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THE BRITISH GAS MULTI-CELL MODEL FOR CALCULATING VENTILATION

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ABSTRACT

A multi-cell model for predicting ventilating air-flows is described in detail. Comparisons between prediction and measurements indicate that the method is capable of giving relatively high accuracy for a wide range of ventilation conditions. This applies not only to the prediction of whole-house air change rates, but also to the much more difficult problem of room ventilation rates.

The advantages and disadvantages of multi-cell and single-cell methods are discussed. It is argued that the multi-cell approach is potentially more accurate and more useful. Future development of the British Gas model is outlined.

1. INTRODUCTION

The development of the method described here stemmed from a desire for an accurate means of predicting ventilation rates in dwellings. Such a method would prove valuable for investigating the many aspects of ventilation which are of interest to the Gas Industry. These interests cover a wide range of topics such as energy conservation, safety and comfort. They require a method which is capable of predicting individual room flow rates in addition to whole-house flow rates.

For several reasons the methods of prediction available at the time were unsatisfactory and it was decided to develop our own. The initial version of the method has been described in Ref 1 and at the time it was believed to have had several novel features. In particular it was based on the use of dimensionally homogenous crack flow equations. It also accounted for adventitious background openings and indicated that their spatial distribution was important.

Since that time several improvements have been made. The treatment of stack effect has been made more general. Account is taken of ventilation arising from turbulent flow reversals. Details of these modifications are given in the

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description of the method in Section 2. Section 3 discusses the data requirements of the method and the problem of specifying background leakage areas. This problem is also mentioned in Section 4 where the performance of the method is discussed. In Section 5 the advantages and disadvantages of a multi-cell model compared to a single cell approach are set down, and in the final section future developments are considered.

2. DESCRIPTION OF METHOD

2.1 Basis of the method

The basis of the method is a solution of the simultaneous equations describing the flow of air through the network of openings in the dwelling, coupled with the continuity equation. Essentially the mean pressures inside the dwelling are determined. Having calculated these, an approximate allowance for ventilation arising from turbulent pressure fluctuations is made.

Natural ventilation arises from pressures generated across openings by the action of the wind (wind effect) and by the buoyancy of the internal air (stack effect). Both of these effects will generally be present and the method copes with this by superposition of pressures. Essentially, the wind determines the external pressure distribution and the stack effect modifies the internal pressures. Calculations with the early method[1] showed that when treated this way the two effects combined to give a whole-house air change rate which at low speeds depended mainly on temperature difference.

2.2 Flow equations.

Two forms of flow equation are used to describe the flow through the three different types of opening which are considered.

For purpose-provided openings (*e.g.* a simple air vent), a constant discharge coefficient C_Z is assumed, so that the flow equation is simply

$$\overline{Q}_i = C_Z A_i \sqrt{\frac{2\overline{\Delta P}_i}{\rho}}$$

where

$\overline{Q}_i$ = mean volume flow rate, m^3/s

C_Z = discharge coefficient

A_i = physical open area, m^2

ρ = air density, Kg/m^3

$\Delta\overline{P}_i$ = mean pressure across opening, Pa.

Two other types of opening are recognized, *i.e.*, component cracks and background leakage areas. The former are identifiable cracks which occur in doors and windows. Background leakage areas are the openings which remain when the component cracks and purpose-provided openings are sealed. As far as is known, the early version of our method was the first to account specifically for the background areas. For both types of opening the crack flow equations given in Ref 2 are used. These equations are dimensionally homogenous and explicitly recognize that for narrow openings viscosity is important and the discharge coefficient is therefore a function of flow rate. The form of the equation is

$$CA\bar{Q}^2 + \frac{BzL^2}{4\mu}\rho\,\bar{Q} - \frac{2A^3\,\overline{\Delta P}}{\rho} = 0$$

where

C,B = empirical constants given by the crack geometry
z = crack depth, m
L = crack length, m
μ = air viscosity, Ns/m^2.

It is worth noting that A is the physical open area, rather than a hypothetical effective open area, such as can be obtained by assuming a constant value for the discharge coefficient.

The equations have been shown[2] to be capable of describing accurately the steady state flow through component cracks, even when a mixture of cracks is considered, such as is often encountered on doors and windows. It is also considered justifiable to use the equations for background areas, although as demonstrated in Ref 2 they are less accurate. This is presumably due to a greater influence of viscosity for background areas and their greater complexity. It should be possible to derive more accurate empirical equations for these openings but in their absence we make use of the above crack flow equations.

2.3 Wind effects

The pressures generated on the external surfaces of the dwelling are unsteady due to wind turbulence, and this unsteadiness is transmitted to the interior by flow through the openings. Thus the internal pressure $P_I(t)$ is a function of time. The pressure difference $\Delta P_i(t)$ across the ith crack is

$$\Delta P_i(t) = P_{Ei}(t) - P_I(t)$$

where

$P_{Ei}(t)$ = external pressure on crack i, Pa
$P_I(t)$ = internal pressure at crack i, Pa.

It is assumed that the internal and external pressures have mean values which are independant of time, over a sufficiently long period of time T. Thus the mean pressure difference is given by

$$\overline{\Delta P}_i = \overline{P}_{Ei} - \overline{P}_I \qquad (1)$$

where the bar denotes the average over time T. The above assumption is valid for turbulence encountered in wind tunnels, but at full scale the mean values will generally vary slowly with time because of low frequency fluctuations in wind conditions. However it is felt that the assumption is reasonable for times T of order 10 minutes.

Over the same time the net mass flow into the dwelling is assumed to be equal to zero, i.e., it is assumed that the air density inside the dwelling is constant,

$$\sum \rho_i \bar{Q}_i = 0,$$

for the summation over all openings. There will be differences between the internal and external air densities (this gives rise to the stack effect), but for the continuity equation the differences are negligible. Hence the above equation can be simplified to

$$\sum \overline{Q}_i = 0. \qquad (2)$$

Quasi-steady flow is then assumed such that Eq 1 and 2 can be solved using the crack flow equations. Essentially, $\overline{\Delta P}_i$ in Eq 1 can be expressed in terms of $\overline{Q}_i$ and Eq 1 and 2 can be solved to give $\overline{P}_I$.

The assumption of quasi-steady flow is of course an approximation, particularily for higher frequency pressure fluctuations, and also for high flow rates where the relationship between $\overline{Q}$ and $\overline{\Delta P}$ is nonlinear. The errors inherent in this assumption have not been investigated in detail because it is felt that they are less important than the uncertainties relating to background areas and to the more direct effect of turbulence discussed in the following paragraph.

Having calculated $\overline{P}_I$, the value of $\overline{\Delta P}_i$ for each crack is known. Superimposed on this mean value will be a fluctuating component $\overline{\Delta P}'_i$ which is often large enough to cause flow reversal in the crack. This source of ventilation is of course not accounted for by the steady flow equations and no account of it was taken in the early version of our method. However we have carried out tests on simple model windows in a wind tunnel, as reported in Ref 3. The results of this work have been used as a basis for accounting in the method for ventilation due to flow reversal. Earlier work[4,5] with large openings (i.e., openings whose diameter is very much larger than their depth, such as an orifice plate) indicated that this source of ventilation should not be neglected, but apart from the early theoretical studies of van der Held[6] (this important paper seems to have been barely appreciated) there were no known results for cracks. Recently however full-scale results have been published[7,8] and these confirm that account should be taken of flow reversal through small openings. If anything, the model-scale results in Ref 3 give a low indication of the turbulence ventilation, because the wind tunnel used for the tests did not give the best simulation of actual wind turbulence. Nevertheless the relationship obtained between ventilation rate and turbulence intensity can be used for a more general prediction, although more work in this area is of course required.

With the assumption that $\Delta P_i(t)$ has a Gaussian distribution the mean effective ventilation rate due to one of the two windows was given approximately by, for $\overline{\Delta P}_i = 0$,

$$\overline{Q}_{Ti} = 0.5*0.8*\sqrt{\frac{2}{\pi}}\,\Delta P_{iRMS}\frac{8A^3}{BzL^2\mu\rho} \qquad (3)$$

where

ΔP_{iRMS} = the root-mean-square of the fluctuating component of $\Delta P_i(t)$.

In the equation the factor 0.8 is the "efficiency" of the process (see Ref 3). The above equation applies to low flow rates, and under this condition the corresponding equation for the mean flow is

$$\overline{Q}_i = \frac{8A^3}{BzL^2\mu\rho}\overline{\Delta P}_i \qquad (4)$$

4.2 Recent comparisons

Further natural ventilation measurements have been made for the sealed house condition using a recently developed system based on the constant tracer concentration technique. The system has been developed to allow more accurate simultaneous measurements of fresh air entry into each room. A brief description of the system is given in Ref 12.

Nineteen tests have been done with all internal doors open (as with the previous series) and thirty-three with the internal doors closed. These measurements will allow more reliable comparisons to be made for the room flow rates and these are of special interest. The meteorological conditions for these comparisons are : wind speed 0.5 to 5 m/s; wind direction, 150 to 110 degrees, temperature difference, 2 to 17 °C. The results are preliminary; further ventilation measurements for other house conditions are to be made, and no attempt has been made to improve the background distribution determined from the previous comparisons.

Considering the whole-house air change rates first, Fig. 4 shows the comparisons for the same background distribution as for Fig. 2. Even though a great deal of complexity has been added by closing the internal doors, the results produced a mean ratio Rp/Rm of 1.02, and a standard deviation of 0.19. The reduction in the standard deviation by a half is particularily encouraging and would seem to be due to the greater accuracy of the new measurement system. The standard error interval of the mean agreement is now ±0.05.

The comparisons for the individual rooms are very interesting, because the predictions are obviously much more sensitive to the chosen background distribution. In fact the conditions used are particularly severe, because the component cracks are sealed so that background areas are the only source of ventilation. Fig. 5 shows the results for the four bedrooms, which are upstairs. For clarity a distinction has only been made between the open and closed door cases. Bearing in mind the severity of the conditions, the agreement is felt to be extremely encouraging. We are not aware of any other comparisons for individual rooms (i.e. for simultaneous measurements of fresh air entry) against which our comparisons could be judged.

It is hoped that much useful information will come from the comparisons with the new measurements, but since these are in an early stage it is not proposed to comment on Fig. 5 in detail. Only two points will be made. First, the tendency for the upstairs flow rates to be underestimated by the prediction method is accompanied by overestimations for the downstairs rooms. Second, the occurrence of several points for which the method predicts no fresh air entry into rooms in contrast to the measurements, may well be due to the assumption regarding the effect of turbulence on background areas.

5. MULTI-CELL AND SINGLE-CELL MODELS

The British Gas model is a multi-cell type, because there are many aspects of ventilation for which it is desirable to know where and at what rate air enters the house (e.g., the effective removal of water vapor, the sizing of radiators in low energy houses, the efficient operation of mechanical systems). It is however possible to develop single-cell models, whereby the house is treated as a single space and only a rough idea of where the air enters can be obtained. It is worthwhile therefore to consider the advantages and disadvantages of the two approaches.

The main disadvantage of the multi-cell approach is the large amount of data required for a solution. This stems from the fact that the spatial distributions of pressures and openings are required. For the background openings, a direct method for the measurement of the distribution still remains to be developed. The main advantages are (1) it is inherently more accurate for whole-house air change rates, (evidence for this can be seen in the need to specify background distributions) and (2) the individual room flow rates are obtained in detail. As a result a multi-cell model has a potentially much wider range of application. For example, it might conceivably be used as an alternative to experimental techniques for continuous monitoring of ventilation in test houses or to simulate ventilation phenomena, perhaps accounting for user behavior patterns.[13] It can also be used to investigate the effect of detailed changes to the ventilation characteristics of a house.

The main advantage of a single-cell approach is its relative simplicity. For example, it might be based on whole-house leakage characteristics and fairly coarse pressure distributions. In doing this, one sacrifices both accuracy and information about room flow rates. As a result, single-cell methods are likely to be restricted to use in design procedures where rough values are acceptable.

6. FURTHER WORK

Further work on the method is required before it can be put to general use. Included in this of course are the need for more comparisons with measurements in houses, and the need to develop a direct method for determining background distributions. The assumptions relating to the effects of turbulence need to be assessed and perhaps improved. It remains to be seen whether or not more detailed attention should be given to the external pressure distribution, e.g., accounting for correlations between pressures at different points. This would introduce much greater complexity and may not be justifiable in terms of greater accuracy. The underlying assumption of quasi-steady flow through cracks is unlikely to be changed for the same reason.

Work has yet to be done on generalizing and simplifying the data requirements. It might be possible to go a long way in this direction, without significantly affecting the accuracy attained.

More attention needs to be given to the problem of pulsating flows through large areas such as open windows, since these are only treated approximately at present. Finally the seasonal changes which apparently occur in structures may need to be given consideration.

7. CONCLUSIONS

The multi-cell method developed by British Gas has been assessed using measurements in a house for a wide range of ventilation conditions.

Comparisons between predicted and measured whole-house air change rates have shown very encouraging agreement. Probably more important however, are the comparisons which have been made for the room flow rates. Although these are of a preliminary nature, they too are very encouraging. The indications are that the method has considerable potential for investigating ventilation phenomena with more accuracy than has been possible in the past.

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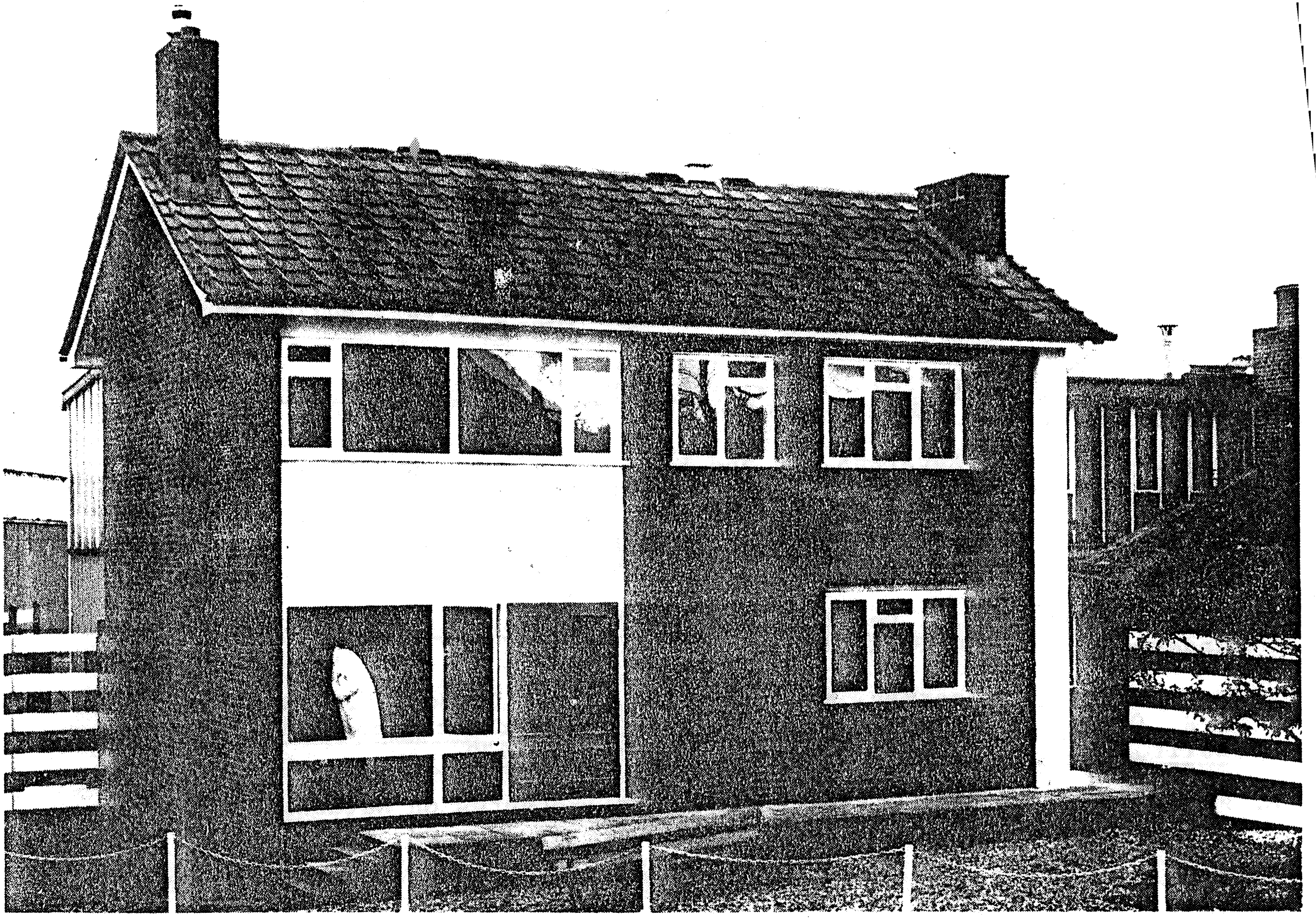

Plate 1 View of test house, showing west face

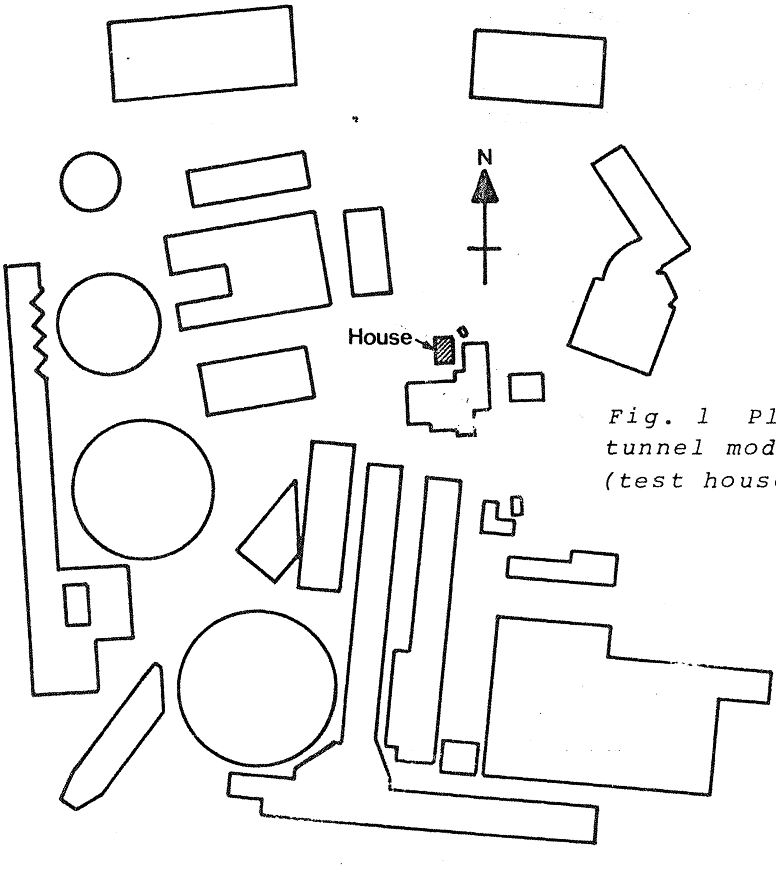

Fig. 1 Plan view - 1/200 scale wind tunnel model of test house site (test house is indicated by shading)

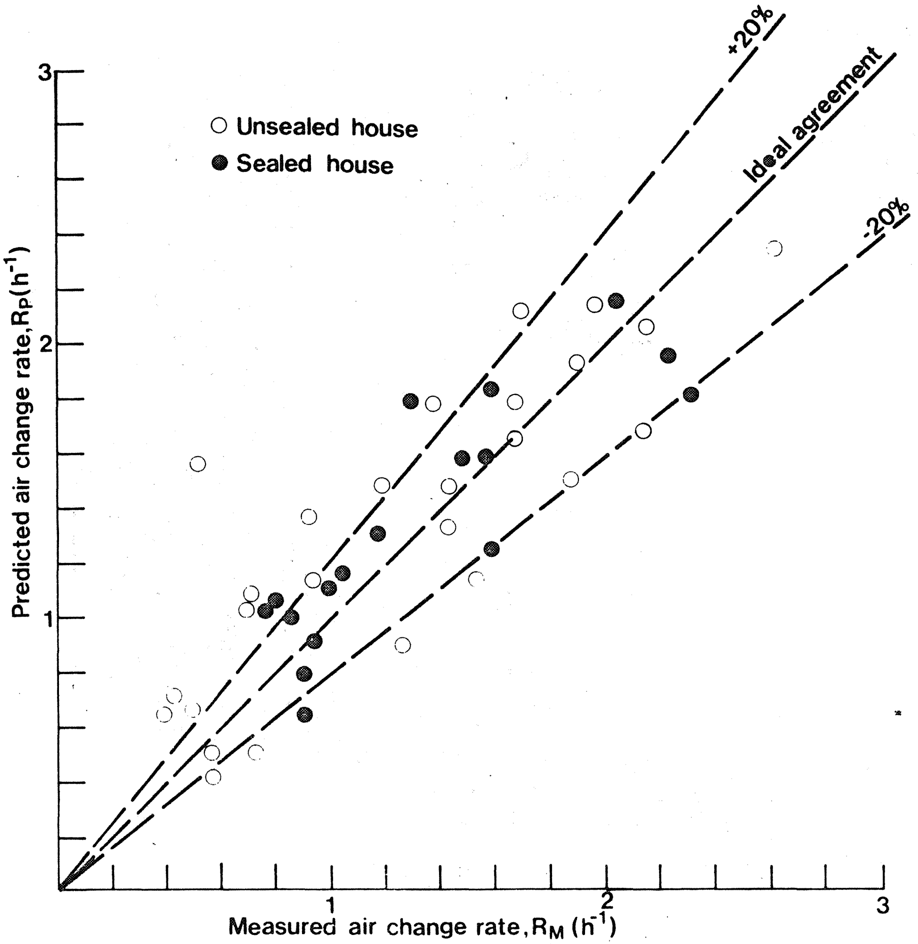

Fig. 2 Comparison of predicted and measured air change rates for natural and mechanical systems, normal and sealed house

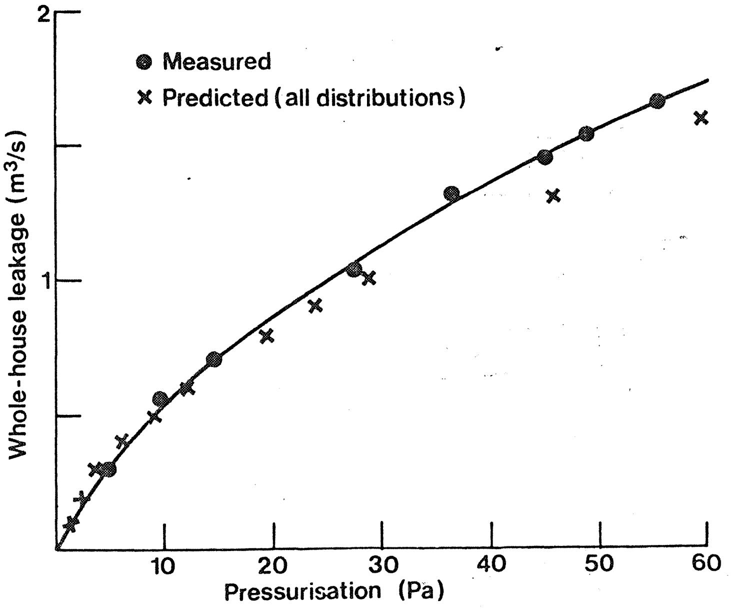

Fig. 3 Pressure-leakage characteristics of sealed test house and of model distributions

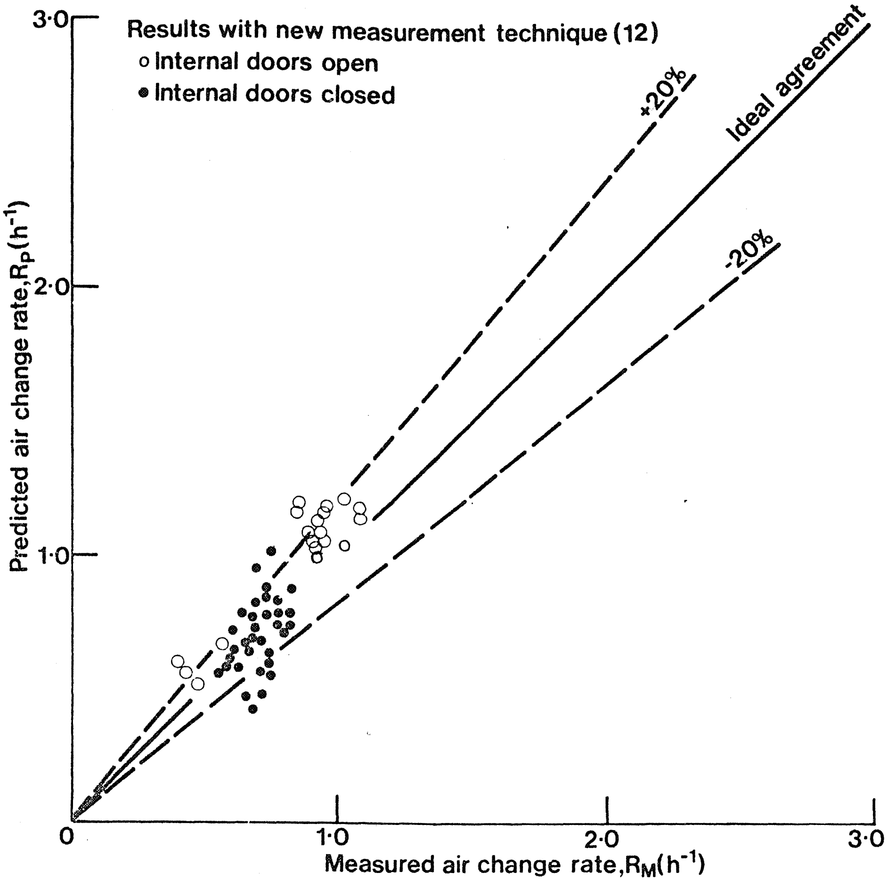

Fig. 4 Comparison of predicted and measured air change rates for sealed house, internal doors open and closed

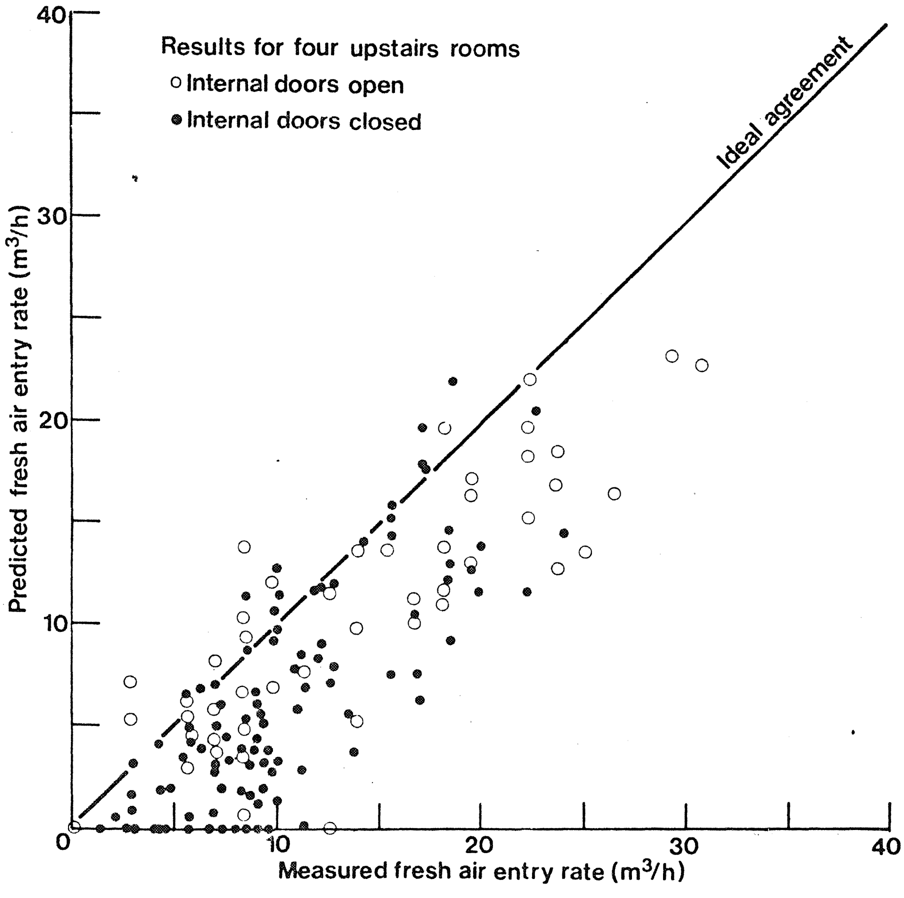

Fig. 5 Comparison of predicted and measured ventilation rates for individual rooms, internal doors open and closed