The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Comparing Predicted and Measured Passive Stack Ventilation Rates

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Synopsis

BRE have experimental data for the flows found in Passive Stack Ventilation (PSV) ducts from a test house in Garston. These data cover different duct diameters, number of bends and roof terminals, all measured over a variety of weather conditions.

In the first part of this paper the data are analyzed to separate temperature and wind effects, and to see how well they fit well to the expected model of duct flow.

The second part gives a comparison of the same data with predictions from the single zone ventilation model BREVENT. Extensive research at BRE has improved the modelling of PSV ducts within this computer model, and this new information was used to try to calculate the flows in the duct for the measured weather conditions.

The results show good correlation between the predicted and measured duct flow velocities. Care was needed in identifying the effective volume of the building to give this good result. More work is needed on the interaction between PSV flow elements, and whether using a multi-zone model would give better results.

Introduction

Passive Stack Ventilation (PSV) is a method for providing ventilation which does not require any power or action by the user. It consists of a pipe running from a room, upwards to the roof of the building, and extracts air from the room due to the combined effects of the temperature difference between inside and out, and the wind on the terminal of the PSV device. There has been research for some time into how effective it is, and whether it should be being more widely applied [1,2].

In a previous paper Parkins reported on an experiment in a house at BRE Garston to measure the flows through a range of PSV systems. Full details can be found in that paper [3] and another paper at this conference [4], but the velocity in the PSV was measured alongside the weather conditions.

In this paper the results of the earlier experimental study are examined using basic duct flow theory, and the BRE domestic ventilation model BREVENT. This model is a single zone, mass balance model of air flow in buildings, described in full in the manual to BREVENT [5]. It is designed for use in housing, but can be applied to other buildings, and is available in a 'User-friendly' form. BREVENT models all of the main components of air flow in housing: infiltration, small openings, windows, extract fans, combustion appliances and, of course, PSV.

Experimental data

Figure 1 shows a typical result from the experiments carried out in 1990, with the velocity of air in the duct plotted against the temperature difference. There is considerable scatter in these data, reflecting the fact that flow rates are a function of wind speed, wind direction and temperature difference. In order to make more sense of the data it is helpful to look at the cause of the flow, and whether the temperature and wind effects can be separated out.

The pressure difference ΔP across a PSV is given by [5]

$$\Delta P = \Delta C_p . ½ \rho_o U^2 - \Delta\rho\, gh \qquad (1)$$

Where

ΔC_p	C_{pt} - C_{pI} i.e. difference in pressure coefficient between the PSV terminal C_{pt} and inlet C_{pI} calculated from the difference between internal and external static pressures. This is generally negative. ()
ρ_o	density of air outside the building (kgm^{-3})
U	wind speed (ms^{-1})
$\Delta\rho$	ρ_o - ρ_I , between internal and external air density (kgm^{-3})
g	acceleration due to gravity (ms^{-2})
h	height of PSV terminal above ground level (m)

The average speed of flow v through the duct is then governed by:

$$v = \left(\frac{2\Delta P}{K\,\rho}\right)^{½} \qquad (2)$$

Where K is the complete loss coefficient for the PSV system, and is discussed fully later. Combining (1) and (2), and using the ideal gas law relationship $\rho_o T_o = \rho_I T_I$ to convert the densities into temperature differences:

$$v^2 = \left(\frac{\Delta C_p}{K} . \frac{T_I}{T_o} . U^2\right) + \left(\frac{2}{K} . \frac{\Delta T}{T_o} . gh\right) \qquad (3)$$

Now the main variables are the wind speed U and the temperature difference ΔT and a comparison of either can be made against the PSV flow speed by manipulation of equation (3). Dividing both sides of (3) by U^2 and then plotting v^2 / U^2 against ΔT is expected to give a straight line if the other values are fairly constant. Similarly, dividing both sides of (3) by ΔT shows that a plot of $v / (\Delta T)^{½}$ against $U / (\Delta T)^{½}$ gives a straight line as well. An example of the second of these is shown in figure 2. It shows that the data from figure 1 are much clearer in this form than in the original, untreated format, and that stack flow speed is linear with wind speed in the absence of temperature difference.

Figure 1: v vs DT, system 2

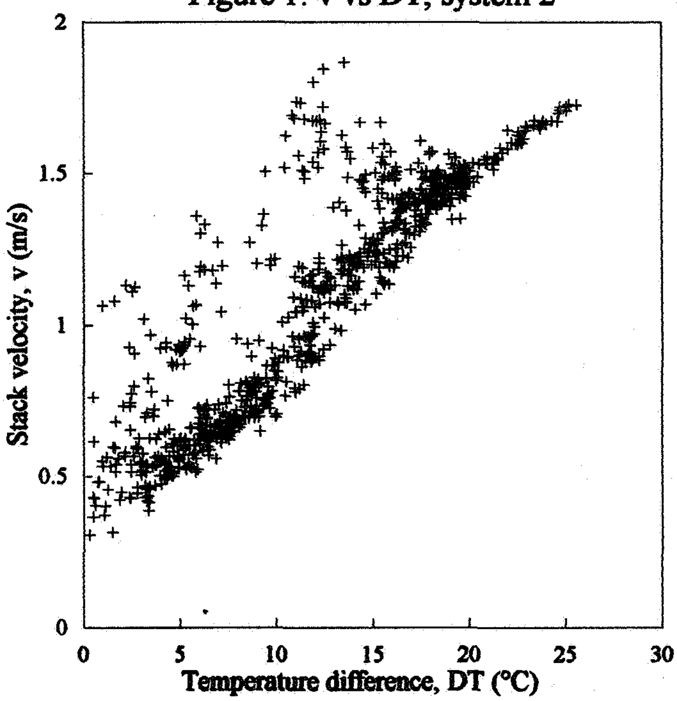
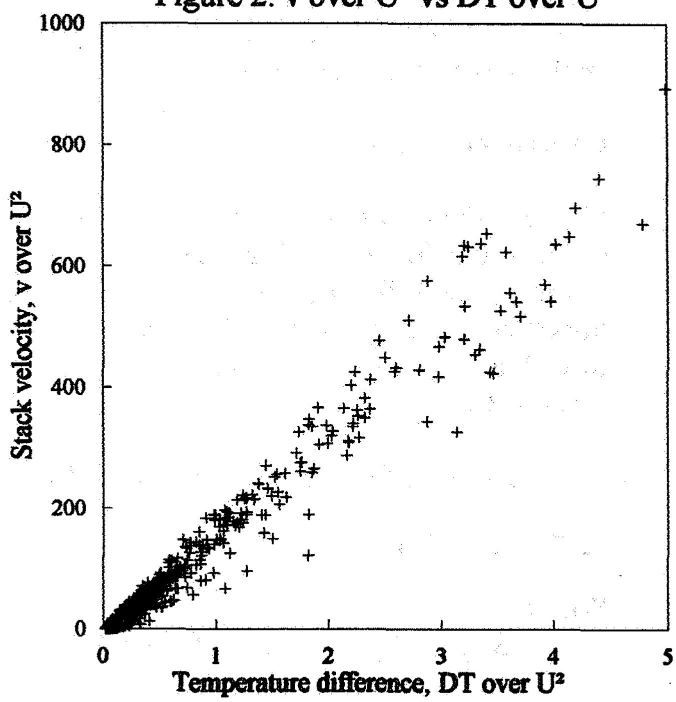


Figure 2: v over U² vs DT over U²



Finding the gradient and intercept from these plots enable us to find a value of the loss factor K. However putting this value into the BREVENT model to be discussed next shows that the values of K predicted are much too high. This is because the simple model of a PSV discussed here ignores the effect of the rest of the building on the PSV flow. This is also discussed in the next sections.

The other significant insight to be gained from equation (3) is when wind effects are expected to dominate over temperature effects and vice versa. If the requirement is for 90% of the contribution to mean one effect is dominating, inserting typical values for the variables in (3) indicates that:

a) If $\Delta T = 10°C$ then U must be greater than 10 ms^{-1} to dominate
b) If $\Delta T = 10°C$ then U must be less than 1 ms^{-1} for ΔT to dominate

These indicate that for most conditions which occur naturally then both effects need to be considered. However it is apparent from experimental data [3] that for wind speeds below 2 ms^{-1} it is the temperature effects which are the most significant.

Because of the variability of the stack flow speeds with wind direction, and the generally large temperature effects observed in these data, the remainder of the analysis in this paper considers low wind speed results only. This simplifies the analysis considerably because we can concentrate on the loss coefficients of PSV systems, and ignore the effect of varying wind direction on the suction coefficients of terminals. These suction effects are discussed by Welsh [6].

BREVENT predictions

The BREVENT model uses an equation equivalent to equation (1) above for flow in a PSV with the dimensionless loss factor K is defined by:

$$K = \left(\frac{4fL}{d} + K_1 + K_2\right) \qquad \textbf{(4)}$$

where

d diameter of the PSV pipe (m)
f friction coefficient for the PSV pipe ()
L length of the PSV pipe (m)
K_1 sum of all bend losses ()
K_2 inlet and outlet losses ()

This paper looks at the results from four of the cases measured by Parkins [3]. These are numbered 1, 2, 5, 6 to match the data in that paper. Systems 1 and 2 had 155 mm diameter pipe, 5 and 6 110 mm diameter pipe, whilst systems 1 and 5 contained two bends and systems 2 and 6 had no bends. The two straight systems emerged within the roof and so had a different type of terminal to the two which emerged at the roof ridge. All of this information is needed to model PSV effectively.

The initial calculation of the loss factors K was as follows:

System	d (m)	Bends	Terminal	Terminal loss	4fL/d	K_1	K_2	K
1	0.155	2	Ridge vent	1	1.42	0.56	1.5	3.48
2	0.155	0	Chinese hat	1.1	1.42	0	1.6	3.02
5	0.110	2	Ridge vent	1	2.0	0.56	1.5	4.06
6	0.110	0	Mushroom	2.1	2.0	0	2.6	4.60

The loss coefficient used in BREVENT can be found by multiplying each K by $8 / \pi^2 d^4$, giving values around 4900 ,4200, 22500 and 25500 (m^{-4}) for systems 1, 2, 5 and 6 respectively. This assumes that the friction coefficient f is 0.008, the inlet loss with no ceiling diffuser is 0.5 in each case, and bends cause a loss of 0.28 each. The terminal data are those now supplied with the BREVENT help pages. These data represented the initial best estimates of the values appropriate for the PSV systems, based on tables [7]. However there is uncertainty remaining over the correct values to be used for bend losses, and particularly the way the interaction of two bends should be calculated.

The airtightness of the house had been measured as 13 air changes per hour (ach) at an applied pressure difference of 50 Pa. The house volume is 205 m^3. This information is needed in the BREVENT model to predict the infiltration rate. There were no significant other sources of ventilation during these experiments. The model was run with a range of temperature differences to match those found during the experiments.

Examples of predicted flows against temperature difference for the four systems considered are shown in figures 3 to 6, labelled as BREVENT initial. It is clear that although the fit to the data is not too bad, the model was over predicting the flow rates for any given temperature difference. This means the model was probably missing out, or under-estimating, some of the loss factors. The possible causes of discrepancy are the subject of the next section. Note that the experimental data is stated as centre line velocity, so that the BREVENT prediction needed to be converted to this from the average velocity.

Figure 3: v vs DT, System 1

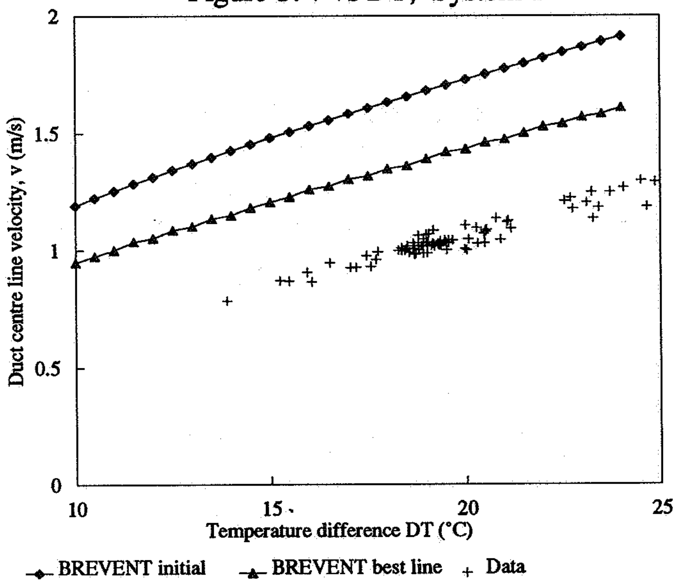


Figure 4: v vs DT, System 2

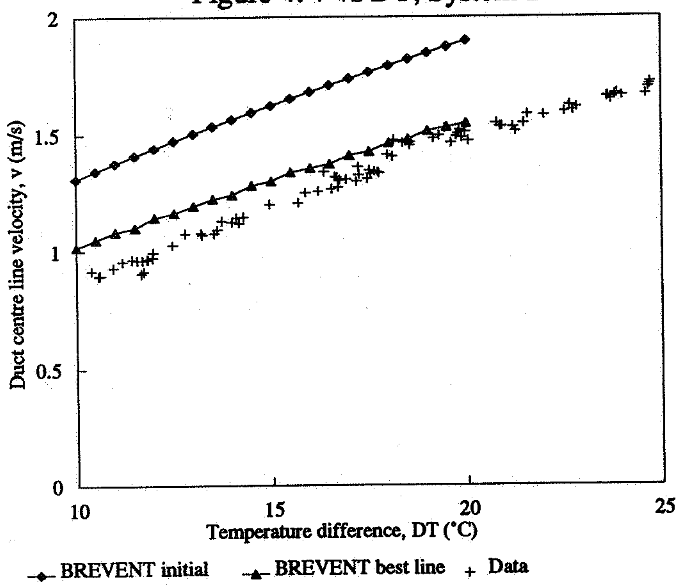


Figure 5: v vs DT, system 5

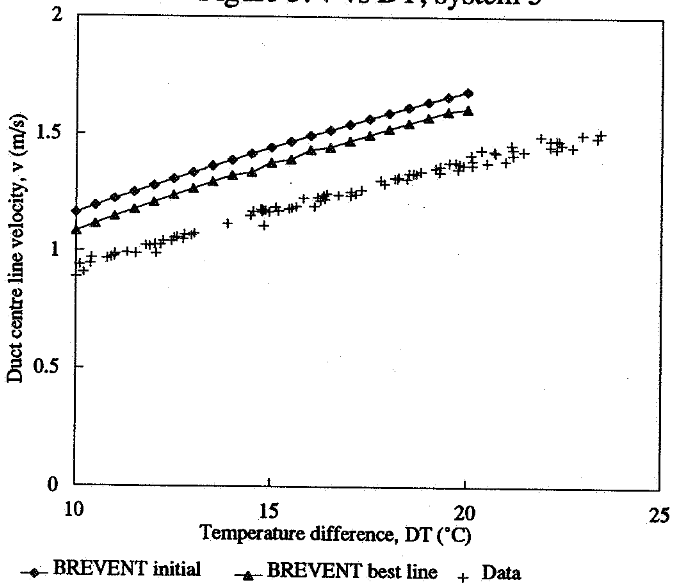
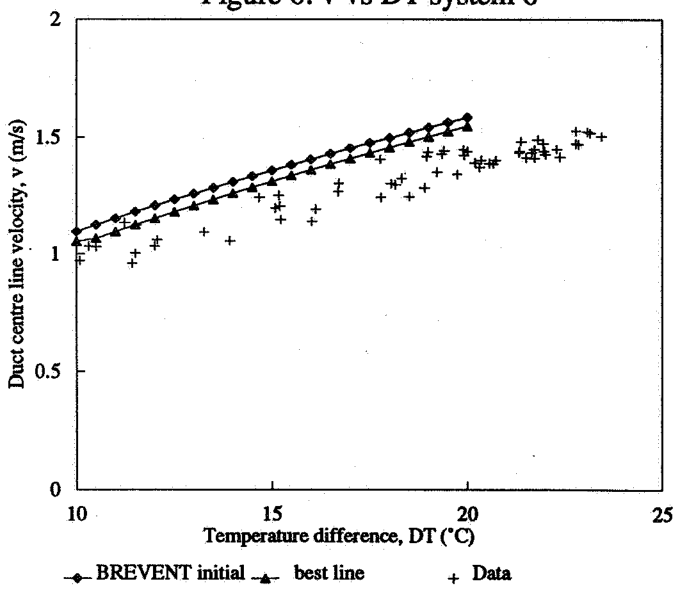


Figure 6: v vs DT system 6



Developments of the model

There were three aspects of the basic model which were felt could be resulting in error. A combination of solutions to all of them was used for the best lines in the figures above.

1) Effect of the kitchen door being closed

In BREVENT all of the inside of a building is assumed to be one well mixed zone. But in these tests, [3] the door to the kitchen where the PSV was sited was closed, so this assumption is not as good as usual. This reduces the effective volume of the house 'seen' by the PSV.

The essential point is that the airtightness of the building is a resistance on the flow up the stack. Closing the kitchen door makes it harder for air from outside the house to reach the PSV, and this reduces the PSV flow. This effect can be well understood by introducing a simple resistance model for air flow. Turbulent air flow can be represented by:

$$Q = \frac{(\Delta P)^{1/2}}{R} \qquad (5)$$

Hence for a PSV system, the Resistance R_D is given by $(\rho_I K \,.\, 8 / \pi^2 d^4)^{1/2}$. For infiltration the equation needs to be adjusted slightly, since the exponent is usually not 0.5, but nearer to 0.6, reflecting the partially laminar nature of infiltration.

$$Q = Q_T \cdot \left(\frac{\Delta P}{50}\right)^{0.6} \approx \frac{Q_T}{1.3} \cdot \left(\frac{\Delta P}{50}\right)^{0.5} \qquad (6)$$

Where Q_T is the flow rate measured at 50 Pa (m^3h^{-1}). This gives a good approximation to the same flows at pressure differences below 10 Pa, which is the region of most interest. Using this then the R value for infiltration is given by $R_I = (1.3.(50)^{1/2}) / Q_T$

To show how this can be applied consider the resistance values given in the table below. The values used are those relevant to the BRE test house, so that the volume is either that for the whole house, 205 m^3, or for the kitchen alone, 35 m^3. The total flow resistance is found by adding the two resistances in quadrature $R_{total} = (R_D^2 + R_I^2)^{1/2}$. This is because of the square root in the flow equation (5).

System	K	R_D		Volume	ach	R_I	R_{total} for line
1	3.5	77	House	205	13	13	78
2	3.0	71	Kitchen	35	11	86	111
5	4.1	164	House	205	13	13	164
6	4.6	175	Kitchen	35	11	86	195

From this it is fairly easy to see that the resistance of the PSV is the dominant effect when the whole house is considered. When the kitchen volume alone is taken the infiltration loss becomes significant. Hence by changing the effective volume of the building to reflect the fact that the kitchen door was closed the total resistance seen by the air flow is increased. This improves the closeness of the modelling fit from BREVENT, particularly for system 2, (figure 4), where the BREVENT best set line is close to that of the data set.

The concept of the resistance model can be useful in predicting expected flows. In fact for the simple situation of the PSV and one other feature in a temperature dominated regime, it can give the same results as BREVENT. However if other flow elements are added then it becomes more complicated, since some elements will be in series, and others in parallel.

This problem shows the limitations of a single zone model, in that a real house is not single zone when internal doors are shut. However, given that this study concerned PSV flow alone it was possible to improve the prediction by treating the kitchen as the only zone of significance.

Other multi-zone effects

In BREVENT the air is either in the building at temperature T_I or outside at temperature T_o. In reality there could well be a temperature difference between zones within the house, and a more advanced multi-zone model of the BREEZE type [8] is needed to model this. Of particular relevance here is the fact that some proportion of the leakage of the kitchen in the test house goes into the other rooms of the house where the temperature difference is less than that to the outside. Hence in a one zone model the leakage taken should be reduced to account for this. However there are no data available for how large this reduction should be, and this remains a problem area.

Applying the reduced leakages to the kitchen gives the effect shown in figure 5. Using the full kitchen leakage for system 5 gives a result almost identical to that for the whole house volume (not shown). For illustration reducing the leakage by 25% produces the improved line on figure 5. This was used for systems 5 and 6 only. More investigation of the multi-zone effects are needed to further improve the closeness of the fit.

2) The bend losses are not well understood

After applying the changes suggested above to the volume in the single zone model the two straight pipe cases give good results compared to the experimental data, both within 20% of measured values, and system 2 within 10%. However the two systems with bends continue to give larger errors, suggesting that the data for bend losses could be an issue. The published data for bend losses shows considerable variation, and this aspect deserves further study. The effect is greater in narrow pipes, so that based on BRE measurements a total value of 0.7 for the two bends is appropriate for system 5, but only 0.4 for system 1. These result in small changes to the predicted flow rates.

An additional feature which has not been addressed is the interaction between the bends and the terminal. These flow elements are not far enough apart in the real PSV system for steady flow profiles to be established by the time the next element is reached, so additional losses may occur.

3) Loss due to reduction of flow area

Changing the bend losses does not bring the system 1 prediction closer to the experimental data. However both systems 1 and 5 used the same terminal, a gas ridge vent. In the BRE laboratory tests this gave a loss factor, better than that of an open pipe. But the spigot on this terminal is fits a 110 mm pipe, and so the wider pipe needed reducing to connect it to the terminal. This gives an additional loss, which has now been included in the model.

In Woods guide [7] the effect of a flow reduction of 50% in area is given as an extra loss of 0.4. This raises the loss factor, but not by enough for the flow to match the data. As with bend losses this does not take any interaction with the terminal into account.

Conclusions

BREVENT is able to predict the passive stack flow in a house to fair accuracy, falling within 10-20% of measurements. Improvements in the given parameters have followed from extra BRE studies into air flow in pipes near the laminar/turbulent transition zone.

The resistance of the building fabric can restrict the flow in a PSV. The loss due to the duct itself may be similar to that due to the rest of the house, especially where the house is airtight, or the assumption of the one zone house is poor. Accounting for this further improves the accuracy of the BREVENT prediction.

Further work on bend losses, and careful consideration of the extra features of a particular system are needed to give detailed assessment of PSV flows.

Acknowledgement

This work was supported by the Building Regulations Division of the Department of the Environment, and is published with their permission. The views expressed are those of the authors and not of the Department.

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