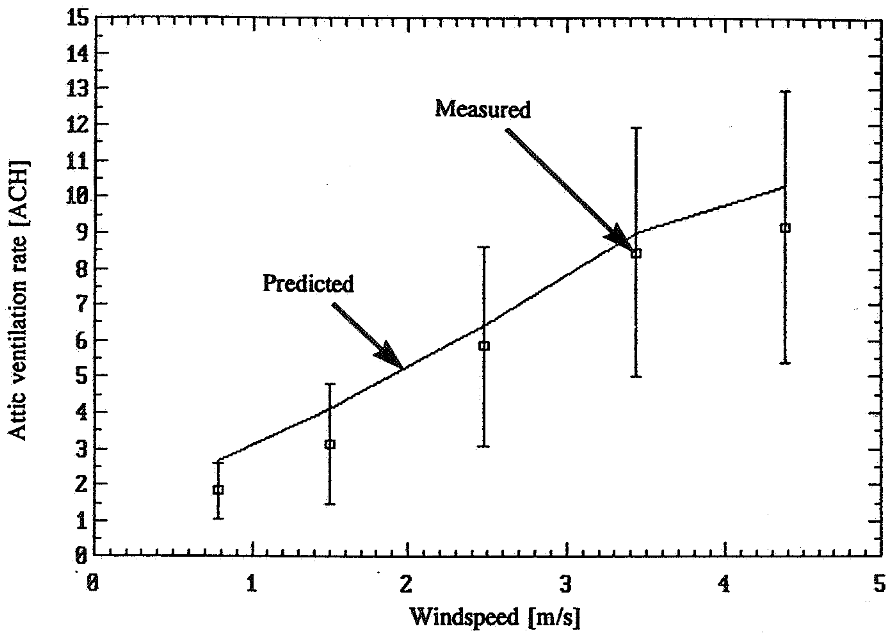

Figure 4. Measured and predicted attic ventilation rates for attic 6 at AHHRF (3522 hours). Bars represent one standard deviation of measured data.

9 Summary

The AVENT model presented here was developed to provide a simple method for estimating attic ventilation rates that is able to account for changing weather, leakage distribution (e.g. soffit, gable or roof ridge) and wind shelter.

This single zone attic ventilation model is based on easy to use algebraic relationships developed from exact numerical solutions to flow through the attic envelope. Model parameters for stack and wind effect were not found by fitting to measured data, but are based on exact theoretical relationships and wind tunnel measurements for pressure coefficients.

The model was validated by comparing predictions to measured data from two attics at AHHRF. The average differences were 13% and 15% for the two attics, which is acceptable given the simplicity of the model and the large variation in measured data.

10 Acknowledgments

The authors gratefully acknowledge the support of CMHC and NSERC. Additional support was provided by the Assistant Secretary for Conservation and Renewable Energy, Office of Building technologies, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

11 References

1. Gorman, T.M., "Modeling Attic Humidity as a function of Weather, Building Construction and Ventilation Rates", Ph.D. Dissertation, College of Environmental Science and Forestry, State University of New York, 1987.
2. Peavy, .A., "A Model for Prediction the Thermal Performance of Ventilated Attics", Summer Attic and House Ventilation, NBS Special Publication 548, 1979, pp.119-145.
3. Walker, I.S. and Forest, T.W., "Attic Venting and Moisture", CMHC report, 1993.
4. Walker, I.S., and Wilson, D.J., "Including Furnace Flue Leakage in a Simple Infiltration Model", Air Infiltration Review, Vol. 11, No. 4, AIVC, Coventry, U.K., September 1990, pp.4-8.
5. Sherman, M.H., and Grimsrud, D.T., "The Measurement of Infiltration using Fan Pressurization and Weather Data", LBL report number 10852, Lawrence Berkeley Laboratory, University of California, 1980.
6. Akins, R.E., Peterka, J.A. and Cermak, J.E., "Averaged Pressure Coefficients for Rectangular Buildings", Wind Engineering Vol. 1, Proc. 5th Int. Conf., 1979, pp. 369-380.
7. Wiren, B.G., "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.
8. Walker, I.S. and Wilson, D.J., "Simple Methods for Improving Estimates of Natural Ventilation Rates", Proc. 15th AIVC Conference, Buxton, UK, September 1994.
9. Forest, T.W. and Berg, "Simulations of Attic Ventilation and Moisture", Canada Mortgage and Housing Corporation Report, 1993.
10. Walker, I.S. and Wilson, D.J., "Evaluating Models for Superposition of Wind and Stack Effect in Air Infiltration", Building and Environment, Vol. 28, No. 2, pp. 201-10, 1993, Pergamon Press.
11. Walker, I.S. and Forest, T.W., "Field Measurements of Ventilation Rates in Flat ceiling Attics", Accepted by Building and Environment, 1995.