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COMBINING AIR INFILTRATION AND EXHAUST VENTIALTION

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To meet ventilation rate standards, a suitable method of estimating combined natural and mechanical ventilation must be found. An air infiltration model, AIM-2, has been developed to predict natural ventilation ates for houses with furnace flues. The predictions of AIM-2 have been used to examine several methods of superposing natural and mechanical ventilation. The melthods of combining the flow ratres examined here are: quadrature (ASHRAE method), pressure adition, linear addition, and one-half of the mechanical ventilation adding linearly with the other half adding as pressure addition. These methods are evaluated by comparing predicted ventilation rates to ventilation rates measured using tracer gas techniques in a house with exhaust fan ventilation. Results indicate that the ASHRAE standard of quadrature addition underestimates the contribution of natural ventilation. Indoor air quality implications are discussed.

Introduction

Recent concern about indoor air quality has brought about the introduction of new ventilation standards. ASHRAE Standard 62-1989 (ASHRAE (1989) recommends 0.35 Air Changes per Hour (ACH) for combined natural air infiltration and mechanical ventilation and the Canadian Standards Association Preliminary Standard F326-1-M (CSA (1989)) recommends 0.3 ACH from a fan only, with any natural air infiltration resulting in a greater ventilation rate. In order to meet these ventilation standards, mechanical ventilation is required. This may take the form of balanced flow air-to-air heat exchangers or exhaust fans. Balanced flow systems are expensive and difficult to maintain and simple exhaust fans are more likely to be utilized in residential buildings, where the additional inflow is through the building envelope. To assist in sizing these exhaust fans to provide sufficient ventilation whilst optimizing energy loads a simple calculation procedure is necessary that will provide estimates of ventilation rates within the uncertainty of predicting natural ventilation rates (typically 20%).

This study uses a simple single zone air infiltration model, AIM-2, developed by the authors to predict the natural ventilation rates due to indoor-outdoor temperature difference (stack effect) and wind pressures (wind effect). Several methods of combining the predicted natural ventilation rates from AIM-2 and a measured exhaust fan flow rate will be examined, and the resulting total ventilation rates will be compared to measured ventilation rates.

Predicting Natural Ventilation Rates Using AIM-2

AIM-2 has been developed to predict natural ventilation rates in buildings that can be treated as a single zone, as can most residential houses, with the advantage that the furnace flue can be treated as a separate leakage site. AIM-2 uses weather data, fan pressurization test results, and estimates of wind shelter and building leakage distribution to estimate the natural ventilation rate. The non-linear pressure-flow relationship:

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

where Q = flow rate through building envelope
ΔP = pressure difference across building envelope
C and n are the flow coefficient and exponent determined from fan pressurization test results

is used in AIM-2, unlike some previous models that assumed orifice flow for building leakage. As with many other simple models AIM-2 calculates the flows due to wind and stack effects separately, as Q_{wind} and Q_{stack} respectively, then superposes them non-linearly to find the combined ventilation rate. This allows us to determine if wind, stack or neither effect is dominant. For a more detailed description of AIM-2 see Walker and Wilson (1990).

Description of Test Facility

The various methods of combining natural air infiltration and exhaust ventilation have been evaluated by comparisons to measured data from the Alberta Home Heating Research Facility (AHHRF). The test facility consists of six unoccupied test houses in an East-West row located at an agricultural research farm 10 km south of the city of Edmonton at 53.5° north latitude. The site is surrounded by flat agricultural land planted with forage and cereal crops in summer and snow covered stubble in winter. The houses are totally exposed to south and east winds, are sheltered by several single story farm buildings 50 m to the west and by a windbreak of trees 250 m to the north. The weather data is measured on site by 10 m high micrometerological towers which means that the measured windspeeds do not have to be corrected for terrain effects.

The house used in this study is house 2 with one house to the east and four houses to the west. Figure 1 shows the configuration of house #2 and its construction details are contained in Table 1. The infiltration rate is monitored by a SF_6 tracer gas system described in Wilson and Dale (1985). An estimate of typical values of error from Wilson and Dale is ±5% ±0.004 ACH (Air Changes per Hour) and the system resolution is 0.003 ACH.

Mechanical Ventilation System

The exhaust ventilation in house #2 is provided by a centrifugal fan with a constant speed AC motor. The fan exhausts through an ASME standard orifice meter used to monitor the flow through the fan. This system exhausted air at a rate of 0.21 ACH (47 m^3/hour) which is about one half of the total ventilation rate. A pressure drop of about 350 Pa across the orifice ensured that the exhaust ventilation rate was constant and independent of the weather induced pressures which were up to about 10 Pa.

The fan was operated on an eight hour cycle, with four hours off followed by four hours on. This allows for the estimation of errors in calculating the natural ventilation rate for time periods close to those where the fan is operating. The exhaust system did not contribute to the total leakage of the building because when the fan was off a damper was closed in the exhaust duct, and when the fan was operating there was a large pressure drop across the exhaust ventilation system. This system is a reasonable simulation of a high pressure exhaust system with a backdraught damper, but does not give a good simulation of a low pressure propeller exhaust fan.

Four Methods of Combining Natural and Mechanical Exhaust Ventilation

1. Quadrature
This is the method recommended by ASHRAE (1989), where the fan pressure and the pressures due to natural effects are added, and assuming orifice flow results in quadrature addition of flow rates:

$$Q_{total} = \left(Q_{AIM-2}{}^{2} + Q_{fan}{}^{2}\right)^{0.5} \tag{2}$$

Where Q_{AIM-2} is the natural ventilation rate calculated by AIM-2
Q_{fan} is the flow rate through the fan
Q_{total} is the total ventilation rate for the building with the fan on.

2. 1/n Superposition
As with the quadrature method, the 1/n superposition method assumes that the natural and fan pressures add. Instead of assuming orifice flow the non-linear building envelope pressure-flow relationship is used (equation (1)), where n is found by fan pressurization testing:

$$Q_{total} = \left(Q_{AIM-2}{}^{1/n} + Q_{fan}{}^{1/n}\right)^{n} \tag{3}$$

3. Linear
Rather than adding pressures, this method simply adds the flow rates. Although there is no scientific basis for this method it is the simplest possible way of combining natural and mechanical ventilation.

$$Q_{total} = Q_{AIM-2} + Q_{fan} \tag{4}$$

4. Kiel-Wilson
This method was developed by Kiel and Wilson (1987), where one half of the fan flow adds linearly, and one half adds as pressure addition. Kiel and Wilson used the idea of a variable infiltration leakage fraction to develop this method. In their previous work Kiel and Wilson assumed orifice flow for building leakage, but in this study the relationship given by equation (1) will be used such that:

$$Q_{total} = \left(Q_{AIM-2}{}^{1/n} + \left(\frac{Q_{fan}}{2}\right)^{1/n}\right)^{n} + \frac{Q_{fan}}{2} \tag{5}$$

Evaluation of Flow Combination Methods

AIM-2 and the four flow combination methods are compared to measured data in Figure 2 and Figure 3, where the stack and wind flow rates calculated by AIM-2 are about equal. These figures illustrate how the ventilation rate changes when the fan is on or off over a 24 hour period. The calculated ventilation rate consistently underpredicts the measured ventilation rate for all combination methods. For periods when the fan is off the ventilation rate is only that predicted by AIM-2, and this too underpredicts. The errors can be quantified using bias and scatter. The bias is the average difference between calculated and measured values and the scatter is the average absolute difference with the bias removed. The bias indicates the average error expected over a long time period and the scatter indicates how well the changes in ventilation rate are tracked.

The bias and scatter for AIM-2 and the flow combination methods are summarized in Table 2. Table 2 contains bias and scatter computed for the data shown in Figures 2 and 3 and for the entire three week test period of 352 hours of measured data. These calculated values use only the last three hours of each four hour fan on or off cycle to remove large uncertainties in the measured ventilation rate due to the sudden change in ventilation rate. As can also be seen in Figures 2 and 3 the models track the changes in ventilation rate well as indicated by the low values of scatter. These variations are caused by changes in weather conditions and indicate that AIM-2 has the correct functional form. The bias errors are much more significant, with all the combination methods underpredicting, ranging from a 4% underprediction using the linear method to 30% for quadrature. These errors are shown graphically in Figure 4.

Included in the errors associated with each combination method is the error in AIM-2's prediction of the natural ventilation rate. AIM-2 underpredicts by 19% (0.06 ACH) and this error should be removed in order to properly evaluate the four flow combination methods. For the linear case this correction can be simply made by adding 0.06 ACH to the total predicted ventilation rate. For the other 3 cases this simple linear correction cannot be made. However, it can be shown that using the average AIM-2 natural ventilation rate over the time period in question and the fan flow rate in equations 3 to 5 produces the same average Q_{total} as averaging the individual Q_{total}'s for each hour. Thus corrected values of Q_{total} may be calculated for each combination method by correcting the bias in the average natural ventilation rate calculated using AIM-2.

Table 3 contains the results for the four combination methods of correcting the natural infiltration rate Q_{AIM-2}. The results show that removing the underprediction from the values of Q_{AIM-2} has increased the predicted total ventilation rates in each case as expected. Since all the methods are similarly effected the order in terms of magnitude of bias error has not changed. In increasing order they range from Quadrature (-23% (-0.12 ACH)) through 1/n superposition (-16% (-0.081 ACH)) and Kiel-Wilson (-7% (-0.03 ACH)) to linear which overpredicts now by 7% (0.03 ACH)). These bias errors are shown graphically in Figure 5 which can be compared to Figure 4 to see the effect of removing the bias error from the AIM-2 predictions. Note that removing the bias from the AIM-2 predictions does not affect the scatter errors and these will be the same as in Table 2.

Conclusions

These results indicate that the Quadrature method of combining natural and exhaust ventilation as recommended by ASHRAE significantly underpredicts the total combined ventilation rate by about 20%. The Kiel-Wilson variable leakage fraction method gives better predictions with an average underprediction of 7%. It is recommended that this method should be used to calculate combined natural and exhaust ventilation since it is simple, has some theoretical scientific basis and the errors are within acceptable limits when compared to measured data that is ±5% ±.004 ACH. It is interesting to note that simple linear addition of flow rates also has an average bias of 7%, but overprediction rather than the underprediction of the other methods. There is no scientific basis for this, the simplest method, to be such a good predictor. The good results obtained by simple linear addition were also found by Kiel and Wilson (1987) for the case of strong exhaust ventilation of 0.85 ACH where the fan flow is dominant. In this study fan and natural flows were equal at about 0.2 ACH. More research is needed in this matter to find satisfactory explanations for linear addition being such a good method of combining natural and exhaust ventilation. Currently measurements are being taken to examine the effect of supply rather than exhaust ventilation.

References

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Table 1 Construction Details of House #2 Tested at AHHRF

The house has a gable roof on elevated roof trusses and a full concrete basement.

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 : 1000 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 solid core fir

Table 2 Differences between measured and predicted ventilation rates Using AIM-2 for natural ventilation rates

		For one day where $Q_{wind} = Q_{stack}$ $\bar{U} = 2.6$ m/s $\overline{\Delta T} = 13$°C (See Figure 2)	For Complete Test Period (3 weeks) $\bar{U} = 4$ m/s $\overline{\Delta T} = 12$°C
AIM-2 FAN OFF	BIAS	-17% (-0.05)	-19% (-0.06)
	SCATTER	7% (0.02)	11% (0.04)
Quadrature	BIAS	-31% (-0.13)	-30% (-0.15)
	SCATTER	8% (0.03)	11% (0.06)
1/n Superposition	BIAS	-24% (-0.10)	-23% (-0.12)
	SCATTER	7% (0.03)	11% (0.06)
Linear	BIAS	-4% (-0.02)	-5% (-0.03)
	SCATTER	5% (0.02)	8% (0.04)
Kiel Wilson	BIAS	-18% (-0.08)	-17% (-0.09)
	SCATTER	6% (0.03)	10% (0.05)

Values in brackets are Air Changes per Hour (ACH)

Table 3 Differences Between Measured and Predicted Ventilation Rates with AIM-2 Bias Removed

		For one day where $Q_{wind} = Q_{stack}$ $\bar{U} = 2.6$ m/s $\overline{\Delta T} = 13$°C	For Complete Test Period (3 weeks) $\bar{U} = 4$ m/s $\overline{\Delta T} = 12$°C
Quadrature	BIAS	-24% (-0.10)	-23% (-0.12)
1/n Superposition	BIAS	-16% (-0.07)	-16% (-0.08)
Linear	BIAS	8% (0.03)	7% (0.03)
Kiel Wilson	BIAS	-8% (-0.03)	-7% (-0.03)

Values in brackets are Air Changes per Hour (ACH)

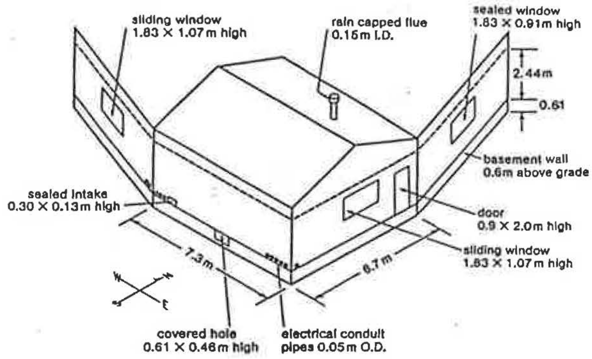

Figure 1 Exploded view of House #2 at AHHRF from Wilson and Dale (1985)

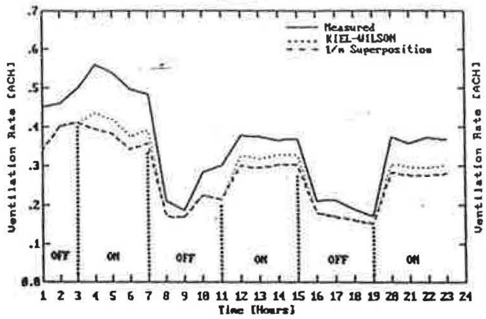

Figure 2. Predicted and measured ventilation rates in House #2 with an open 15 cm diameter flue with Exhaust ventilation cycling every 4 hours for Kiel-Wilson and 1/n Superposition methods

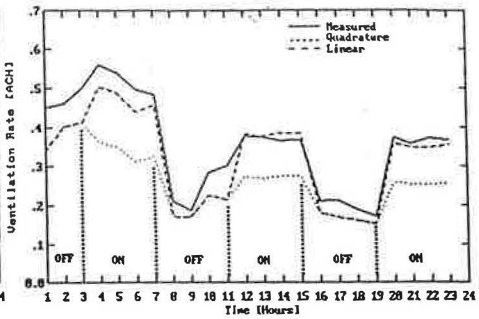

Figure 3. Predicted and measured ventilation rates in House #2 with an open 15 cm diameter flue with Exhaust ventilation cycling every 4 hours for Quadrature (ASHRAE) and Linear methods

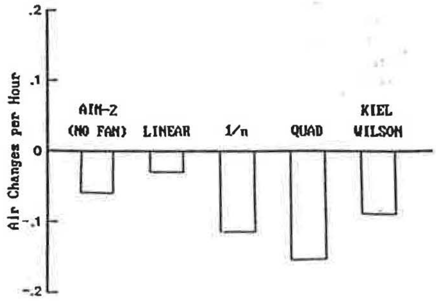

Figure 4. Average bias errors for AIM-2 and the four natural and fan flow combination methods when compared to measured data

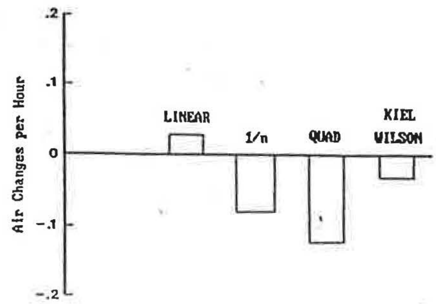

Figure 5. Average bias errors for the four natural and fan flow combination methods when compared to measured data with the bias from AIM-2 removed