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# Subfloor and house ventilation rates: comparing measured and predicted values

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## SYNOPSIS

This paper reports on the use of BRE's domestic ventilation model, BREVENT, to predict subfloor and whole house ventilation rates in a BRE/DoE test house. Before the model could be used though some minor adjustments were necessary because one of its underlying assumptions was that the subfloor temperature was equal to the external temperature. Temperatures measurements over a number of months showed this assumption to be false and so an extra stack term was introduced into the model. However, the overall difference this makes is still quite small, only a few percent at most.

The predicted subfloor ventilation rate matched the calculated value well, particularly when it was stack dominated. When wind played a significant part though the level of agreement deteriorated, particularly when subfloor air bricks were located on unsheltered walls. However, both the subfloor and whole house ventilation rate of the test house appears to be heavily influenced by the stack effect because the suspended floor and ceiling are leaky in comparison to the walls. As a result, subfloor ventilation will be stack dominated about 61% of the time. To improve the prediction of wind affected subfloor ventilation better pressure coefficient data is required.

In a similar vein BREVENT can predict whole house ventilation rates best when the flow is stack dominated. Analysis of the separate stack and wind effects show that the ventilation in the test house will be stack dominated for about 86% of the time. When wind speed does influence ventilation then wind direction also has an effect: winds blowing from the East and West generally give ventilation rates 25% lower than those blowing from the North and South.

## 1. INTRODUCTION

BRE has conducted research on ventilation beneath suspended floors for a number of years [1,2]. Subfloor ventilation is an important subject to study because it is used as a means of controlling moisture and hazardous gases from the ground. *Hartless & White* [2] described the measurement of ventilation beneath the suspended floor of a BRE/DoE test house. The measurements showed that subfloor ventilation was very much affected by the stack effect. This is somewhat at odds to our initial thinking, i.e. wind entering an air brick in one subfloor wall and leaving through another with stack effect taking no part. However, this assumes an air-tight suspended floor; whilst this may be true of pre-cast concrete floor incorporating a gas-resistant membrane it is not the case for a suspended timber floor. In this case, large quantities of air are likely to pass through it. Indeed, *Bassett* [3], *Lilley et al* [4] and *Hedin* [5] have all shown this using pressurisation and tracer gas techniques.

In this paper, the measurements taken by *Hartless & White* are compared to predictions made using BRE's domestic ventilation model, BREVENT [6] so that the mechanisms for subfloor ventilation may be better understood. Further, whole house ventilation rate measurements for the BRE/DoE test house are compared to BREVENT predictions. Before proceeding with this it is worth discussing the subfloor temperatures recorded in one of the energy and environment test house because these data affect the way BREVENT models subfloor ventilation.

## 2. SUBFLOOR TEMPERATURE MEASUREMENTS

As part of their ventilation measurement programme *Hartless & White* measured the air temperature beneath the suspended timber floor of the BRE/DoE test house. These measurements were extended and since March 1995 both the air and concrete oversite temperatures have been monitored continuously. The main finding is that the subfloor temperature, $T_f$, varies very little throughout the day and night but it does follow the expected seasonal trend, ranging from 20°C in the Summer months to 10°C in the Winter months. In fact, it is reasonably well correlated with external temperature, $T_o$. Such a correlation has also been noted by *Welsh* [7] in BRE's radon test house. Further, $T_f$ is correlated extremely well with the concrete oversite temperature. The oscillations in the concrete oversite temperature are minimal and it is approximately equal to the air temperature although it is generally slightly higher.

Subfloor and concrete oversite temperatures continue to be measured and they will be reported on in future work. The next section of this report describes the implications of these subfloor temperature measurements when modelling subfloor ventilation with BREVENT.

## 3. BREVENT: MODELLING SUBFLOOR VENTILATION

BREVENT has been used before to predict subfloor ventilation rates [1], but an important assumption behind the model is that $T_f$ is assumed to equal $T_o$. This simplifies the ventilation calculation because stack effect terms are ignored, but as measurements have shown $T_f$ can be significantly different from $T_o$ (by as much as 15°C). This meant that the equations under-pining BREVENT [6] had to be altered slightly to allow for this. The main change was to incorporate a stack term (i.e. $(\rho_o-\rho_f)gh$ where $\rho_o$ and $\rho_f$ are external and subfloor air density respectively, g is acceleration due to gravity and h is the depth of the subfloor void) into the equations governing the pressure difference across (i) the subfloor air bricks and (ii) the suspended floor.

Despite the potentially large temperature differences mentioned above the effect of ignoring this extra stack term is still likely to be small because of the shallowness of subfloor voids in UK, typically only 20 to 30cm deep. BREVENT works on a mass balance of air flows into and out of the subfloor void and the main house, and all volume flow and ventilation rates are expressed at STP. For the purposes of this work the limit chosen for mass balance was 0.1 kg/hr, and the ventilation rates for the subfloor void and main house were expressed at the subfloor and internal air temperatures ($T_f$ and $T_i$) respectively. A BREVENT comparison exercise showed that the subfloor ventilation rate was indeed affected by taking a unique $T_f$ rather than assuming it was equal to $T_o$. In fact, the percentage change was directly proportional to $T_f$-$T_o$. For example, for the BRE/DoE test house a value of $T_f$-$T_o$ of 15°C gave a 4% difference in the subfloor ventilation rate. Although the effect for typical values of $T_f$-$T_o$ is small it was decided to continue to use the revised version of BREVENT.

## 4. MODELLING SUBFLOOR VENTILATION IN BRE/DoE TEST HOUSE

### 4.1 Input data

The dimensions of the test house (including those of the subfloor void) and the layout of the site are given elsewhere [2].

One of the key input variables for any ventilation model is the total leakage of the building envelope and its distribution around the external surfaces. A pressurisation test on the test house gave a total leakage of 17.2 ach (i.e. 3,560 $m^3$/hr) at 50Pa (n = 0.61). *Hartless & White* noted that a significant leakage path in the test house was the wall/floor junction with air moving from the subfloor void into the house under the skirtings as well as into the gap behind the plasterboard lining. Since then the floor perimeter has been sealed and the envelope leakage re-measured. A value of 13.8 ach (i.e. 2,860 $m^3$/hr) at 50Pa (n = 0.62) was obtained. Despite this considerable reduction in total leakage (nearly 20%) smoke tests showed that the floor was still quite leaky, particularly around the floor hatches.

This information together with data from *AIVC Technical Note 44* [8] on the size of leakage paths in housing were used to distribute the total leakage around the envelope of the test house. One of the key features of the house is the absence of windows and doors in E-W facing gable walls and so these were assumed to have minimal leakage. Table 1 shows the results of this exercise.

| Surface | Leakage before floor sealing | | Leakage after floor sealing | |
|---|---|---|---|---|
| | ($m^3$/hr at 50Pa) | % of total | ($m^3$/hr at 50Pa) | % of total |
| Floor | 1600 | 45 | 900 | 31 |
| Ceiling | 1200 | 34 | 1200 | 42 |
| Front wall (South) | 330 | 9.2 | 330 | 12 |
| Gable wall (East) | 50 | 1.4 | 50 | 1.7 |
| Back wall (North) | 330 | 9.2 | 330 | 12 |
| Gable wall (West) | 50 | 1.4 | 50 | 1.7 |
| Total | 3560 | 100 | 2860 | 100 |

**Table 1. Estimated distribution of leakage for test house**

The percentage figures are quite interesting. They show that both before and after sealing over 70% of the total leakage is estimated to be through the floor and ceiling.

Another significant input variable for BREVENT is the pressure coefficient data. BREVENT contains sets of pressure coefficient data which have been obtained from BRE wind tunnel tests on a range of general housing models. However, none of the available sets corresponds exactly to the environment in which the test house is situated, i.e. a single row of detached houses with partially sheltered front and back walls.

This particular problem of the wind environment around a single row of detached houses has been tackled before in a number of papers arising from ventilation work carried out on the Alberta Home Heating Research Facility (AHHRF) in Canada, e.g. *Wilson & Walker* [9] and *Walker & Wilson* [10]. Further, *Walker* [11] has reviewed pressure coefficient data for sheltered buildings as measured by a number of workers. Unfortunately, an important consideration is the need for pressure coefficients on the lower part of the wall where the subfloor air bricks are located. Generally, wall-averaged data are used so one pressure coefficient applies to the whole wall but in practice there are variations over the surface. BREVENT has data for the lower wall as derived from the original wind tunnel measurements.

Therefore, a judgement was made to use the BREVENT set of data corresponding to a 20% housing density. Housing density is defined as the area occupied by buildings divided by the area of the site. In order to simplify calculations it was assumed that the N-S and E-W directions were lines of symmetry. This meant all wind directions could be reduced to a single quadrant, and this quadrant was then divided into four sectors. As a result, only four sets of pressure coefficient data were required. Generally speaking, during the subfloor measurement programme, the prevailing wind direction was the SW.

### 4.2 BREVENT predictions

Following on from *Hartless & White* the results of two measurement runs are compared to BREVENT predictions. For Run 1 air bricks were open on the E-W facing walls, and for Run 2 they were open on the N-S facing walls. The results of the two runs are plotted in graphs 1a to 2b in two ways: (a) as subfloor ventilation rate against time, and (b) as predicted versus measured subfloor ventilation rate. The line shown in the (b) graph is the 1:1 line, i.e. predicted rate matching measured rate perfectly.

For Run 1, graphs 1a and 1b show good agreement between predicted and measured values. In this case BREVENT predicts the subfloor ventilation rate to within 7%. For Run 2 there are times when the agreement between measured and predicted rates is poor. Graph 2a shows that these times correspond to instances of sharp rises and falls in the measured subfloor ventilation rate. Again, as confirmed in graph 2b, the predicted rate is below the measured rate, but the general daily trend in subfloor ventilation is predicted correctly.

The main reason for the differences between predicted and measured rates can be put down to wind speed, U. As noted by *Hartless & White* the subfloor ventilation of the test house is heavily influenced by the stack effect. Wind speed only plays a part when it is reasonably high and air bricks are open on the front and back walls. For Run 1 where air bricks were open on the sheltered gable walls the agreement between measured and predicted is good because the wind cannot greatly affect subfloor ventilation. When the air bricks are on open on the front and back walls the wind does have an effect when its speed is high enough. For Run 2 a dramatic deterioration in the agreement between predicted and measured rates is seen. For a further run (not shown here) where the air bricks were open on all four walls the agreement appears to be good most of the time.

The reason for the poor agreement in some instances is that the wind is not being properly modelled since the pressure coefficient data used do not adequately represent the environment around the test house. Many of the problems with selecting pressure coefficients for this house have already been discussed, so it would appear that the only way to proceed is to build a scale model of the test houses and the environment immediately around them and obtain the required data from wind tunnel measurements.

The agreement between measured and predicted rates is good at times despite inadequate pressure coefficient data because stack effect virtually dominates subfloor ventilation in these cases. There are two reasons for this stack dominance: (i) open air bricks are located on the sheltered gable walls, and (ii) the test house is effectively acting as a chimney. As discussed previously, the gable walls are relatively air tight and so over 70% of the total envelope leakage is estimated to be through the floor and ceiling. In other words, air enters the house through the subfloor air bricks, is drawn up through the floor and exits through the ceiling. This is the dominant mechanism for air movement in the test house, and this is only affected when U is high enough to overcome it by blowing on either the front or back wall thereby causing cross ventilation. The same thing can happen if air bricks are open on the front and back walls: more air will flow across the void and not as much will flow up through the floor.

Inspecting the graphs of subfloor ventilation plotted against wind speed and subfloor ventilation plotted against temperature difference in *Hartless & White* we can estimate that subfloor ventilation is stack dominated when $T_i$-$T_o$ (= $\Delta T$) is greater than 6°C and that wind only becomes a significant influence for U greater than 3.5m/s. Analysing the weather data recorded at BRE we see that subfloor ventilation will be stack dominated 61% of the time, and the wind will only have a significant influence for 7% of the time.

## 5. MODELLING WHOLE HOUSE VENTILATION RATES

### 5.1 BREVENT predictions

Since the floor perimeter has been sealed the whole house ventilation rate has been measured continuously using $SF_6$. Data is recorded at about half hour intervals. Therefore, as a further test of BREVENT, the model was used to predict ventilation rates in the test house. The input data used for these runs was as described in section 4.1 with the obvious difference of a tighter floor and a subfloor ventilation area reduced to just four open air bricks on the East facing gable wall. In the light of the experience gained from the subfloor ventilation predictions, two months in 1995 were analysed in detail: March (generally a windy month) and July (generally a calm month).

Graphs 3a and 3b show measured compared to predicted whole house ventilation rates for March 1995. It is obvious that BREVENT consistently over-predicts the ventilation rate. Graphs 4a and 4b are the equivalent graphs for July 1995 and they show a good correlation between measured and predicted values. In fact, BREVENT predicts the ventilation rate to within about 5%. The main reason for this difference is that the wind speeds during March are consistently higher (average 3.8m/s with a maximum of nearly 20m/s) than during July (average 2.4m/s with a maximum of nearly 8m/s). As a result, the problems outlined in section 4.2 are still apparent. The floor may have been tightened considerably but it is still leaky and so stack flow continues to dominate.

## 5.2 Stack and wind dominated house ventilation

As described in section 4.2 it is helpful to analyse how ventilation is affected by the wind and stack effect. To this end we can use the approach of *Warren & Webb* [12]. They proposed a simple infiltration model (the forerunner of BREVENT) for houses and calculated the infiltration (ventilation) flow rate, $Q_V$, in terms of the total leakage of the house envelope, the height of the house envelope (H), U, $\Delta T$ and an infiltration rate function, $F_V$. Similarly, they also calculated two other infiltration flow rates, $Q_W$ (for wind dominated ventilation, i.e. $\Delta T=0$) and $Q_B$ (for stack dominated ventilation, i.e. U=0) and, accordingly, proposed two further infiltration rate functions: $F_W$ and $F_B$. The function $F_B$ depends on the house shape and the distribution of leakage among the walls, ceiling and floor. The function $F_W$ in addition depends on the surface pressure coefficients. Using these relationships, *Warren & Webb* were able to separate out the wind and stack effect terms by plotting a graph with the following dimensionless co-ordinates:

$$X = \frac{Q_W}{Q_B} = \frac{F_W}{F_B}.\frac{1}{(Ar)^n} \qquad Y = \frac{Q_V}{Q_B} = \frac{F_V}{F_B}.\frac{1}{(Ar)^n} \tag{1}$$

where Ar = Archimedes number = $\Delta T g H / T_i U^2$. Using a range of U, $T_i$ and $T_o$ with a constant $T_f$ (10°C) and wind direction (North), BREVENT was used to predict whole house ventilation rates for the test house. From these predictions the average values obtained for $F_B$ and $F_W$ were 0.224 and 0.025 respectively. The value for $F_B$ is comparable to the values achieved by *Warren & Webb*, but the value for $F_W$ is much lower. It is perhaps not surprising that $F_B$ is an order of magnitude greater than $F_W$ since this accords with the observation that ventilation in the test house is stack dominated. With these values for $F_B$ and $F_W$ graph 5 was plotted using the above dimensionless co-ordinates. The graph shows a single curve bound by the two asymptotes Y=1 and X=Y which is identical to the results achieved by *Warren & Webb*. The first of these two asymptotes is the stack dominated region, and the second is the wind dominated region.

Accordingly, *Warren & Webb* proposed the limit for stack dominated infiltration as, $Q_V/Q_B \leq 1.1$, and for wind dominated infiltration as, $Q_V/Q_W \leq 1.1$. Close inspection of the wind speeds and temperature differences at the above limits show that for the test house

- $U/\Delta T \leq 0.7$ for stack dominated infiltration, and,
- $U/\Delta T \geq 11$ for wind dominated infiltration.

Following on from this and using the wind and temperature data obtained from March to November 1995 we can see that stack dominated infiltration of the test house will occur about 86% of the time and that wind dominated infiltration will occur about 0.4% of the time.

## 5.3 Effect of wind direction

The effect of wind direction has not been studied in detail up to this point since stack effect has been the dominant driving force for ventilation. The main reference to directional considerations has been to the location of subfloor air bricks. Following on from section 5.2 though we can study the influence of wind direction on the ventilation rate in the test house by selecting cases where $U/\Delta T > 1.4$. This limit is somewhat arbitrary but was chosen because it was twice the limit for stack dominated infiltration thereby ensuring that wind played a significant part in driving ventilation. Reviewing the wind speed and temperature difference data for March and July 1995 shows that this condition was met for just under 6% of the time.

Having isolated cases where wind effects are significant we can investigate the effect of wind direction in particular. This can be accomplished using the method of *Wilson & Walker*. They used this approach to derive "shielding factors" for the AHHRF by normalising the measured house ventilation rates. The AHHRF and the DoE/BRE test houses are similar in that they a row of detached houses with, in the former case, no shielding and, in the latter case, minimum shielding to the South. In other words, the shielding factor for southerly winds will be one.

This procedure was carried out on the measured data for March and July 1995 and the results are plotted in graph 6. The upper and lower dotted lines on the graph represent 95% confidence limits. The graph shows that the normalised ventilation rate has a minimum for both easterly (0.9) and westerly (0.75) winds which is to be expected considering the layout of the houses. For northerly and southerly winds the normalised ventilation rate has a maximum which is about 1.1 for both directions. (This is a consequence of similar degrees of shelter to the North and South as well as equivalent leakages for these two walls.) This means that the difference between maximum and minimum (i.e. unsheltered and sheltered) ventilation is about 25%, which is similar to the figure achieved by *Wilson & Walker* in a comparable case. The 95% confidence limits are quite narrow for winds from the South and SW simply because this is the prevailing wind direction and hence there are more cases of wind influencing ventilation. Overall, this analysis would benefit from studying data for the whole year.

## ACKNOWLEDGEMENTS

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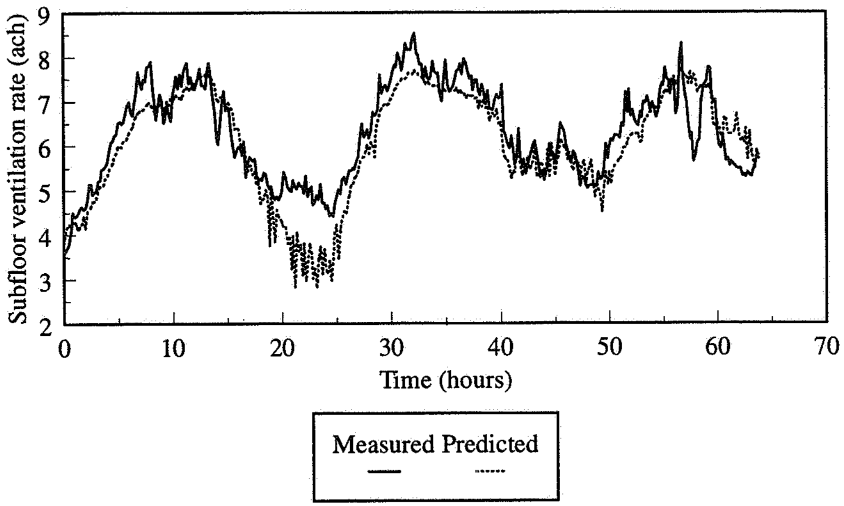
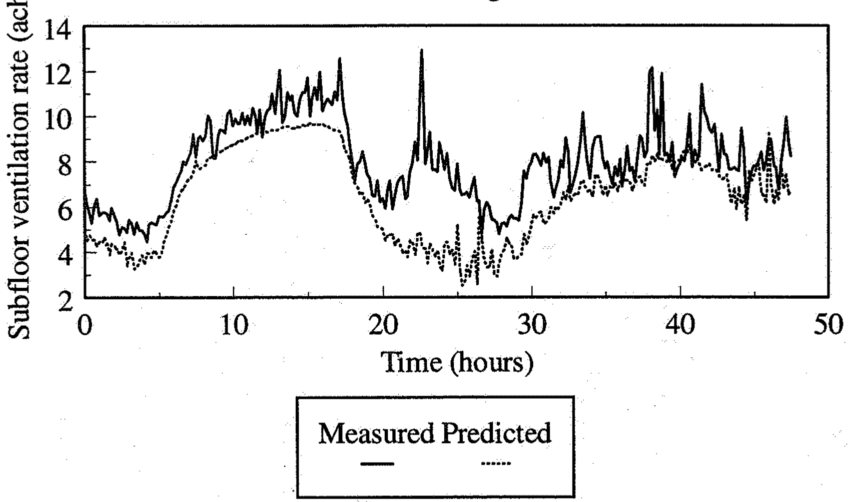
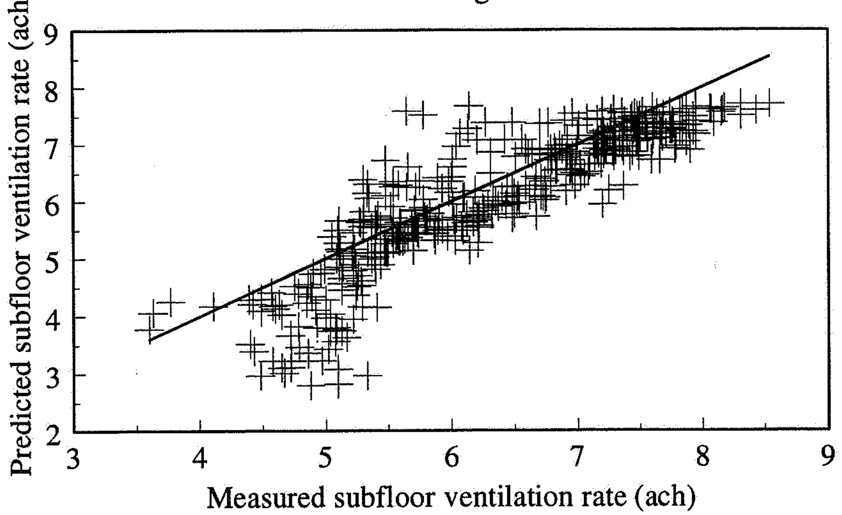
1a. Measured and predicted subfloor ventilation rates
Run 1: 6-9th August 1993



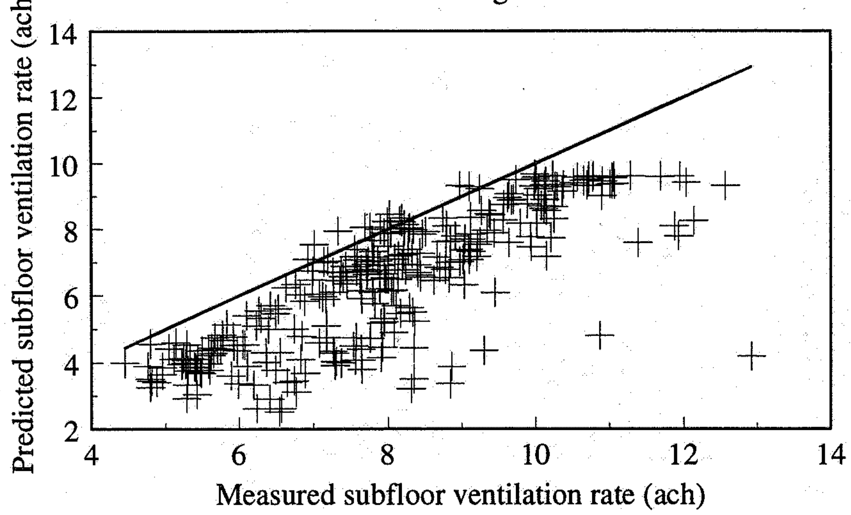

2a. Measured and predicted subfloor ventilation rates
Run 2: 18-20th August 1993




1b. Predicted versus measured subfloor ventilation rate
Run 1: 6-9th August 1993

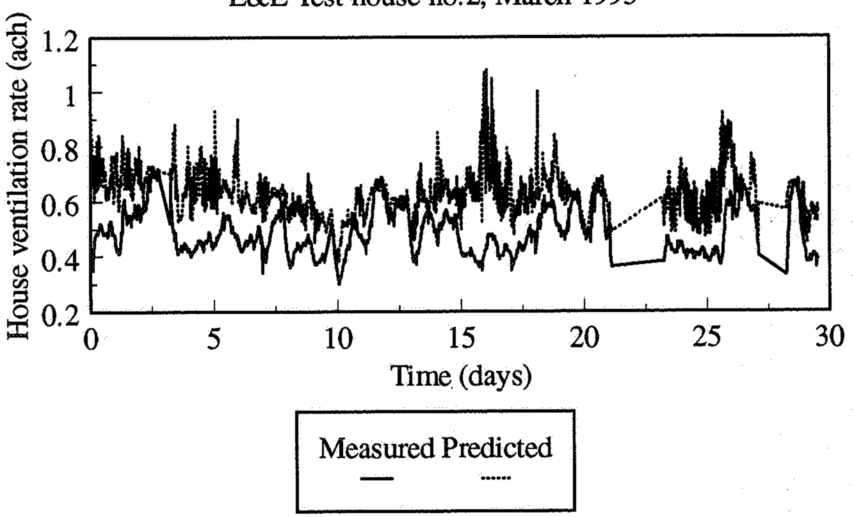



2b. Predicted versus measured subfloor ventilation rate
Run 2: 18-20th August 1993



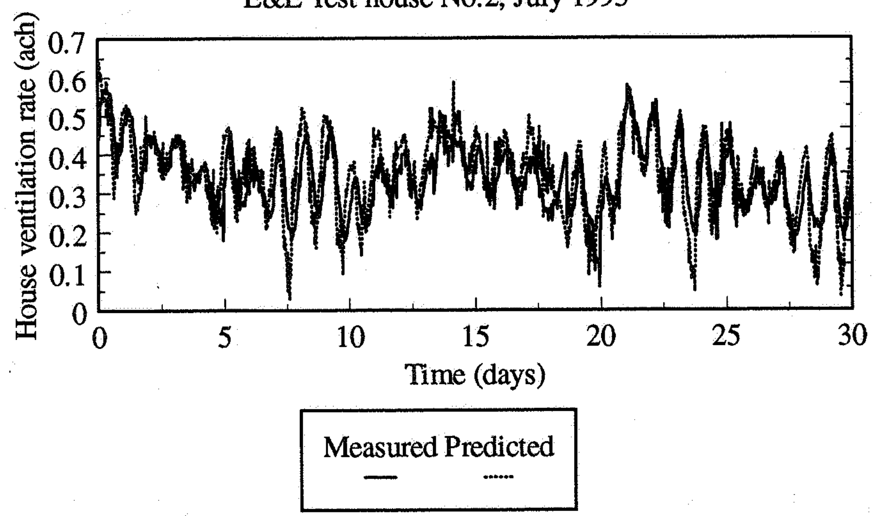
3a. Measured and predicted whole house ventilation rates

E&E Test house no.2, March 1995



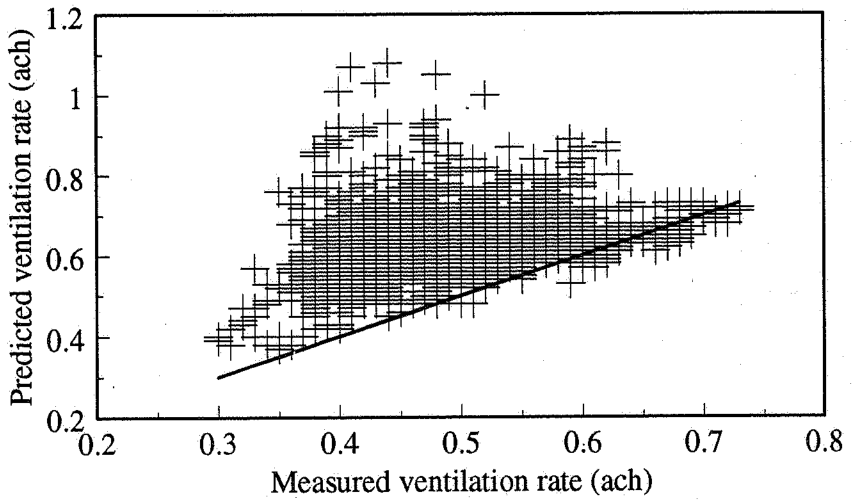

4a. Measured and predicted whole house ventilation rates

E&E Test house No.2, July 1995



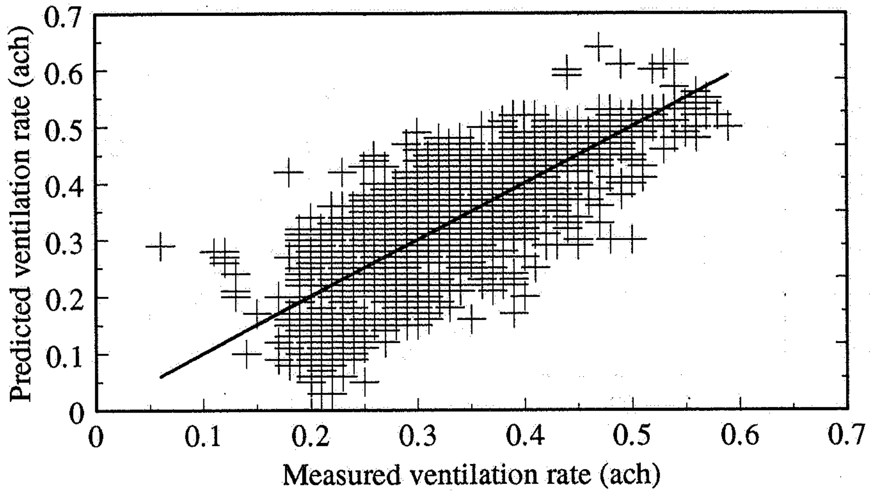

3b. Measured and predicted whole house ventilation rates

E&E Test house No.2, March 1995

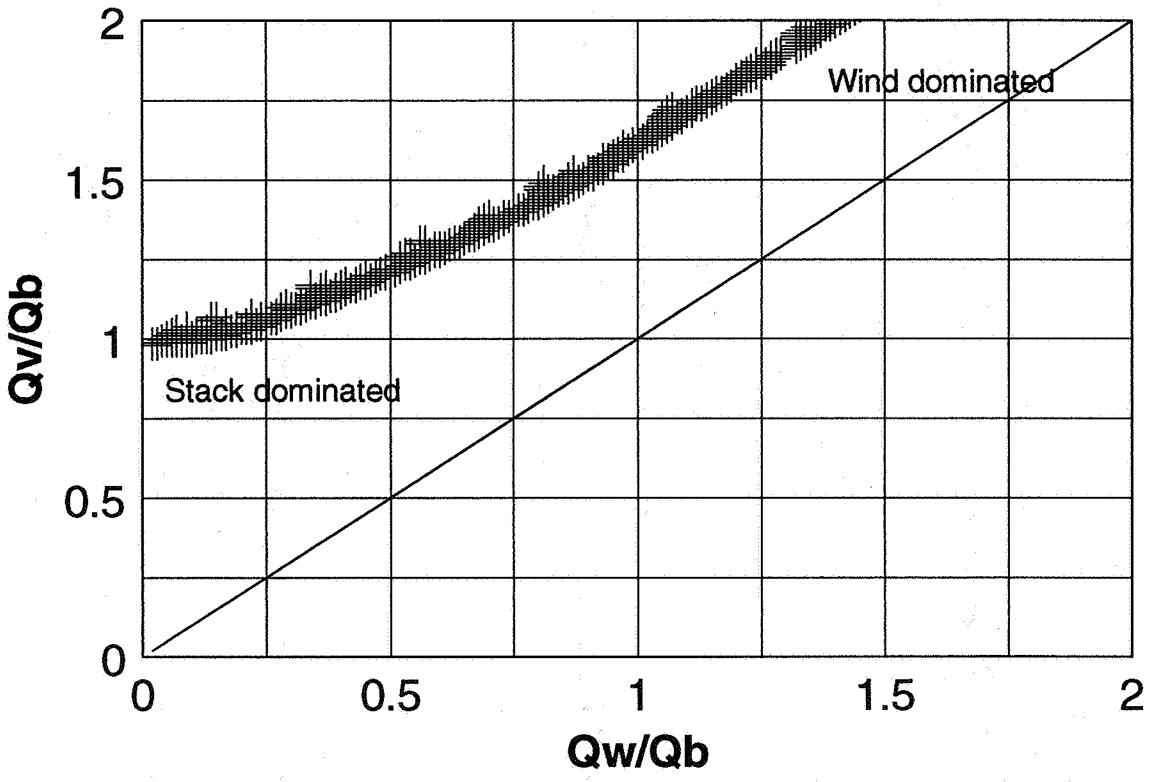



4b. Measured and predicted whole house ventilation rates

E&E Test house No.2, July 1995



## 5. Dimensionless plot of ventilation




## 6. Effect of wind direction on ventilation rates

Test house No.2 (March and July 1995)