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A Parametric Study of Ventilation as a Basis for Design

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An earlier, simple, parametric study of ventilation is extended to cover more realistic buildings. The mathematical model which forms the basis of the study is briefly described and non-dimensional graphs are derived to present the results of the model in a very compact and comprehensive form.

The importance of ceiling leakage when predicting ventilation is demonstrated and the significance of this to validation of models is discussed.

It is shown that by making acceptable approximations, a wide range of buildings can be covered by a small number of graphs. This leads to the possibility of a very simple graphical procedure for estimating ventilation with relatively high accuracy. A correspondingly simple means of estimating ventilation associated with turbulent pressure fluctuations is proposed.

NOMENCLATURE

a, b	coefficients in quadratic flow equation
Ar	Archimedes number based on h and Ur
A_c^*/A_t	ratio of ceiling open area to total open area
A_1, A_2, A_3, A_4	open areas on walls
Cp_1, Cp_2, Cp_3, Cp_4	surface pressure coefficients on walls
$\Delta Cp_1, \Delta Cp_2, \Delta Cp_3$	pressure difference coefficients, relative to Cp_1
Cp_{r1}, Cp_{r2}	roof pressure coefficients
Cp_r	average roof pressure coefficient
Cp_{rms}	coefficient of root-mean-square of pressure fluctuations
ΔCp_r	pressure difference coefficient of roof, $Cp_1 - Cp_r$
$C_{d\infty}$	discharge coefficient of opening at high Reynolds number
h	height of upper ceiling
q	flow rate through opening
Q	ventilation flow rate
Q_t	effective additional ventilation due to turbulence
R	leakage Reynolds number parameter, $R \equiv C_{d\infty}/Re_L$
S	ventilation rate coefficient
St	coefficient of ventilation rate due to turbulence
T	temperature
ΔT	temperature difference between interior and exterior
U_B	equivalent wind speed of buoyancy
U_r	reference wind speed
W_1, W_2, W_3	weather parameters, $\Delta Cp_1/Ar^2$ etc
W_r	weather parameters of roof, $\Delta Cp_r/Ar^2$
Re_L	whole-house leakage Reynolds number
Re	crack flow Reynolds number

1. INTRODUCTION

AN EARLIER paper [1] described a parametric study of ventilation (natural and mechanical) for a very simplified building, i.e. a house with openings on only two walls.†

In the present paper the study is extended to much more realistic representations of houses. Attention is here restricted to natural ventilation, because the inclusion of mechanical flows does not differ in principle to the simple cases considered earlier. The present study does, however, include a treatment of ventilation associated with turbulent pressure fluctuations which was not previously covered. No distinction is made between ventilation and infiltration, it being assumed that the leakage characteristic of the house includes purpose-provided and adventitious openings. Following a brief description in Section 2 of the prediction method which has been used for the work, the derivation of the non-dimensional graphs is described in Section 3. Examples of the graphs are presented in Section 4, where the importance of certain parameters is discussed. It is then shown how, in Section 5, it is possible to reduce the number of graphs required to cover a wide range of building types, thereby offering a simple graphical method for predicting ventilation rates. In Section 6, a simple but approximate method of accounting for wind pressure fluctuations is described.

It is important to realise that the use of non-dimensional parameters is not an academic exercise. Only by using such parameters can a truly general study be made and general conclusions be drawn. The crux of a ventilation study is the non-dimensional equation for the flow through openings and this is briefly discussed in the following.

2. DESCRIPTION OF PREDICTION METHOD

The prediction of ventilation rates basically consists of two parts—the specification of input data and the use of equations which relate ventilation rate to the input data. It is perhaps a reflection on the state of knowledge of building ventilation characteristics that the available pre-

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† See Appendix 2 for the correction of some errors in [1] which were not eliminated during proof reading.

diction methods are distinguished more by their different treatments of input data than by the basic physical equations employed.

The method used for the present study is known as VENT2. It is the single-cell version [2] of the multi-cell model VENT [3]. It differs from most methods in the form of flow equations used. In deriving it, the aim was to minimise the assumptions made about the data input.

2.1 *Specification of input data*

Ideally, the input data would consist of the following :

(i) external surface pressure distributions due to the wind,
(ii) internal surface pressure gradients due to buoyancy,
(iii) distribution of openings in the surfaces,
(iv) geometry (size and shape) of the openings.

Surface pressure distributions are specified in terms of a pressure coefficient Cp and a reference wind speed Ur. This is standard practice and has been adopted for most prediction methods. Also in common with most single-cell methods, the assumption is made that Cp does not vary over the surface of a wall.

The internal surface pressure gradient is assumed to be constant, which corresponds to a uniform internal temperature.

No specific assumptions are made about the distributions of openings in the envelope of the building other than that the openings are discrete. The distribution is specified by the user in terms of the heights of the openings.

The main assumption concerns the geometry of the openings. It is assumed that all openings are identical. This is done because it means that the flow characteristics of the openings are then simply related to the leakage characteristic of the whole building [1], which is often measured.

VENT2 does have the facility to distinguish between purpose-provided air vents and adventitious openings, and ideally such a distinction should be made. It has not been done in the present exercise, on the grounds of simplicity.

Compared to some single-cell methods, the above assumptions are minimal. This means that a computer is required to obtain the predictions. However, the predictions need only be carried out once and presented in non-dimensional graphs, thereby by-passing the need for a computer for subsequent purposes.

2.2 *Flow equation*

The equations which relate the ventilation rate to the input data are the mass continuity equation and the flow equation for the openings. Only the latter need be considered here, although it should be noted that, as in [1], the density ρ has been taken as constant as far as the continuity equation is concerned.

All known methods assume steady flow, so that the flow equation required is one which relates the discharge coefficient C_d of an opening to the Reynolds number of the flow through it, i.e.

$$C_d = F(Re), \tag{1}$$

where the function F depends only on the shape of the opening. An equation of this type is implicit in all prediction methods (except purely empirical ones) although it is rarely seen explicitly.

For VENT2 the equation is:

$$C_d^2 = \frac{Re}{c+d\,Re}, \tag{2}$$

where c and d are constants for a given shape and $d = 1/C_{d\infty}^2$, where $C_{d\infty}$ is the value of C_d at very high values of Re. The Reynolds number is based on the flow rate through the opening, q, and a representative dimension, which can be taken as $\sqrt{A}$ where A is a cross-sectional area, i.e.

$$Re \equiv \frac{q\sqrt{A}}{A\nu} = \frac{q}{\sqrt{A}\nu}$$

where ν is the kinematic viscosity. The discharge coefficient is defined as

$$C_d \equiv \frac{q}{A}\sqrt{\frac{\rho}{2\Delta p}}$$

where Δp is the pressure difference across the opening.

Using these definitions, equation (2) can be seen to be the quadratic flow equation

$$\Delta p = aq^2+bq. \tag{3}$$

where a and b are constants for a given geometry (shape and size) of opening. Support for the quadratic equation can be found in [4] and more recently in [5] and [6].

A more commonly used equation is the so-called power law

$$q = C\Delta p^{\beta}$$

where C and β are constants for a given geometry. Although the power law owes its popularity to experimental measurements, these have often been made at high pressures outside the range of natural ventilation and could equally support the quadratic equation. It has been shown in [7] that the differences between the power law and the quadratic can be large at the low pressures of interest. Evidence is also available that β is not constant and that it varies with Re. This can be seen in [8] and in the discussion to [9] (the paper on its own gives a different impression).

For these reasons, the quadratic equation forms the basis of VENT2 and, of course, the graphs presented below. It is probable that qualitatively similar results would have been obtained with the power law, but they would differ quantitatively. The form of the power law results is discussed in Appendix 3.

3. DERIVATION OF GRAPHS

For the simple house treated in [1], the dependence of the infiltration rate Q on the various factors which determine it was expressed by the relationship

$$\frac{Q}{C_{d\infty}A_T U_B} = f\left[\frac{Cp_1-Cp_2}{A_r^2}, \frac{Cd_\infty}{Re_L}\right], \tag{4}$$

where f denotes a function which depends only on the non-dimensional distribution of the openings. The dependence on the size of openings is accounted for by $C_{d\infty}$ and Re_L. Re_L is defined as $\rho U_B/bA_T$ and can be identified as a Reynolds number based on the equivalent air speed U_B and a characteristic dimension of the openings.

To distinguish it from Re in equation (1), Re_L is called the whole-house leakage Reynolds number. To make use of the graphs it is not necessary to know the value of Re_L, but only the value of $C_{d\infty}/Re_L$ which is given by

$$\frac{C_{d\infty}}{Re_L} = \frac{1}{\sqrt{2\rho}}\frac{1}{U_B}\frac{b}{\sqrt{a}}$$

and this can be obtained from the leakage characteristic of the house (and ΔT and h).

The relationship expressed in (4) does not have the same wide validity as (1). It is valid only with the assumption of identical openings and for a two-parameter flow equation (2).

All of the symbols in equation (4) are defined in the Notation, and at this stage it is only necessary to consider the three non-dimensional parameters which are referred to as follows

$$\frac{Q}{C_{d\infty}A_TU_B} \text{ – ventilation rate coefficient, } S$$

S is simply a non-dimensional form of Q.

$$\frac{Cp_1 - Cp_2}{A_r^2} \text{ – weather parameter, } W_1.$$

W_1 is the ratio of the wind and buoyancy pressures. Cp_1 and Cp_2 are wind pressure coefficients on walls 1 and 2.

$$\frac{C_{d\infty}}{Re_L} \text{ – leakage Reynolds number parameter, } R$$

R is a parameter which relates to the flow characteristics of the openings in the building, and to the reference speed U_B.

In [1], calculations were carried out with VENT2 so that the function f in equation (4) could be defined by lines of constant R on a graph of S against W_1. Equation (4) applies to a terraced house with no ceiling openings (i.e. openings only on the two exposed walls). For greater realism, it is necessary to consider houses with extra walls and with openings in the upper ceiling.

3.1 *Effect of extra walls*

When an extra wall is added to represent a semi-detached house (no ceiling openings), a further wind pressure coefficient Cp_3 is introduced. It is shown in Appendix 1 that this simply introduces an extra weather parameter, so that the functional relationship becomes

$$\frac{Q}{C_{d\infty}A_TU_B} = f\left[\frac{Cp_1-Cp_2}{Ar^2}, \frac{Cp_1-Cp_3}{Ar^2}, \frac{C_{d\infty}}{Re_L}\right]. \quad (5)$$

Similarly, extending the treatment to a detached house with an extra coefficient Cp_4 gives

$$\frac{Q}{C_{d\infty}A_TU_B} = f\left[\frac{Cp_1-Cp_2}{Ar^2}, \frac{Cp_1-Cp_3}{Ar^2}, \frac{Cp_1-Cp_4}{Ar^2}, \frac{C_{d\infty}}{Re_L}\right]. \quad (6)$$

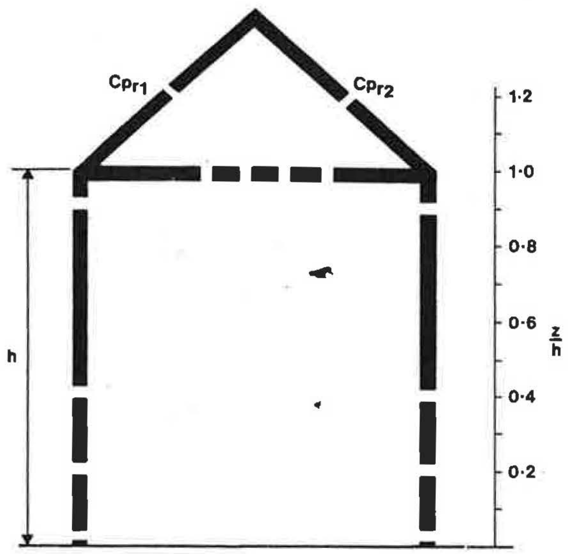

Fig. 1. Roof and loft simulation and vertical distribution of openings for Section 4.

3.2 *Effect of ceiling openings*

The presence of ceiling openings introduces a large number of extra variables associated with the roof and the loft (e.g. roof pressure coefficient, roof leakage, loft temperature), but fortunately the influence of most of them will often be small, as far as the ventilation of the living space is concerned. (The influence on loft ventilation will, of course, be large.)

Figure 1 shows how the roof and the loft are simulated by VENT2. The main assumption is that the roof leakage can be represented by two identical openings at the same height above the ceiling. Now, as far as the house infiltration rate is concerned, the only quantity of importance is the static pressure immediately above the ceiling openings. Under non-zero wind conditions it is a reasonable approximation to assume that this pressure is determined by the average of the two roof coefficients, i.e.

$$Cp_r = \frac{Cp_{r1} + Cp_{r2}}{2}.$$

The result of this approximation is that the inclusion of ceiling openings adds only one extra weather parameter, so that the functional relationships for the three house types become

$$\frac{Q}{C_{d\infty}A_TU_B} = f\left(\frac{\Delta Cp_1}{Ar^2}, \frac{\Delta Cp_r}{Ar^2}, \frac{C_{d\infty}}{Re_L}\right) \quad (7)$$

$$\frac{Q}{C_{d\infty}A_TU_B} = f\left(\frac{\Delta Cp_1}{Ar^2}, \frac{\Delta Cp_r}{Ar^2}, \frac{\Delta Cp_r}{Ar^2}, \frac{C_{d\infty}}{Re_L}\right) \quad (8)$$

$$\frac{Q}{C_{d\infty}A_TU_B} = f\left(\frac{\Delta Cp_1}{Ar^2}, \frac{\Delta Cp_2}{Ar^2}, \frac{\Delta Cp_3}{Ar^2}, \frac{\Delta Cp_r}{Ar^2}, \frac{\Delta C_{d\infty}}{Re_L}\right). \quad (9)$$

For brevity, ΔCp_1, ΔCp_2, ΔCp_3 and ΔCp_r have been substituted for $(Cp_1 - Cp_2)$, $(Cp_1 - Cp_3)$, $(Cp_1 - Cp_4)$ and $(Cp_1 - Cp_r)$ respectively.

There is little doubt that the above treatment of ceiling openings is a simplification, but it does take explicit account of roof pressures. It will be seen below that the weather parameter associated with these pressures can have a very large influence on ventilation rates.

The conditions under which the treatment is least valid include the case where the roof leakage is not much greater than the ceiling leakage (in practice this should be rare) and the case when wind speeds are low and temperature differences are large. For all of the calculations carried out here, the roof leakage has been taken as twice the house leakage, the loft temperature difference as half that of the living space, and the height of the roof openings as 20% greater than the ceiling height.

4. EXAMPLES OF GRAPHS

For all of the graphs in this section, the vertical distribution of openings on the walls is constant. (The effect of varying this distribution was discussed in Ref. 1 and some further examples will be given in Section 5.) The chosen distribution is shown in Fig. 1. It is more realistic than those used in [1], but it remains to be seen from experimental work whether a more typical distribution can be found.

For the present study, attention is focused on the effect of the distribution of openings between walls and ceiling. To describe these distributions, the following conventions have been adopted. The wall distribution is shown as a ratio of the form $A_1:A_2$ (when $A_1:A_2$ is 1:2 there is twice the open area on wall 2 than on wall 1). The amount of open area in the ceiling is described by the ratio A_c/A_t (for $A_c/A_t = 0.33$, one third of the total open area is in the ceiling).

An additional convention is that wall 1 is defined as the wall with the most positive pressure coefficient. This means that ΔCp_1, ΔCp_2 and ΔCp_3 are never negative.

4.1 *Graphs for terraced houses*

(i) *No ceiling openings*, $A_c/A_t = 0$. Figure 2 shows the solution of equation (4) with $A_1:A_2$ equal to 1:1. The graphs for asymmetric solutions 1:2 and 2:1 are given in Fig. 3. It is possible to show results for two distributions in one figure without confusion, because the two sets of results differ only for moderate values of W_1, i.e. the ventilation rate is not very sensitive to the wall distribution on a terraced house.

It is easy to see the reasons for this. At low values of W_1, buoyancy is dominant and the ventilation rate depends only on the vertical distribution of openings, which has been kept constant. At high values of W_1, wind pressures are dominant and because it is only the difference between the pressures which is important (not the actual pressures) it does not matter whether the largest open area is on the windward or leeward wall.

Figure 4 shows the same behaviour for the complementary distributions 1:3 and 3:1. Clearly, there is scope for simplification by taking average curves to cover complementary distributions. For example, the maximum difference between the values of S for the two distributions is approximately 20%, so an average curve would be accurate to within $\pm 10\%$. For design purposes, this would be acceptable, and in most cases the error would be much less than 10%.

At very low values of W_1, the curves are completely independent of the wall distribution, as can be seen by comparing Figs 2, 3 and 4 for $W_1 < 1$. At high values of W_1 this is not true, but in some circumstances one might still accept the further simplification of replacing Figs 2, 3 and 4 by one graph. The maximum difference between the 1:1 and 1:3 distributions occurs for $W_1 = 10$ and is approximately 50%. Thus, using the 1:2 curves for the three distributions implies a maximum error of $\pm 25\%$.

(ii) *With ceiling openings*, $A_c/A_t \neq 0$. The introduction of ceiling openings means that the results (of equation 7) cannot be presented on one graph. The approach adopted here is to retain plots of S against W_1, but the curves of constant R are replaced by curves of constant W_r. Figure 5 shows an example for a wall distribution of 1:2, $A_c/A_t = 0.40$ and $R = 1.5$. Superimposed on this figure is the curve for the case with no ceiling openings ($R = 1.5$, from Fig. 3).

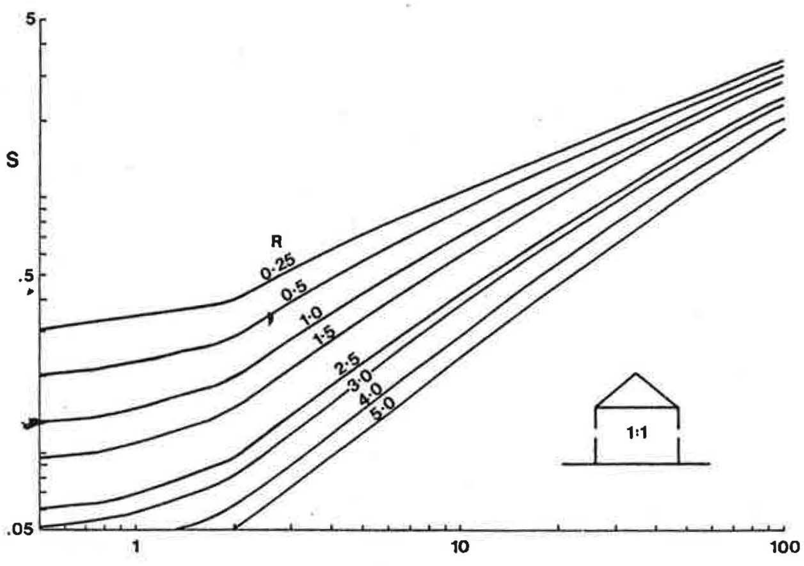

Fig. 2. Results for terraced house $A_c/A_t = 0$, $A_1:A_2$ ratio 1:1.

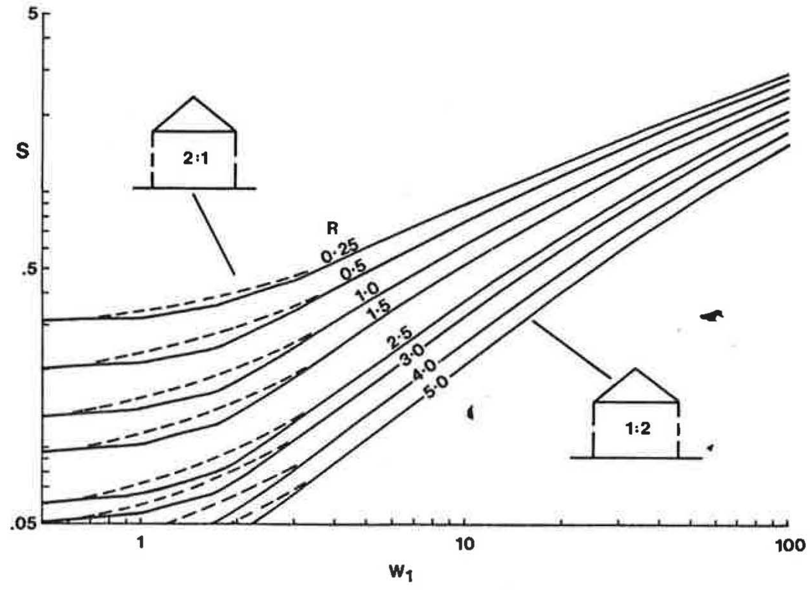

Fig. 3. Results for terraced house $A_c/A_t = 0$, $A_1:A_2$ ratios 1:2 and 2:1.

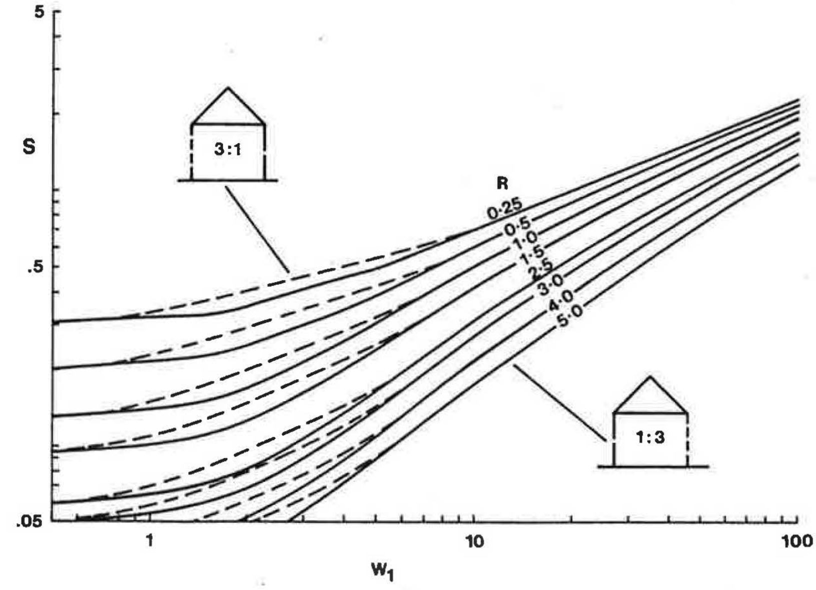

Fig. 4. Results for terraced house $A_c/A_t = 0$, $A_1:A_2$ ratios 1:3 and 3:1.

It is immediately apparent that ceiling openings can have a profound effect on the ventilation rate, particularly at low values of W_1. For $W_1 = 1.0$, the value of S is 0.10 with no ceiling openings. With ceiling openings and with $W_r = 2.5$, the ventilation rate is more than 2.5 times larger. The reason for this is that the ceiling openings act in a different way to openings on the walls, because stack effect and wind effect act in concert. With wall openings, the two effects tend to counteract one another.

This observation has considerable relevance to the validation of prediction methods. If good agreement between prediction and measurement is obtained when no account is taken of ceiling openings, the agreement is possibly fortuitous. In the above comparison we have taken $A_c/A_t = 0.40$, which might be untypically large, but there is very little information available in the literature. The value of W_r chosen is probably not untypical however, because roof pressures tend to be lower than pressures on vertical walls, particularly with low-pitched roofs, and one might expect ΔCp_r to generally be less than ΔCp_1.

4.2 *Graphs for semi-detached and detached houses*

The introduction of a further weather parameter W_2 for semi-detached houses (and two further parameters, W_2 and W_3, for detached houses) means that a very large number of graphs are needed to present the solutions to equation 5 (or equation 6 for detached houses). Although there is no difficulty in producing them, they are unwieldy and it would be useful if they could be dispensed with, by adopting an approximate procedure with only a small loss of precision. Such a procedure is now described. It will be adapted in Section 5 to arrive at a proposed

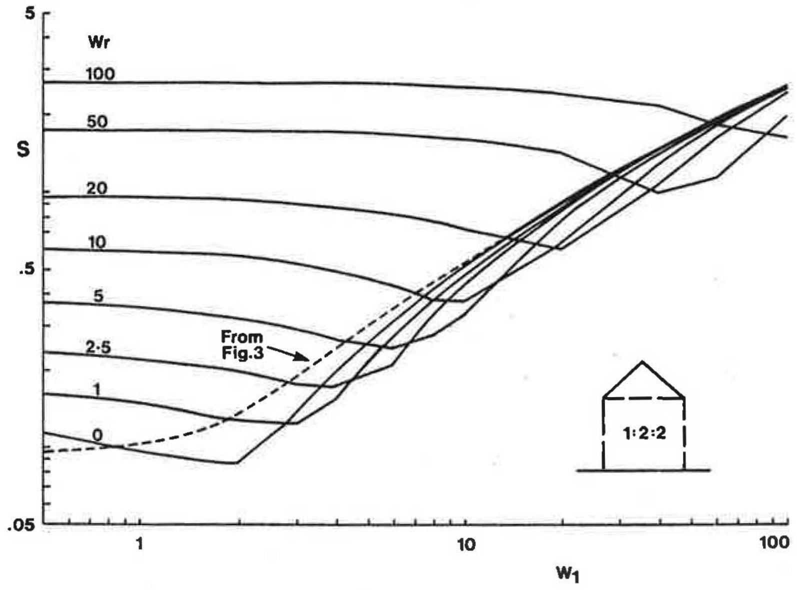

Fig. 5. Results for terraced house $A_c/A_t = 0.4$, $R = 1.5$, $A_c:A_1:A_2$ ratio is 1:2:2.

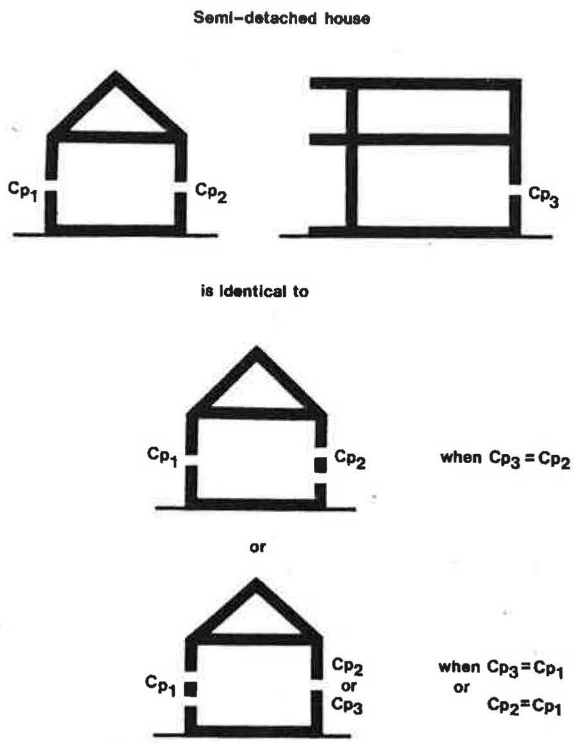

Fig. 6. Reduction of semi-detached house to equivalent terraced houses $A_c/A_t = 0$, $A_1:A_2:A_3$ ratio is 1:1:1.

simple design procedure. For the present, however, it is considered in its basic and less approximate form.

The procedure is to reduce the semi-detached house (or detached house) to an equivalent terraced house. As shown in Fig. 6, for a semi-detached house with a uniform wall distribution ($A_1:A_2:A_3$ is 1:1:1), the only feature which distinguishes it from a terraced house is that two of the walls do not have the same value of pressure coefficient. It two walls do have equal values (e.g. $Cp_2 = Cp_3$), the semi-detached house is indistinguishable from a terraced house with $A_1:A_2$ equal to 1:2. Similarly, if $Cp_2 = Cp_1$, the ventilation of the house will be identical to that of a terraced house with $A_1:A_2$ equal to 2:1.

Thus, a logical way of reducing semi-detached houses to terraced houses is to take the two walls with the closest Cp values and to combine their openings on one wall with a Cp equal to the average of the two. In this way, the semi-detached house reduces to a terraced house with $A_1:A_2$ equal to 1:1, 1:3 or 3:1.

By adopting the above procedure, the three Figs 2, 3 and 4 cover a very wide range of buildings with very small errors, e.g. see Fig. 7. The procedure could be extended to cover buildings with ceiling leakage by pro-

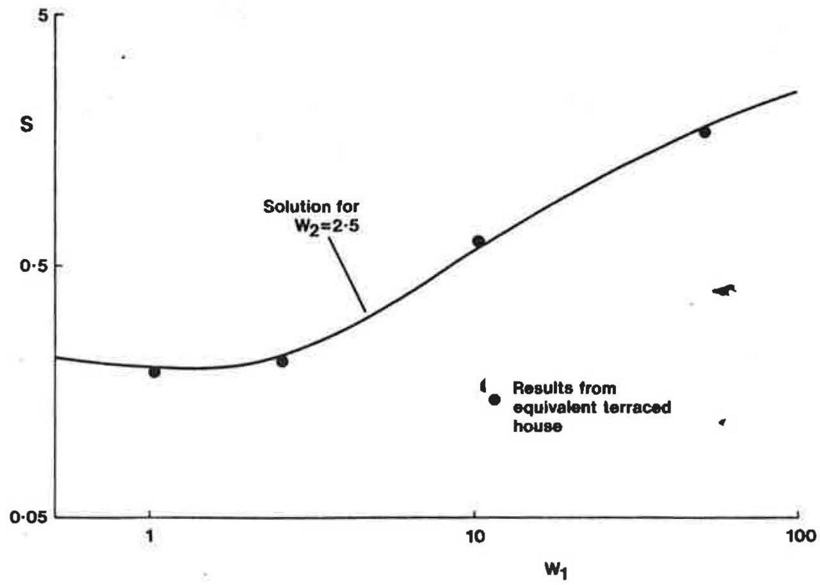

Fig. 7. Solution for semi-detached house ($A_c/A_t = 0$, $A_1:A_3$ ratio 1 : 1 : 1) compared with results using equivalent terraced house.

ducing extra graphs for terraced houses with ceiling leakage, as in Fig. 5. This does, however, lead to a rather large number of graphs and it would clearly be useful for general design purposes if ceiling leakage could be covered by a small number of graphs. A proposal for such a series of graphs is described in the following.

5. A SIMPLE ESTIMATION PROCEDURE FOR DESIGN

The procedure described in Section 4.2 is not suitable for general design purposes because a large number of graphs is still required. Unless the design value of R happens to coincide with one of the curves on the graphs, it is necessary to make use of at least two graphs and interpolate between them. The advantage of graphs like those in Figs 2, 3 and 4 is that the interpolation can be done visually from one graph.

To make use of these graphs, it is necessary to reduce a house with ceiling openings to a terraced house without ceiling openings. This can be done in the manner described below, subject to the restriction that the ceiling open area is the same as that on each of the walls. This uniform opening distribution should be acceptable for general purposes, since it is probably not untypical, and the real distribution will not be known.

5.1 *Description of procedure*

The procedure is basically the same as that in Section 4.2, insofar as the ceiling openings are transferred to one of the vertical walls, depending on the value of the roof pressure coefficient Cp_r. The difference is that the ceiling openings are placed on the appropriate wall at ceiling height. This wall, therefore, has a vertical distribution of openings which is different to the other wall.

Figure 8 illustrates the procedure for a terraced house with ceiling openings. The equivalent house without ceiling openings will have one of four possible opening distributions. Two of these will rarely be encountered in practice, because they arise when the roof pressure coefficient is large and positive in relation to the other pressure coefficient.

These two distributions can therefore be neglected, so that the solutions for terraced houses with ceiling openings can be obtained from the graphs for the equivalent terraced house with $A_1:A_2$ equal to 1 : 2 or 2 : 1.

For semi-detached houses with ceiling openings there are six possible equivalent terraced houses, but three of these are unlikely to be encountered, as shown in Fig. 9. Graphs are only required for opening distributions 1 : 1, 1 : 3 and 3 : 1. For detached houses, there are eight possible distributions, but again only half of these are of real interest, i.e. distributions 1 : 4, 4 : 1, 2 : 3 and 3 : 2. From the above it can be seen that nine graphs are required to cover the three types of houses with ceiling openings. In fact, this number can be reduced further, because, for example, the solutions for distributions 2 : 3 and 3 : 2 can be obtained from the graph for 1 : 1, with only small errors.

For many design purposes, four graphs would suffice. These are given in Figs 10–13 and the graph to use for any particular case is determined from Table 1. The corresponding value of W_{1e} is obtained by taking the average of the pressure coefficients assigned to the two walls.

In the unlikely event that the ceiling openings are assigned to wall 1, the above graphs should not be used. Instead, the graph shown in Fig. 14 can be used to obtain an approximate result. It is simply one of the graphs corresponding to this rare case.

To conclude this section, it can be noted that the effect of varying the vertical distribution of openings can be assessed by comparing Figs 2 and 4 with their equivalents in Figs 10–12. For example, the only difference between Figs 11 and 3 is that the houses have different vertical distributions of openings, yet large differences (up to 25%) are apparent at low values of W_1. To obtain high accuracy from a prediction method at low wind speeds, a knowledge of the vertical distribution is needed.

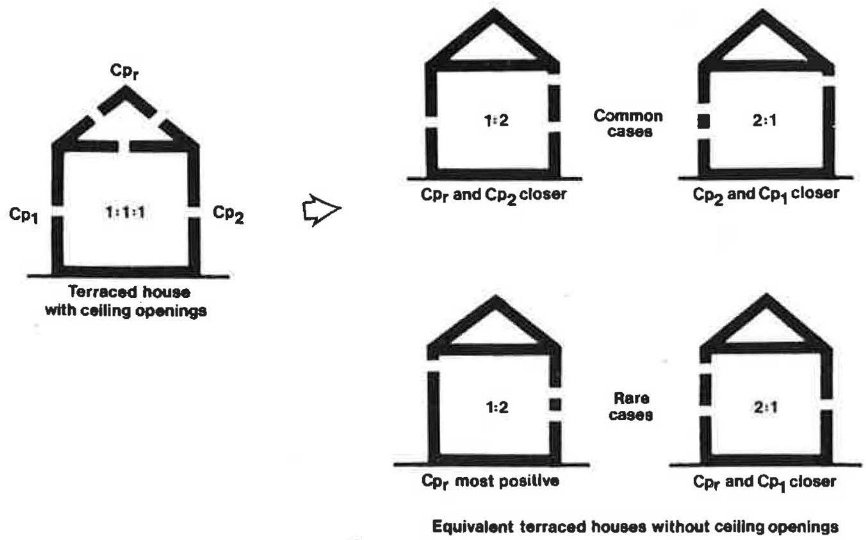

Fig. 8. Reduction of terraced house with ceiling openings ($A_c : A_1 : A_2$ ratio 1 : 1 : 1) to equivalent terraced house without ceiling openings.

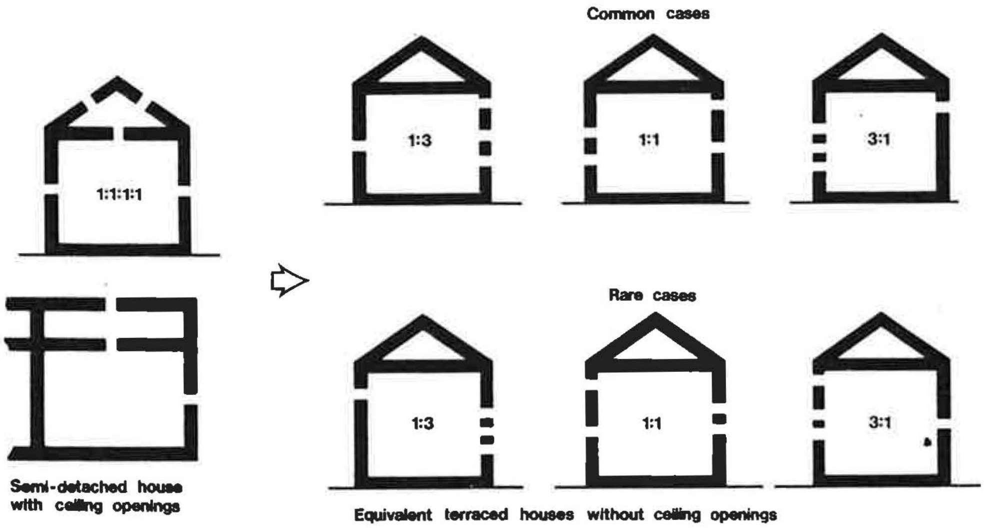

Fig. 9. Reduction of semi-detached house with ceiling openings to equivalent terraced house without ceiling openings.

6. VENTILATION DUE TO TURBULENCE

As noted in Section 2, the mathematical model assumes quasi-steady flow, so that a ventilation rate associated with turbulent wind pressures can be calculated separately from the main calculation of Q. In VENT2, this is done by calculating for each opening an effective ventilation rate due to turbulence, Q_t. The rate is determined by the type of opening (it is set to zero if the opening is classed as background leakage) and by the relative magnitudes of the mean and the root-mean-square of the pressure difference across the opening. The individual rates are summed to give an effective whole-house rate $Q_t (= \Sigma q_t)$. This treatment relies on several approximations and assumptions, some of which are rather tentative [3].

In view of this, a full series of graphs for Q_t, similar to those for Q is not considered justifiable. Instead, the following approximate procedure is proposed as a quick method for estimating Q_t.

The effective ventilation rate due to turbulence is calculated with the same flow equation as the steady flow through the opening (with the steady pressure difference replaced by the root-mean-square of the pressure fluctuations), but with an additional term to take account of the fact that additional ventilation only ocurs when the fluctuations are large enough (relative to the mean pressure) to cause flow reversal. The functional relationship between the non-dimensional parameters for the effective ventilation should, therefore, be similar to that for the steady flow, but with an extra term, i.e. approximately

$$\frac{Q_t}{C_{d\infty} A_T U_B} = f_t\left(\frac{\Delta Cp_1}{Ar^2}, \frac{C_{d\infty}}{Re_L}, \frac{Cp_{rms}}{\Delta Cp}\right), \tag{10}$$

for a terraced house with no ceiling openings. Using

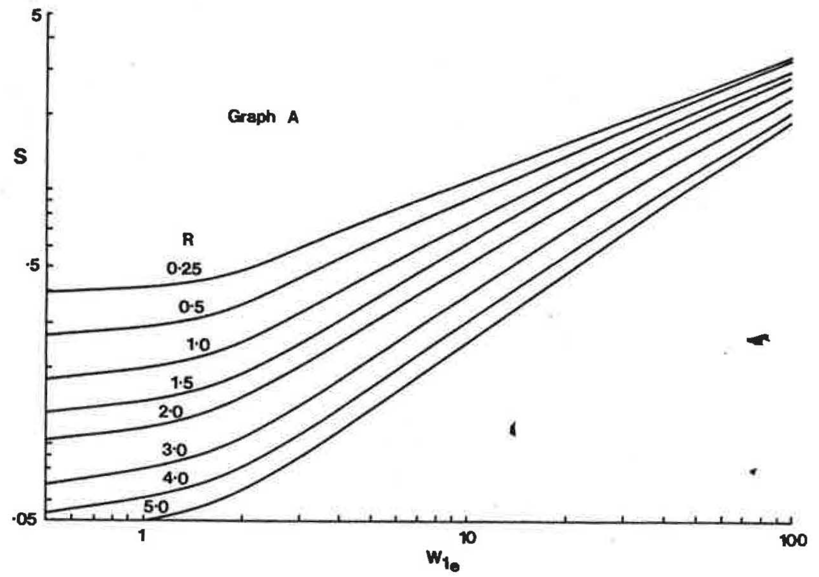

Fig. 10. Graph 'A' of an example set for design purposes. See Table 1.

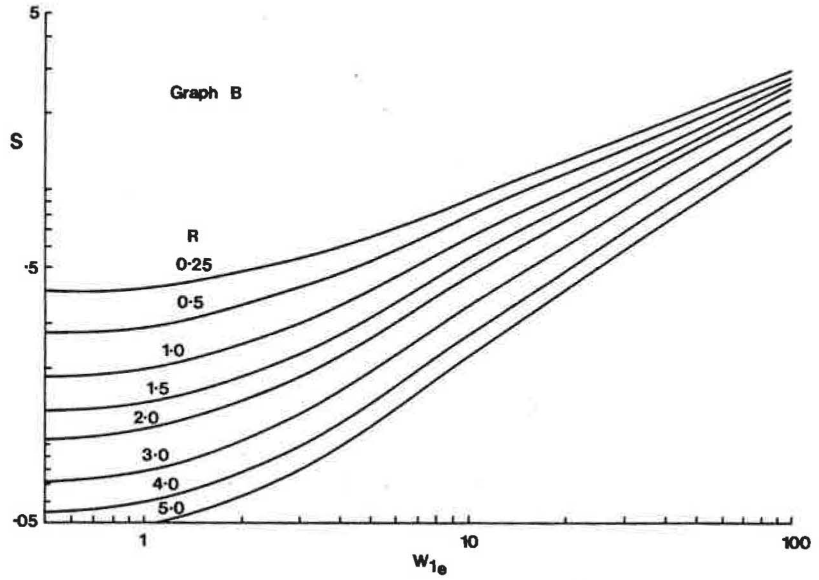

Fig. 11. Graph 'B' of an example set for design purposes. See Table 1.

equation (4), the above relationship can be expressed in the form

$$\frac{Q_t}{C_{d\infty}A_TU_B} = f_t\left(\frac{Q}{C_{d\infty}A_TU_B}, \frac{C_{d\infty}}{Re_L}, \frac{Cp_{rms}}{\Delta Cp}\right). \qquad (11)$$

Calculations have been made for a terraced house (no ceiling openings, $A_1 = A_2$) and the results are shown in Fig. 15. Some simplifications have been made in this presentation, i.e. the results are shown as straight lines passing through a common origin, which is not precisely true.

It is suggested that Fig. 15 be used to estimate Q_t, to complement the procedure of Section 5. For example, suppose a value for $S = 2.0$ with $R = 1.0$ is obtained from the procedure, the turbulence contribution can be obtained directly from Fig. 15, provided that the coefficient of the turbulent pressure fluctuations Cp_{rms} can be specified. Supposing $Cp_{rms} = 0.15$ and $\Delta Cp = 0.5$, then $Cp_{rms}/\Delta Cp = 0.30$, and from the figure the estimated value of S_t is 0.44. The total ventilation rate $(S+S_t)$ is thus 2.44.

Cp_{rms} is a measure of the fluctuating component of the pressure difference across the openings. Admittedly the specification of Cp_{rms} is neither easy nor precise [3] but Fig. 15 is at least useful for estimating errors arising from the complete neglect of the turbulence contribution. Such errors will be at their largest (relatively speaking) when the following conditions occur—low temperature difference, high wind speed and low ΔCp. The last condition is important, because it is generally taken to mean that the ventilation rate is not greatly influenced by wind speed.

A low value of ΔCp is often associated with a "sheltered" building, i.e. one which is closely surrounded by buildings or other obstacles. This type of sheltering could, however, generate high turbulence levels so that $Cp_{rms}/$

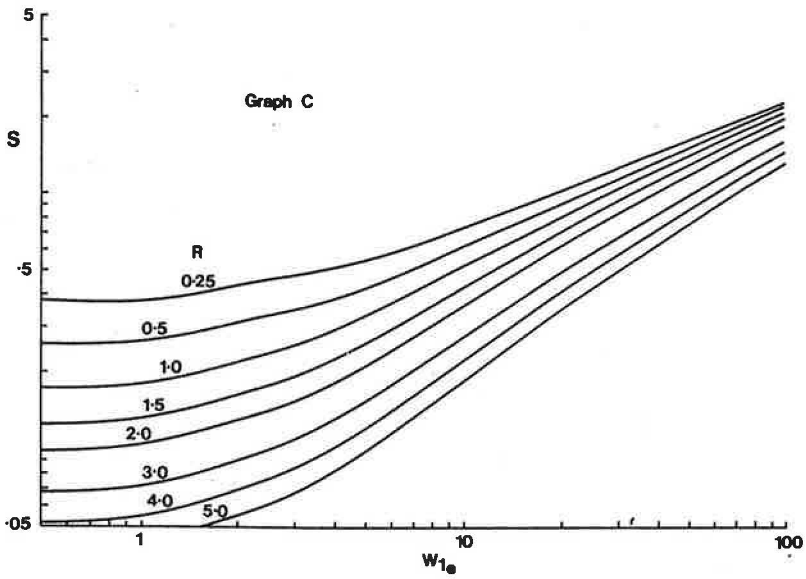

Fig. 12. Graph 'C' of an example set for design purposes. See Table 1.

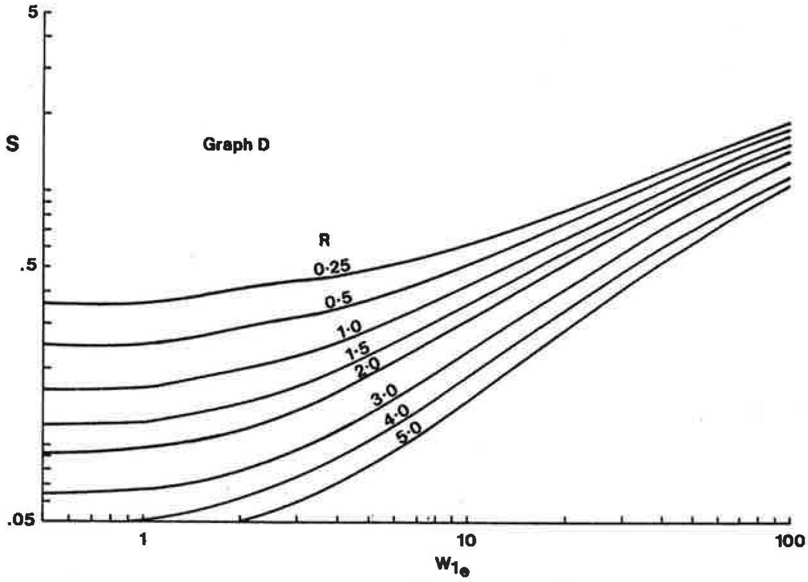

Fig. 13. Graph 'D' of an example set for design purposes. See Table 1.

Table 1.

Actual house type (all with ceiling openings)	Opening distribution of equivalent terraced house	Graph to be used
Terraced	1:2	B (Fig. 11)
Terraced	2:1	B (Fig. 11)
Semi-detached	1:3	C (Fig. 12)
Semi-detached	3:1	C (Fig. 12)
Semi-detached	2:2	A (Fig. 10)
Detached	1:4	D (Fig. 13)
Detached	4:1	D (Fig. 13)
Detached	2:3	A (Fig. 10)
Detached	3:2	A (Fig. 10)
Houses for which pressure distribution is such that ceiling openings are assigned to Wall 1.		E (Fig. 14)

ΔCp is high, S_t is correspondingly high and the ventilation rate remains dependent on wind speed, despite the low value of ΔCp. It is not necessarily correct, therefore, to associate the term "sheltered" with a building whose ventilation is not influenced by wind. This will only be true if both ΔCp and Cp_{rms} are reduced by the sheltering.

One final point needs to be made about Fig. 15. The results were obtained for a house in which 70% of the total leakage is through background leakage openings. Such openings are assumed to not respond to turbulent pressure fluctuations. Only component openings and air vents are assumed to contribute to Q_t [3]. If, when using Fig. 15, the percentage of these openings is different to 30% the values of S_t should be altered in direct proportion to the percentage.

7. CONCLUSIONS

Non-dimensional graphs derived from prediction methods are very useful for ventilation studies. They

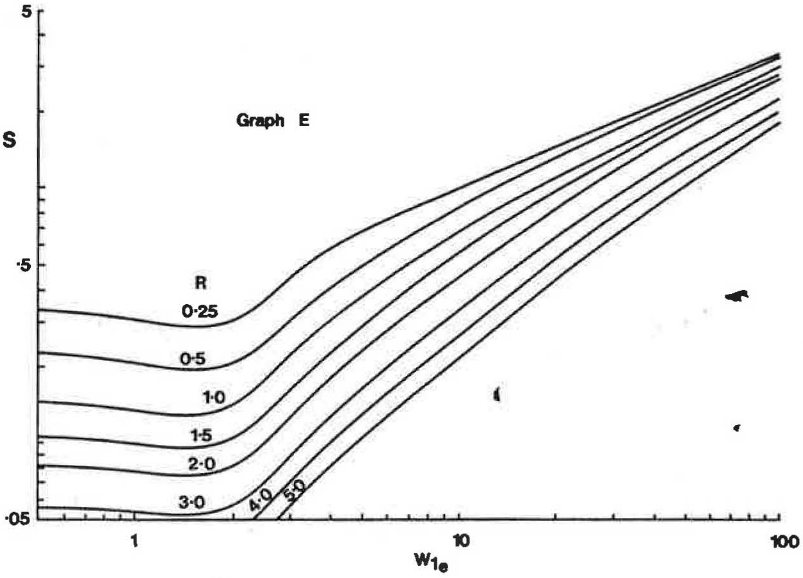

Fig. 14. Graph 'E' of an example set for design purposes. See Table 1.

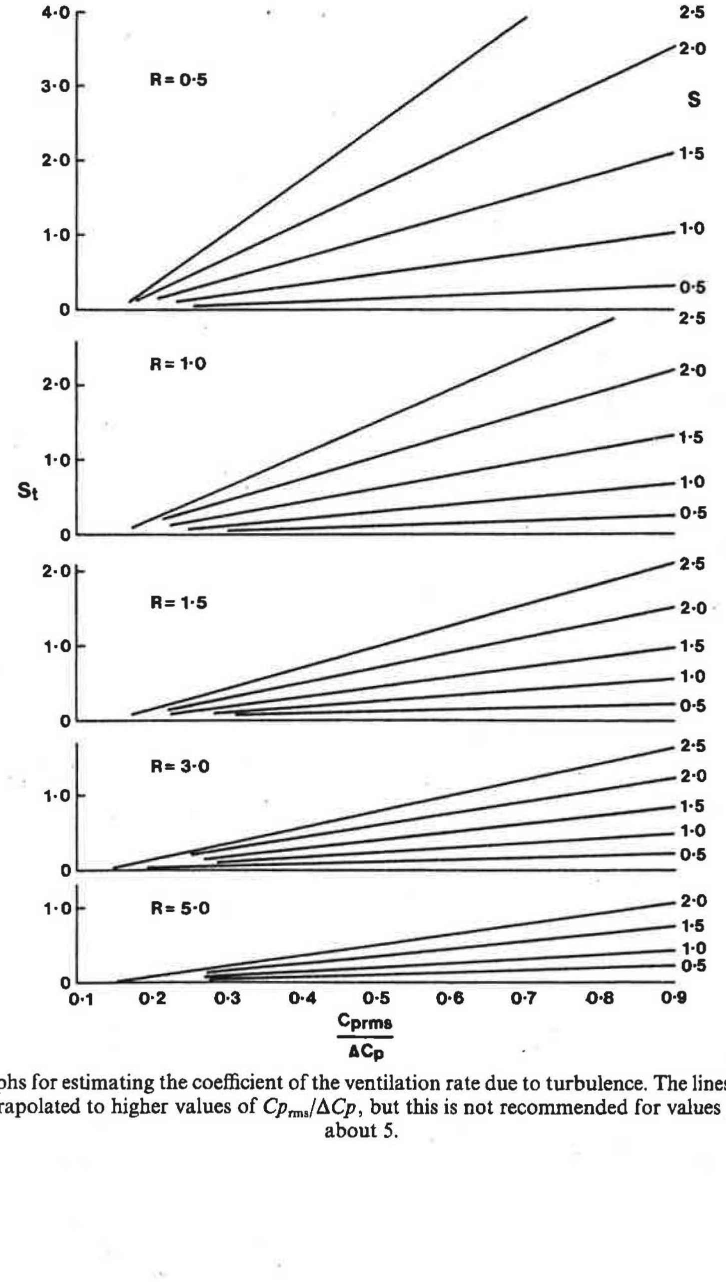

Fig. 15. Graphs for estimating the coefficient of the ventilation rate due to turbulence. The lines of constant S can be extrapolated to higher values of $Cp_{rms}/\Delta Cp$, but this is not recommended for values greater than about 5.

can be used to show the sensitivity of the predictions to different parameters in a general way. They can also be used to predict ventilation rates from a complex model without the need for a computer. Both of these uses have been illustrated in the paper. They have in fact been combined to show how a simple graphical procedure can be derived, which allows ventilation rates to be estimated for virtually all weather conditions, house types and air leakages likely to be encountered in the U.K.

Only five graphs are needed for the simple procedure described. More or less graphs could be used, depending on the level of accuracy required and the purpose for which the method is to be used (the procedure described is intended to illustrate the concept and was not derived for a specific purpose).

Included in the method is a means of estimating the ventilation associated with wind pressure fluctuations. Most methods neglect this entirely, with the implication that houses which are sheltered by other buildings have ventilation rates which are not greatly influenced by wind speed. This could be a misconception, because the reduction in mean wind pressures due to sheltering is not necessarily accompanied by a reduction in the pressure fluctuations.

Some general points about the sensitivity of prediction methods have been illustrated. In particular it has been shown that ceiling leakage can have a very large influence on ventilation rates. This needs to be taken into account when carrying out validations of methods with experimental data. More experimental data is needed on ceiling leakage and on the relative values of ΔCp_r and ΔCp_l to assess their importance.

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APPENDIX I

The flow rate Q_i through opening i on wall j is related to the pressure coefficient of wall j by

$$f\left(\frac{Q_i}{AU_B}\right)=\frac{P_R-P_I}{\rho_0 U_B^2}+\frac{Cp_j}{2A_r^2}-\hat{z}_i, \qquad \text{(A1)}$$

and all the flow rates are related by the continuity equation

$$\sum_n\left(\frac{Q_i}{AU_B}\right)=0. \qquad \text{(A2)}$$

Equations A1 and A2 are equations 5 and 6 in [1], with the function f replacing the quadratic for brevity. If there are n openings in total, there are n flow equations, plus the continuity equation. The $(n+1)$ unknowns are the Q_i and (P_R-P_I).

Using equation A1, one can express (P_R-P_I) in terms of the flow through opening $i=1$ on wall $j=1$, i.e.

$$\frac{P_R-P_I}{\rho_0 U_B^2}=f\left(\frac{Q_1}{AU_B}\right)-\frac{Cp_1}{2A_r^2}+\hat{z}_1. \qquad \text{(A3)}$$

On substitution for (P_R-P_I), the flow equations for the other openings are

$$f\left(\frac{Q_i}{AU_B}\right)=f\left(\frac{Q_1}{AU_B}\right)+\left(\frac{Cp_j-Cp_1}{2A_r^2}\right)+(\hat{z}_1-\hat{z}_i). \qquad \text{(A4)}$$

It can thus be seen that equations A4 and A2 constitute an equation for the flow through opening $i=1$. The pressure coefficient terms which appear in that equation are of the form

$$(Cp_j-Cp_1)/2A_r^2.$$

For a terraced house (no ceiling openings) $j=1$ or 2, so that Q_1 depends on

$$(Cp_2-Cp_1)/2A_r^2.$$

Using the same procedure, it can be shown that Q_2, Q_3, Q_4, etc. depend on the same pressure coefficient parameter. Hence the total flow rate depends on that parameter.

If one now considers an extra wall, i.e. $j=1$, 2 or 3, it will be found that the flow rate through opening 1 depends on

$$(Cp_2-Cp_1)/2A_r^2 \quad \text{and} \quad (Cp_3-Cp_1)/2A_r^2.$$

For openings on wall 2 ($j=2$) the relevant parameters are

$$(Cp_1-Cp_2)/2A_r^2 \quad \text{and} \quad (Cp_3-Cp_2)/2A_r^2$$

and for openings on wall 3, they are

$$(Cp_1-Cp_3)/2A_r^2 \quad \text{and} \quad (Cp_2-Cp_3)/2A_r^2.$$

The above 6 parameters can be reduced to

$$(Cp_2-Cp_1)/2A_r^2 \quad \text{and} \quad (Cp_3-Cp_1)/2A_r^2$$

since the remaining four parameters can be formed from these two.

It can thus be seen that the addition of the extra wall simply introduces an extra parameter

$$(Cp_3-Cp_1)/2A_r^2.$$

The above argument can be extended to any number of walls.

The above result is intuitively obvious, because the flow through the openings depends only on pressure differences. When there are only two pressure coefficients, Cp_1 and Cp_2, the relevant parameter must be

$$(Cp_2-Cp_1).$$

When there are three walls, the relevant parameters are

$$(Cp_2 - Cp_1), \quad (Cp_3 - Cp_1) \quad \text{and} \quad (Cp_3 - Cp_2),$$

but only two of these are independent so they can be replaced by

$$(Cp_2 - Cp_1) \quad \text{and} \quad (Cp_3 - Cp_1).$$

APPENDIX 2

In [1] the term on the right hand side of the first equation in Section 4.1 should be

$$\frac{1}{\sqrt{2}}\sqrt{\frac{\Delta Cp}{A_r^2}+2},$$

and this equation applies to Case 2, not Case 1.

In Fig. 11 the area used for nondimensionalising the mechanical flow rate Q_M is A and not A_T.

APPENDIX 3

The functional relationship for the power law corresponding to equation 4 is

$$\frac{\alpha^{-1/\beta} Q^{1/\beta}}{\rho U_B^2} = f\left(\frac{\Delta Cp}{A_r^2}\right),$$

which has the advantage that the results can be shown by a single curve, although the effects of α and β can not be isolated.

If the leakage of the house at a pressure difference Δp_L is denoted by Q_L, the coefficient α can be expressed as $Q_L/\Delta p_L^\beta$ so that

$$\frac{Q}{Q_L} = \left(\frac{\rho U_B^2}{\Delta p_L}\right)^\beta f^\beta\left(\frac{\Delta Cp}{A_r^2}\right)$$

which is equivalent to the expression F_v for the infiltration rate given in [10]. Note however that it is not necessary to treat A, and wind direction ϕ as separate variables. Their effect is accounted for by the single parameter $\Delta Cp/A_r^2$.