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Practical Methods for Improving Estimates of Natural Ventilation Rates

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Synopsis

This paper discusses four concepts that have been found useful in improving estimates of ventilation rates in residential buildings. These concepts are improved methods for describing leakage distribution and wind pressures:

1. Separation of large, well defined "local" leakage sites from the background building leakage.
2. Changing surface pressure coefficients to account for the effect of upwind obstacles.
3. Making wind pressures (in terms of pressure coefficient and wind shelter) continuous functions of wind direction.
4. Development of a wind shadow shelter model specifically tailored for buildings in urban locations.

The effectiveness of the implementation of these four concepts was examined by comparing predicted ventilation rates using a computer model (LOCALEAKS) that incorporates these concepts to several thousand hours of ventilation measurements from the Alberta Home Heating Research Facility (AHHRF). The houses at AHHRF have been tested in several leakage configurations to evaluate the model performance over a wide range of parameters. For brevity, a single leakage configuration is discussed in this paper that shows the success and failures of the model in predicting ventilation rates for complex leakage and shelter configurations. The above methods for improving ventilation calculations can be applied to other models and are not restricted to use in the ventilation model used for this study.

1 LOCALEAKS Ventilation Model

This ventilation model was specifically developed to incorporate the methods for improving ventilation rate estimates outlined above. LOCALEAKS balances the flow in and out through the building leaks by applying the power law pressure flow relationship, given below, to each leakage site,

$$M = \rho C(\Delta P)^n \qquad (1)$$

where M is the mass flow rate [Kg/s], C is the flow coefficient [m^3/sPa^n], n is the leakage exponent, ρ is the air density [Kg/m^3] and ΔP is the pressure difference [Pa] across the leak. The flow coefficient is split into distributed and localised leakage, and the pressure difference is due to a combination of stack and wind effects, and the pressure that acts to balance the inflow and outflow.

1.1 Pressure Differences For Flow Through House Leaks:

The total pressure difference across each leak can be written in terms of a reference wind parameter, P_U, and stack effect parameter, P_T, common to all leaks:

$$P_U = \rho_{out}\frac{U_H^2}{2} \qquad (2)$$

$$P_T = g\rho_{out}\left(\frac{(T_{in}-T_{out})}{T_{in}}\right) \tag{3}$$

where ρ_{out} is the outdoor air density, U_H is the eaves height wind speed [m/s], g is the gravitational constant (9.81m/s^2), T_{in} is the indoor temperature [K] and T_{out} the outdoor temperature [K]. The total pressure difference is due to a combination of the wind and indoor-outdoor temperature difference effects and the pressure that acts to balance the inflows and outflows ΔP_I.

$$\Delta P = CpS_U^2P_U - ZP_T + \Delta P_I \tag{4}$$

Equation 4 is applied to every leak for the building with the appropriate values of pressure coefficient (Cp) wind shelter factor (S_U) and Z (the height above grade). Thus, each leak is defined by its height, shelter and pressure coefficient.

2 Leakage Site Separation

2.1 Distributed Leakage

The unintentional "background" leakage through cracks and holes is distributed in six separate locations: ceiling, floor, and each of the four walls. The flow coefficient C_{dist} for the distributed leakage and exponent n_{dist} are found from a fan pressurization test, or estimated from similar construction types. The same value of n_{dist} is used for all sites, and the flow coefficient is given by Equation 5, with wall, ceiling and floor level leaks specified as a fraction of the total.

$$C_{dist} = C_{ceiling} + C_{floor} + C_{wall1} + C_{wall2} + C_{wall3} + C_{wall4} \tag{5}$$

2.2 Local Leakage Sites

Local leakage sites may be at floor level, in the ceiling, and in the walls. The default assumption for these sites is that they act like sharp edged orifice holes with $n_{local} = 0.5$ and an effective flow area of C_dA_{local}, where C_d (typically 0.6) is the discharge coefficient and A_{local} is the flow area of an opening. Alternately, the flow coefficient C_{local} and n_{local} may be specified for each local leakage site. For wind pressures each local leak is given the same pressure coefficient and wind shelter as the surface it is located in. LOCALEAKS uses a single averaged wind pressure coefficient for each wall of the building, so that only the height above grade of each local leakage site needs to be specified, rather than its horizontal location on a wall.

3 Changing Pressure Coefficients to account for Upwind Obstacles

The wind pressure coefficients, Cp, are taken from wind tunnel tests. It is assumed that there is no specific horizontal location for a leak on a wall and so extremes of pressure coefficients occurring at corner flow separations, for example, are not included. This assumption allows the simplification of using wall averaged pressure coefficients.

A set of comprehensive wind tunnel tests that cover many different wind directions have been presented by Akins, Peterka and Cermak [1]. Their Cp's are representative of isolated houses but it has been found in the development of LOCALEAKS that a change of side wall Cp is necessary for houses in a row. For an isolated building the side wall is about Cp = -0.65

based on Akins, Peterka and Cermak's measurements. For houses in a row with the wind along the row, the upwind houses change the flow pattern around the building so that large flow separations do not occur on the sidewalls. This requires a reduction in magnitude of the side wall pressure coefficient to about Cp = -0.2. This value was found by Wiren [2] in tests of row house shelter and is suggested by model errors in passive ventilation studies performed by Wilson and Walker [3]. Analysis of Wiren's data by Walker [4] has shown that for a house to be considered to be in a row only one upwind house is necessary because the closest obstacle dominates the wind flow pattern. The wind pressure coefficients for the other walls are taken directly from Akins, Peterka and Cermak. For wind perpendicular to the upwind wall they are: Cp = 0.6 for the upwind wall and Cp = -0.3 for the downwind wall.

4 Making Pressure Coefficients a Continuous Function of Wind Direction

When the wind is not normal to the upwind wall the above pressure coefficients do not apply. An harmonic trigonometric function was developed to interpolate between these normal values to fit the variation shown by Akins, Peterka, and Cermak and Wiren. For each wall of the building the harmonic function for Cp was empirically developed in the following form:

$$Cp(\theta)=\frac{1}{2}[(Cp(1)+Cp(2))(\cos^2\theta)^{\frac{1}{4}}+(Cp(1)-Cp(2))(\cos\theta)^{\frac{3}{4}} +(Cp(3)+Cp(4))(\sin^2\theta)^2+(Cp(3)-Cp(4))\sin\theta] \quad (6)$$

where Cp(1) is the Cp when the wind is at 0° (+0.60)
Cp(2) is the Cp when the wind is at 180° (-0.3)
Cp(3) is the Cp when the wind is at 90° (-0.65 or -0.2)
Cp(4) is the Cp when the wind is at 270° (-0.65 or -0.2)
and θ is the wind angle measured clockwise from the normal to the wall.

This function is shown in Figure 1 together with data from Akins et. al. for a cube. The error bars on the data points in Figure 1 represent the uncertainty in reading the measured values from the figures of Akins, Peterka and Cermak. Equation 6 fits the measured data within about Cp = ±0.02 except at about 150 degrees and 210 degrees (which are the same by symmetry) where the equation overpredicts the Cp by about 0.1. Figure 2 shows Equation 6 with Cp's from another data set from ASHRAE [5](Chapter 14) which it also fits well.

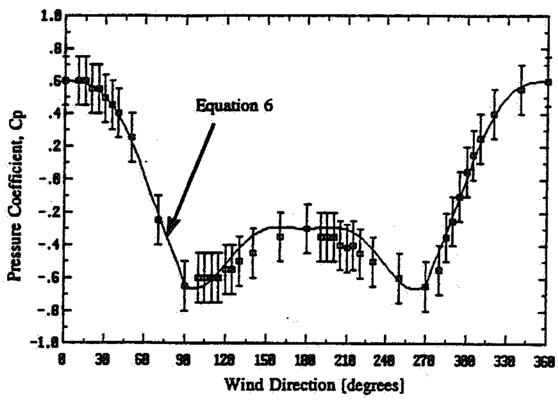

Figure 1. Wind Angle Dependence of measured (data from Akins et.al. (1979)) and predicted wall pressure coefficients for isolated buildings

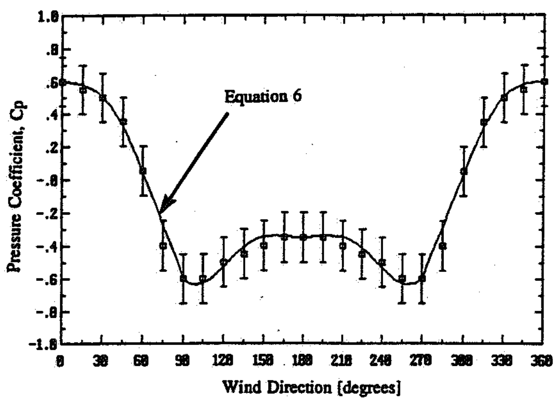

Figure 2. Wind Angle Dependence of measured (data from ASHRAE (1989)) and predicted wall pressure coefficients for isolated buildings

The function in Equation 6 was chosen to have the above form so that if a different data set were to be fitted then only the values for when the wind is normal to one wall are required and the function will estimate the intermediate values for different wind directions. Equation 6 is shown in Figure 3 for the row pressure coefficients where the sidewall Cp is -0.2. There are no intermediate measured values but this figure shows that Equation 6 produces reasonable pressure coefficients for this case. The value for pressure coefficient at the top of the furnace flue is Cp=-0.5, based on measurements by Haysom and Swinton [6].

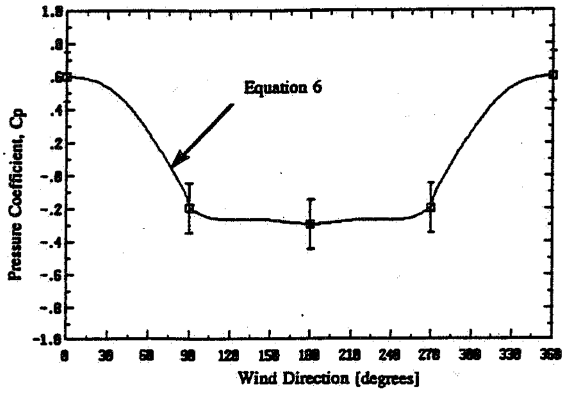

Figure 3. Wind Angle Dependence of Wall Pressure Coefficients for Houses in a Row.

5 Wind Shadow Shelter

To improve shelter estimates the wind shadow shelter method was developed to calculate numerical values for the reduction in velocity caused by an upwind obstacle. The shelter method is based on work by Walker and Wilson [7]. The shelter factor, S_U, is used to reduce the eave height wind speed, U_H, in the flow approaching the building to produce an effective wind speed U, such that

$$U=S_U U_H \tag{7}$$

U calculated from Equation 7 is used to calculate the wind pressure on each wall in Equation 4. When the walls are not sheltered, $S_U = 1.0$ and complete shelter corresponds to $S_U = 0$. Wind shadow wake shelter uses self-preserving three dimensional wake theories of Counihan, Hunt and Jackson [8] and Lemberg [9] to determine the rate of recovery of wind speed in the wake of an upwind obstacle. The theories are combined with wind tunnel measurements of Peterka, Meroney and Kothari [10], Lemberg [9] and Wiren [2] to develop appropriate relationships for wind shelter factor (or windspeed multiplier), S_U, to be used in the near wakes of interest in building shelter problems.

The wind shadow concept is analogous to the shadow produced by an obstacle in front of a light source that is cast onto another surface. The projection of the wake downstream of the sheltering obstacle is the "wind shadow". If a surface is partially covered by the wind shadow of the projected wake, then the shelter factor is weighted by the amount of wall area covered by the wind shadow to obtain the average shelter factor for the wall.

For this study, a computer programme was used to calculate S_U for all four walls of the test buildings at AHHRF every one degree of wind angle. The houses are in an east-west row, and are exposed for north and south winds and shelter each other for east and west winds. The calculated values of S_U are illustrated in Figures 4 and 5. Figure 4 is for the North facing wall and shows the symmetry of its shelter with a maximum wind speed reduction factor of $S_U = 0.43$ for winds from 110 and 250 degrees. Figure 5 is for the East facing wall where the shelter is asymmetric because the sheltering building is closer for east winds than west winds. For East winds (90 degrees) the shelter is maximum with $S_U = 0.25$. For West winds the shelter is less with $S_U = 0.61$. The furnace flue protrudes above the houses and is assumed to be unsheltered, and $S_U = 1.0$ for the flue.

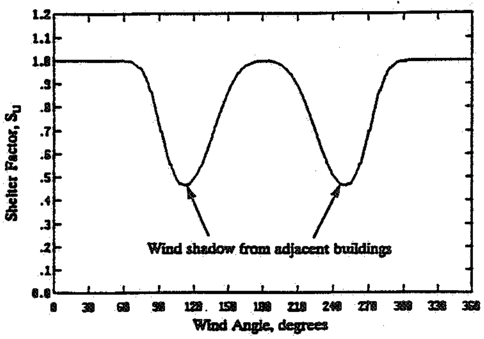

Figure 4. Wind Angle Dependence of Shelter Factor, S_U, for the North Wall of a House at AHHRF.

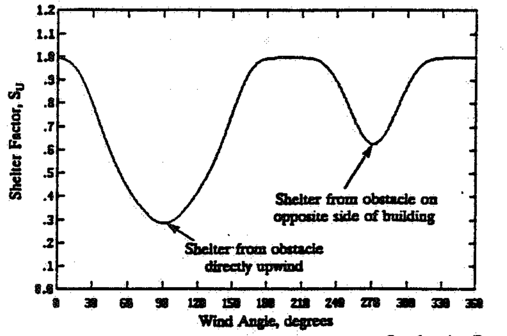

Figure 5. Wind Angle Dependence of Shelter Factor, S_U, for the East Wall of a House at AHHRF.

6 Validation of Improved Leakage Distribution and Wind Pressure Estimates

A detailed description of the measurement facility is given by Wilson and Walker [3]. The house with the most complex leakage distribution is examined here because it is the most difficult to model. In addition to the background leakage of the house (86 cm^2) there is a furnace flue (34 cm^2) , a passive ventilation pipe into the basement (59 cm^2) and an open window (30 cm^2).

To separate the effects of the improvements to ventilation predictions from the behaviour of the rest of the model, the measured data will be compared to predictions with and without the improvements. Without the improvements, the window and basement passive vent leakage were included in the distributed leakage of the walls and floor, the wall and floor leakage were evenly distributed over the four walls, and the flue was included in the ceiling leakage. The shelter factor used was the average for all four walls over all wind directions ($S_U = 0.79$), and the pressure coefficients did not vary with wind angle.

The predictions are evaluated using two parameters - the bias and the absolute error. The bias is the mean of the differences between individual pairs of predicted and measured data. Thus the bias indicates the difference between measurements and predictions over long time periods. The absolute error is the mean of the absolute differences between measurements and predictions. In this case positive and negative errors do not cancel and this provides an estimate of the typical model error for an individual hour. The results are presented in Air Changes per Hour (ACH) using a house volume of 220 m^3. The measured data are sorted into wind and stack dominated parts so that the wind and stack dependence of the predicted and measured ventilation rates may be examined separately.

The computer model used the measured wind speeds, wind directions and indoor and outdoor temperatures to calculate ventilation rates corresponding to every measured ventilation rate, both with and without the improvements. For stack dominated conditions, Figure 6 shows how the model with improvements gives better estimates of the ventilation rate. The upper figure shows every measured data point and the lower figure shows the measured data in bins every 5K of temperature difference, with the error bars representing the standard deviation of the measured data within the bin. For the model, the ventilation rate is calculated for each point, but for clarity, the calculations are also binned every 5K and the average value in each

bin is connected by a line. In this case the bias changed from -19% to -1% (negative errors indicate underprediction) and the absolute error from 19% to 8% by including the improved ventilation estimation methods discussed in this paper. These results illustrate the benefit of allowing the large localised leakage sites (the flue, basement pipe and window) to have their own height above grade instead of being included in the distributed leakage.
For wind dominated conditions the measured and calculated data are shown in Figure 7. In this case, the differences are much less clear than for stack dominated ventilation. However, including the leakage distribution and wind pressure calculation improvements decreased the bias from -12% to -4% and the absolute error from 21% to 12%.

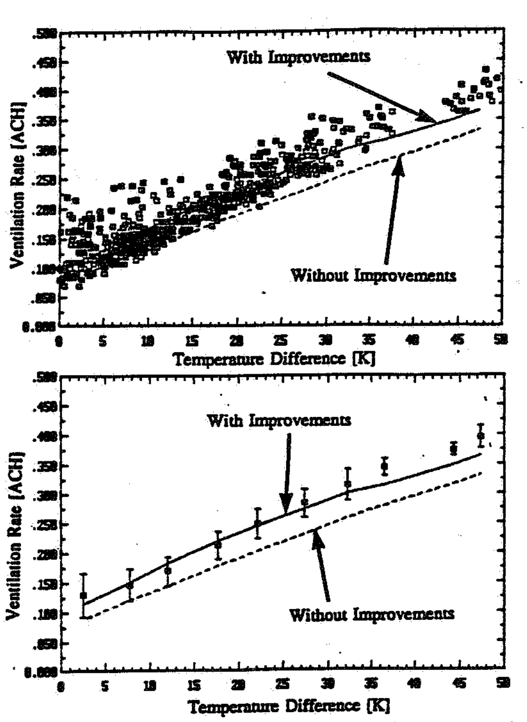

Figure 6. Comparison of Measured and Predicted Stack Dominated Ventilation Rates for House 5 at AHHRF, with a Furnace Flue, Passive Vent and an open Window (659 hours, Mean Temperature Difference = 15.6K, Mean Windspeed = 1.4 m/s).

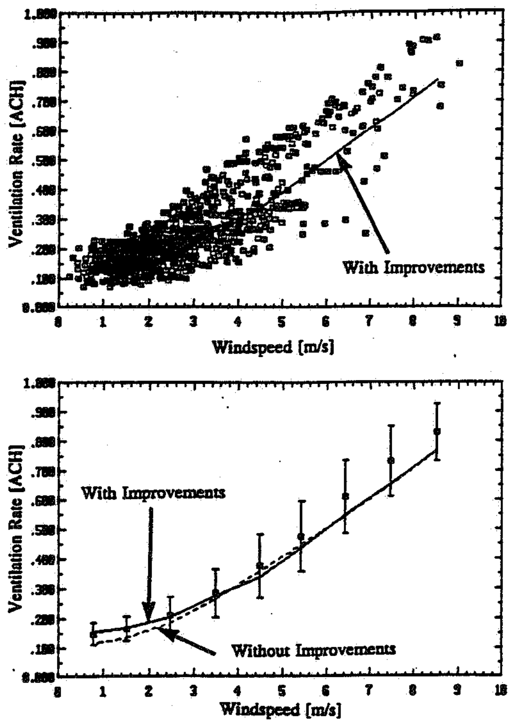

Figure 7. Comparison of Measured and Predicted Wind Dominated Ventilation Rates for House 5 at AHHRF, with a Furnace Flue, Passive Vent and an open Window (1042 hours, Mean Temperature Difference = 9.6K, Mean Windspeed = 2.7 m/s).

To obtain a clearer interpretation of the effects of allowing the shelter and pressure coefficients to vary with wind direction, this data set was replotted to show the variation with wind angle in Figure 8. Figure 8 shows binned data only, where the measured data has been binned every 20 degrees of wind direction. As with the other figures the error bars represent the standard deviation of the measured data for each wind direction bin, and the predicted infiltration rates are shown by a straight line connecting their mean values in each bin. Figure 8 shows that constant shelter and pressure coefficients result in underprediction for south winds (when the building is exposed) and over prediction for east and west winds (when the building is sheltered and the pressure coefficients change). The results of the above data comparisons are summarised in Table 1.

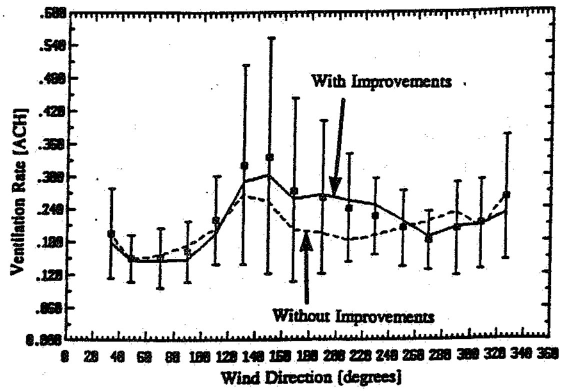

Figure 8. Wind Angle Dependence of Measured and Predicted Wind Dominated Ventilation Rates for House 5 at AHHRF, with a Furnace Flue, Passive Vent and an open Window (1042 hours, Mean Temperature Difference = 9.6K, Mean Windspeed = 2.7 m/s).

Table 1. Summary of Differences Between Measured Data and Model Predictions

	Wind Dominated		Stack Dominated	
	With Improvements	Without Improvements	With Improvements	Without Improvements
Number of points	1042		659	
Mean ΔT	9.6 K		15.6 K	
Mean U	2.7m/s		1.4 m/s	
Mean Measured Ventilation Rate	0.249 ACH		0.202 ACH	
Mean Predicted Ventilation Rate	0.238 ACH	0.220 ACH	0.200 ACH	0.160 ACH
Bias Error	-0.011 ACH -4%	0.030 ACH -12%	-0.002 ACH -1%	-0.038 ACH -19%
Absolute Error	0.031 ACH 13%	0.052 ACH 21%	0.017 ACH 9%	0.038 ACH 19%

8 Summary

Four concepts have been introduced to improve estimates of ventilation rates in houses. These improvements have been incorporated into a ventilation model (LOCALEAKS) whose predictions have been validated by comparison to several hundred hours of measured ventilation rates and flows through individual leaks. LOCALEAKS was also used without localised leakage and changing shelter and pressure coefficients in order to illustrate the effect of these concepts. In every case the improvement produced ventilation rate predictions that were significantly improved (by 10% or more).

The ideas about shelter and pressure coefficients introduced here may be used as input to other ventilation models, and are not restricted to use in LOCALEAKS, because they are parameters that are normally input to a model rather than the functional form of the model itself.

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