NATURAL AND MECHANICAL VENTILATION RATES IN A DETACHED HOUSE: PREDICTIONS

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SUMMARY

The results of a prediction method are compared with experimental measurements. It is shown that the method is capable of giving good agreement for a wide range of ventilation conditions. The need is demonstrated for further work in two important areas—the spatial distribution of background areas and the effects of turbulence.

1. INTRODUCTION

The first part of this paper[1] described the measurements of ventilation rates in a detached house and discussed the effects of sealing windows and the operation of mechanical systems. In this, the second part, the corresponding results of a prediction method are presented and compared with the measurements. It will be seen that the method is relatively complex and it is worthwhile noting the basic reasons why such a method is required.

The importance of ventilation can generally be described under the headings of safety, health, comfort and energy conservation. In the past attention has been paid to the safety aspect (e.g. regarding the operation of combustion appliances), but in recent years growing importance has been attached to other areas. A well publicised example of these is the increased relative importance of ventilation heat losses when total heat loss is reduced by improved fabric insulation. Effective solutions to any problems arising will require a thorough knowledge of the mechanisms of ventilation and means for applying this knowledge in practice. Both measurement and prediction have important roles to play in ventilation studies and each has its own particular advantages and disadvantages. The advantages of a prediction method are that it offers (i) the ability to isolate individual parameters, (ii) control

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over the conditions of 'tests', (iii) the ability to investigate hypothetical cases and (iv) quick answers at minimal cost. The main disadvantage is the uncertain accuracy which stems from the inability to model completely all of the factors which influence ventilation. The main objective of the work described here was to assess the performance of the method in this respect.

No attempt has been made to compare the results with other prediction methods, such as those described in references 8 to 10. Such comparisons are outside the scope of this paper, although they should eventually be made.

2. PREDICTION METHOD

The basic method and the data requirements have been described earlier.[2] Since that time, several improvements have been made and so, in the following brief description, particular attention is given to the changes.

2.1. *Basis of the method*

This is an iterative solution of the continuity equation and the equations which describe the flow of air through openings in the dwelling. The crack flow equations have been described elsewhere.[3] They have been shown to be capable of describing accurately the steady flow through cracks in components (such as doors and windows) and of giving an acceptable description of the flow through background leakage areas. The equations are solved under the assumption that they remain valid when the flow is unsteady. This assumption is discussed further in section 2.2.

Natural ventilation arises from the pressures generated across openings by the action of the external wind and by differences between the internal temperature and the external temperature (i.e. the buoyancy or stack effect). Generally speaking, both these effects will be present and the method copes with this in the following way. The wind determines the external pressure distribution and the stack effect is considered to modify the internal pressure distribution. In the original method the stack effect was determined by making a simplifying assumption about the position of the neutral plane and adding the pressures due to buoyancy to those produced by the wind. This has now been improved by allowing a variable neutral plane position which is adjusted until a solution to the airflow network is produced. Thus the pressure difference across a particular opening is determined by the complex interaction of wind and stack pressure and by the opening type, size and position.

As the method is inherently multicell, wind and stack pressures acting in the loft space are accounted for as well.

2.2. *Effects of turbulence*

A turbulent wind means that the pressure distribution on the exterior of the dwelling is unsteady. This unsteadiness is transmitted to the interior by the flow through the openings. Consequently, the internal pressure $p_o(t)$ varies with time. The pressure difference across the ith crack is:

$$\Delta p_i(t) = p_i(t) - p_o(t)$$

where p_i denotes the external pressure. Over a sufficient time, T, the mean values are considered to be independent of time, such that:

$$\overline{\Delta p_i} = \overline{p_i} - \overline{p_o} \tag{1}$$

Time-mean values are denoted by an overbar—for example, the time-mean of p_i is $\overline{p_i}$. Over the same time, the net flow into the dwelling is zero, i.e.:

$$\sum \overline{Q_i} = 0 \tag{2}$$

where $\overline{Q_i}$ is the flow into or out of the ith opening. At full scale, the mean values of Δp_i, etc. will generally vary slowly with time because of very low frequency variations in wind conditions. However, it is felt that the above equations are sufficiently valid for times T of the order of 10 min.

In our method it is assumed that each $\overline{Q_i}$ is determined by the steady flow equation with $\overline{\Delta p_i}$ as the pressure difference. The $\overline{\Delta p_i}$ in eqn. (1) can thus be expressed in terms of the $\overline{Q_i}$ and eqns (1) and (2) can be solved for $\overline{p_o}$. This assumption of quasi-steady flow is an approximation, particularly for the higher frequency pressure fluctuations. Furthermore, the use of the steady flow relationship between $\overline{Q_i}$ and $\overline{\Delta p_i}$ becomes less valid for higher flow rates where the relationship is not linear. It is not known what errors will be introduced into the prediction of $\overline{p_o}$ by these factors as the time dependence of p_i is not known. However, we can expect the latter to lead to an overestimate of the ventilation rate and it is hoped to estimate the magnitude of these errors at a later date.

Another, probably more important, effect of the turbulence is the occurrence of flow reversal through openings. It is known[4,5] that ventilation arises from flows which are purely pulsating, $\overline{\Delta p_i} = 0$. This source of ventilation is not recognised by the steady flow equation which uses the mean pressure difference $\overline{\Delta p_i}$ and no account was taken of this in the early version of our method. However, there is evidence[4,5] that ventilation arising from flow reversal is not negligible and so the method has been modified to take it into account.

This has been done on the basis of the results obtained with a model.[5] Assuming that $\Delta p_i(t)$ has a Gaussian distribution, it was found that the effective ventilation rate due to one (of two) windows was given by:

$$\overline{Q_{T_i}} = 0{\cdot}5 \left[0{\cdot}8 \sqrt{\frac{2}{\pi}} \, (\overline{\Delta p_i'^2})^{0\cdot5} \, \frac{8A^3}{BzL^2\mu} \right] \tag{3}$$

for $\overline{\Delta p_i} = 0$, where $\Delta p_i'$ denotes the fluctuating component of $\Delta p_i(t)$, μ the viscosity and A, B, z and L specify the physical characteristics of the crack. In the equation, the factor 0·8 is the 'efficiency' of the process (see reference 5). The above equation applies to low flow rates and under this condition the corresponding equation for the mean flow is:

$$\overline{Q_i} = \frac{8A^3}{BzL^2\mu}\overline{\Delta p_i} \qquad (4)$$

Equations (3) and (4) can be rearranged to give:

$$\overline{Q_{T_i}} = 0{\cdot}4\sqrt{\frac{2}{\pi}}\frac{(\overline{\Delta p_i'^2})^{0\cdot 5}}{\overline{\Delta p_i}}\overline{Q_i}F$$

and it is this equation which is used to estimate $\overline{Q_{T_i}}$. F is a factor which accounts for the occurrence of large mean pressures, with which the pressure fluctuations will not be large enough to cause flow reversal and $\overline{Q_{T_i}} = 0$. This will roughly be the case when $\overline{\Delta p_i} > 3(\overline{\Delta p_i'^2})^{0\cdot 5}$ and linear interpolation is used between this case and the case when $\overline{\Delta p_i} = 0$. The $\overline{\Delta p_i}$ for each opening is obtained from the prediction in the normal way and if the root-mean-square (rms) value of the pressure fluctuations $(\overline{\Delta p_i'^2})^{0\cdot 5}$ is known, an estimate of each $\overline{Q_{T_i}}$ can be obtained. This rms value is, however, not known, because from wind tunnel tests we obtain only the rms value of the external pressure fluctuations $(\overline{p_i'^2})^{0\cdot 5}$. One can expect a positive correlation between the external pressures, because of the large turbulence length scales in relation to the size of the house, and for this reason it seems probable that $\overline{p_i'^2}$ will generally be greater than $\overline{\Delta p_i'^2}$. The situation is complicated by the fact that external pressure fluctuations acting on large openings are likely to be followed more closely by the internal pressure than pressures acting on small openings. Consequently, for large openings $\overline{\Delta p_i'^2}$ is likely to be much less than $\overline{p_i'^2}$ whereas, for small openings, $\overline{\Delta p_i'^2}$ could conceivably be greater than $\overline{p_i'^2}$.

Further work needs to be done to obtain an idea of the differences between these pressures. For the present calculations we have therefore made some simplifications. The rms level of the external pressure fluctuations has been assumed to be uniform over the surface of the house, with a coefficient of 0·3. This has been done on the basis of the wind tunnel measurements (see section 2.3.1 below). It has also been assumed that:

$$(\overline{\Delta p_i'^2})^{0\cdot 5} = 0{\cdot}5(\overline{p_i'^2})^{0\cdot 5}$$

This factor of one half between the rms levels of the two pressures has been arbitrarily chosen to reflect the effect of a positive correlation between external pressures. Some preliminary tests which have recently been carried out on the house indicate that it is not unreasonable.

Finally, it has been assumed that ventilation by flow reversal is only significant for component cracks. For background openings it has been neglected. The argument for this is that the flow paths through these openings are likely to be longer and more restrictive than for component cracks. It follows that the pressure fluctuations which cause ventilation will be restricted to lower frequencies and the contribution to ventilation will be smaller.

To summarise the above, it is assumed that the ventilation rate of the house can be considered as the sum of two components, i.e. that due to mean pressures and that due to pressure fluctuations. It is also assumed that the presence of the fluctuations does not introduce large errors into the use of the steady flow equation. These assumptions are inherent in any prediction method which uses mean values of the external and internal pressure distributions and the steady flow equations to calculate ventilation rates. A rigorous treatment of the problem would require knowledge of the correlations between the external pressures at the openings, because the instantaneous pressure difference across any one opening will be influenced by the flows through the other openings.

2.3. *Data required*

The data required for ventilation predictions consist of external pressures and details of the openings. The former are obtained from a wind tunnel model and the latter from an actual test house.

2.3.1. External pressures: The external pressures have been obtained from wind tunnel tests on a 1/200 scale model of the house and its surroundings up to a radial distance of 200 m. In the early report on the method,[2] a 1/50 scale model with only the adjacent buildings was used. This may be fairly satisfactory for mean pressures, but a much smaller scale is required for measuring fluctuating pressures because of the need to match the dwelling size and the length scales of the wind turbulence. These scales are generated in the wind tunnel by a coarse turbulence grid and an array of toy bricks (Lego) in a similar manner to that described in reference 6. The mean velocity profile was set to simulate an urban environment.

The measurements were made with a differential pressure transducer (Furness), with one side connected to the static line of a pitot-static tube mounted in the freestream.

A smaller pitot-static tube was mounted at the same point as the anemometer at full scale and this was used to obtain the relationship between pressures measured at this reference point and the freestream reference point. In this way, the surface pressures could be expressed in terms of a reference speed U_{ref} at the same point which was used at full scale. There are, of course, inaccuracies in this procedure. The small pitot tube is in a highly turbulent flow and will tend to overestimate the local velocity. This is perhaps fortuitous because the anemometer at full scale records a speed rather than a velocity. It was also necessary to align the small pitot tube with the freestream direction and, for the comparison between the predictions and the measurements, given below, it has been necessary to assume that the reference wind direction is the same as the freestream direction. (To remove uncertainty about the local wind velocity it is intended to investigate this further, in the wind tunnel, with a pulsed wire anemometer.) For most cases this is probably a reasonable assumption, but there are some doubts about westerly winds for which the test site lies downstream of large gasholders (see Fig. 1). Incidentally, the gasholders introduce a rather unique variable into the comparisons, by virtue of the fact that their height varies. This variation was not monitored during the full-scale tests. Most of the

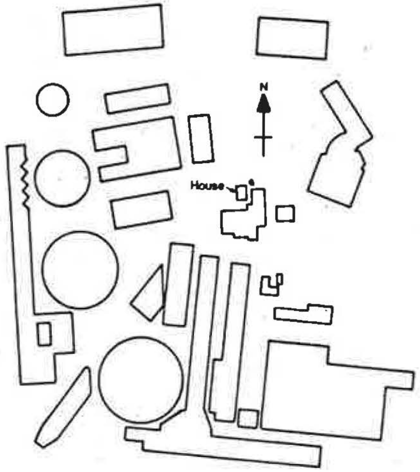

Fig. 1. Plan of 1/200th wind tunnel model.

pressure measurements on the model were made with the gasholders at 75 % of their maximum height. Tests were, however, carried out on the effects of height variation and the changes in surface pressures on the house were generally small, although on the west face changes of about 25 % were observed. No transition strips were used on the gasholders, despite their circular shape.

Figure 2 is an example of the variation of a surface pressure coefficient, Cp_i, with wind direction, for two windows, where:

$$Cp_i \equiv (\overline{p_i} - p_{\text{ref}})/\tfrac{1}{2}\rho U_{\text{ref}}^2$$

The values of Cp_i for the west face window which are greater than unity might be due to inaccuracies in the referencing procedure.

For measuring $\overline{p_i'^2}$, the reference static pressure was heavily damped by using a very long connection in the manometer. Measurements made at one wind direction (0°) indicated that it was reasonable to assume a uniform distribution of $\overline{p_i'^2}$, with a coefficient Cp_i' of 0·3:

$$Cp_i' \equiv \frac{(\overline{p_i'^2})^{0\cdot 5}}{\tfrac{1}{2}\rho U_{\text{ref}}^2} = 0\cdot 3$$

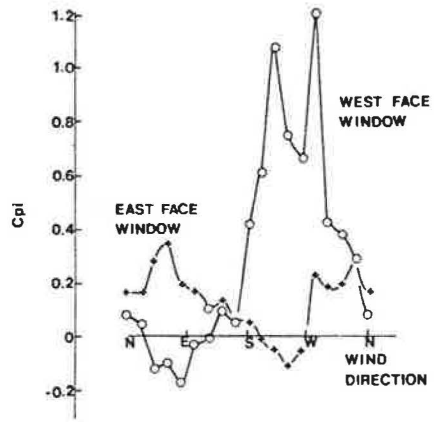

Fig. 2. Variation of pressure coefficient with wind direction for two windows.

2.3.2. Specification of openings in the test house: All of the purpose-provided openings were permanently sealed for the ventilation measurements in the test house and so the only openings which need to be specified are component cracks and background leakage areas.

The manner in which the component cracks are specified has been described in reference 2. The crack flow equation for each crack has been found by a pressurisation test. This was done for greater accuracy, but in principle the equations can be determined from the crack geometry and physical measurement.

Pressurisation tests have been carried out to specify the background leakage area of each room and the whole-house pressure/flow characteristic has also been obtained (see Fig. 3). For an early report[2] only one point on this characteristic was measured and it was thought desirable to improve on this by measuring several points. The latest characteristic has also been measured with the house in its sealed

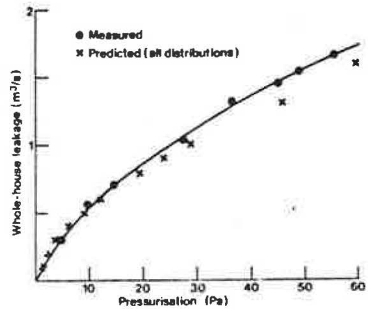

Fig. 3. Predicted and measured leakage characteristics of sealed house.

state which is more relevant, because it is used to assess the background areas. Comparison with the early single measurement shows that it is not compatible with Fig. 3. This is considered to be due to the fact that, in the intervening period, the method of sealing the ground floor was changed, as described in reference 1.

As pointed out in reference 2, it is necessary to specify the distribution of the background areas which communicate with the outside. This spatial distribution is as important to accurate prediction as the distribution of external pressures. At present the background distribution is chosen by a semi-empirical procedure. The first step is to ensure that the distribution satisfies the whole-house leakage characteristic. Since there are many distributions which will do this, it is then necessary to select a distribution which produces predictions in good agreement with ventilation rates measured under a certain condition. For the present work, the natural ventilation rates in the unsealed house have been used for this purpose. Having determined the distribution the method can then be used to see how well it predicts ventilation under other conditions. These conditions are the sealed house with natural ventilation and the mechanically ventilated house, sealed and unsealed. Thus, although the background distribution is partly chosen to fit some of the measured ventilation rates, the other ventilation measurements provide a means for assessing the performance of the method. This is an acceptable procedure for the development of the method but for general use, of course, the background distribution will have to be specified as part of the data input. Future tests on the leakage characteristics of dwellings should therefore include an investigation of this distribution. One possible method involves the measurement of the leakage characteristics of a room or cell with the pressurisation of adjacent cells. When the pressure in two cells is made equal no flow will occur across the communicating areas. Thus, by elimination, the background areas of each face could be determined. At the time of writing this technique was being investigated, but recently some results have been obtained.[11]

Calculations have been carried out with about twenty different distributions but, for simplicity, only three of these will be considered in this paper. The first, DA, is an extreme case and has the total background area (which communicates to the outside) distributed over the walls of the dwelling. The second and third, DB and DC, are more reasonable as some of the background area is applied to the floor and ceiling. These two distributions gave the best agreement of all the distributions examined and have therefore been selected for presentation. Table 1 shows the distributions in terms of the percentage of the total open area, A_T. It should be noted that A_T is the sum of the 'physical' open areas which are the areas used in the crack flow equations. They can be considered as effective crack areas.

All three distributions give a reasonable prediction of the leakage characteristic of the house (see Fig. 3) at low pressures. It was, however, not found possible to obtain good agreement over the complete pressure range of the measurements. It was

TABLE 1
DISTRIBUTION OF BACKGROUND LEAKAGE AREAS

Distribution	*Percentage of A_T*			
	As component cracks	*As background through:*		
		External walls	*Ceiling to loft*	*Floor to basement*
DA	34	66	0	0
DB	34	34	20	12
DC	34	10	28	28

All figures are percentages.

therefore decided to concentrate on pressures below 10 Pa, because pressures greater than this will only be rarely encountered at full scale. The reason for the inability to obtain a good fit to the measured characteristic is almost certainly connected with the approximate nature of the crack flow equations for describing flows through background areas.[3]

The predictions with DA and DB which are shown first do not include an allowance for turbulence. It will be seen, however, that DB gives good agreement, thus illustrating the need to describe the spatial distribution of backgrounds.

For distribution DC the ventilation produced by turbulence was taken into account. Using an allowance for turbulence with DB, too large flows were predicted, the increase in total ventilation being 10–20% for the unsealed case. DC has the same total area as DB but most of the background areas are assigned to the ceiling or floor.

3. DISCUSSION OF RESULTS

The predictions for natural ventilation of the house (unsealed and sealed) are given in Figs 4, 5 and 6 for the distributions DA, DB and DC, respectively. The predictions of DB with turbulence are shown in Fig. 7.

Figures 8 and 9 compare prediction and measurement for the three mechanical systems (sealed and unsealed) for distributions DB (no turbulence correction) and DC.

Figures 10 and 11 show the comparisons for all ventilation conditions for DB and DC.

Finally, comparisons of the ventilation rates for individual rooms (kitchen, lounge, bedroom 4) are given in Figs 12 and 13 for distribution DC.

3.1. Whole-house air change rates

In each of Figs 4, 5 and 6 showing the natural ventilation results, values of E and σ are quoted. E is the average of the differences between all predicted and measured points and σ is the standard deviation of this difference.

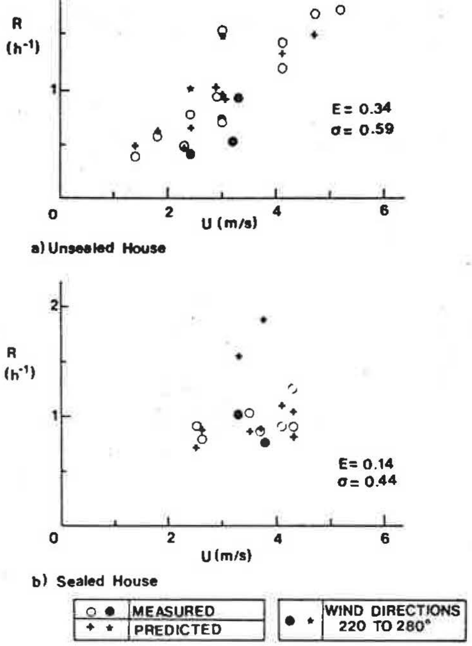

Fig. 4. Comparison of measured and predicted natural ventilation rates. Distribution DA.

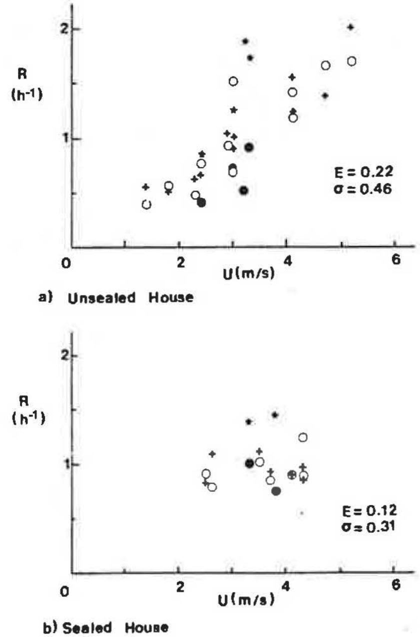

Fig. 5. Comparison of measured and predicted natural ventilation rates. Distribution DB. For key see Fig. 4.

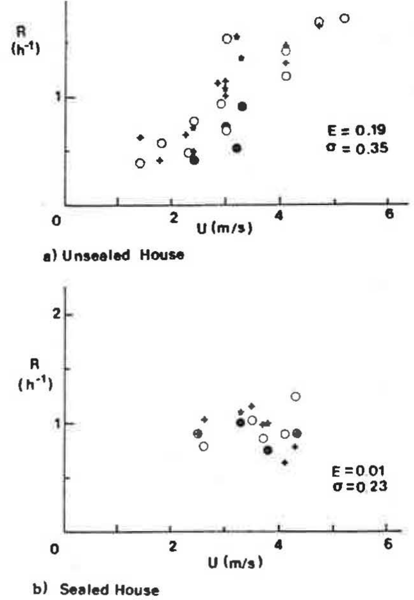

Fig. 6. Comparison of measured and predicted natural ventilation rates. Distribution DC with turbulence included. For key see Fig. 4.

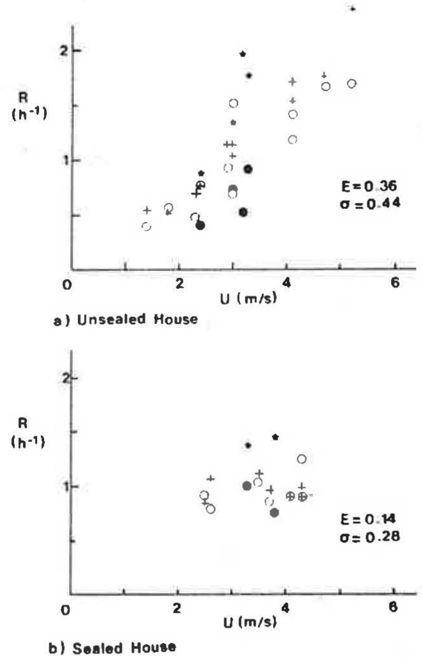

Fig. 7. Comparison of measured and predicted natural ventilation rates. Distribution DB with turbulence. For key see Fig. 4.

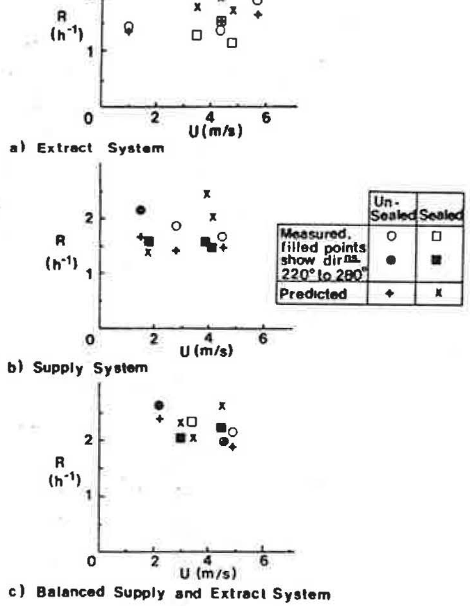

Fig. 8. Comparison of measured and predicted mechanical ventilation rates. Distribution DB.

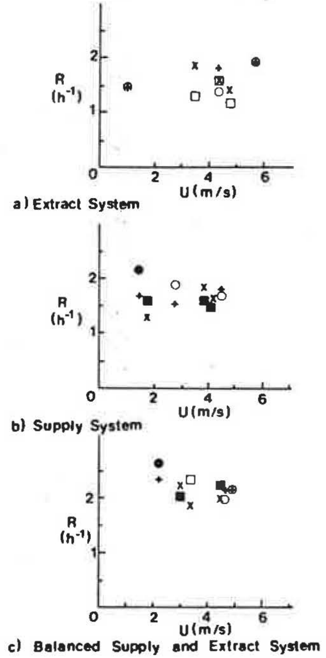

Fig. 9. Comparison of measured and predicted mechanical ventilation rates, turbulence included. Distribution DC. For key see Fig. 8.

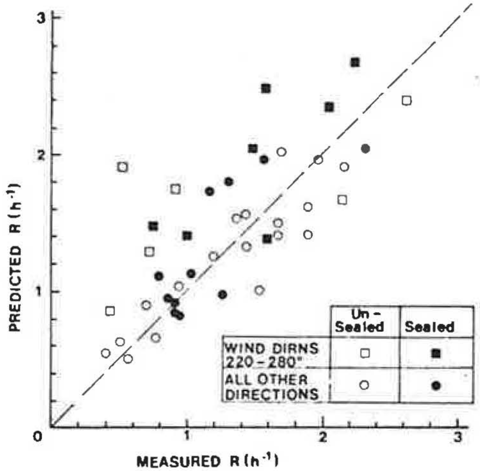

Fig. 10. Direct comparison of predicted and measured ventilation rates for all conditions. Distribution DB.

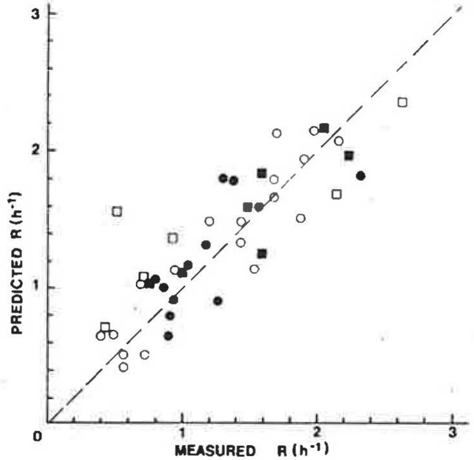

Fig. 11. Direct comparison of predicted and measured ventilation rates for all conditions. Distribution DC. For key see Fig. 10.

Considering first those predictions without a correction for turbulence, it seems clear from the values of E and σ that distribution DB is superior to the more simple case of DA.

The agreement for DB is considerably improved if the results for the wind directions lying within the range 220° to 280° are omitted from the comparison. These points are identified in Fig. 5 and the predictions considerably exceed the measurements. This is felt to be connected with the fact that for westerly winds the

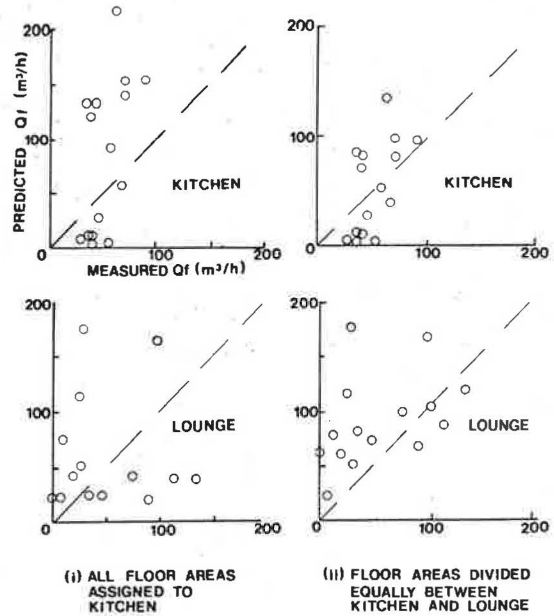

Fig. 12. Direct comparisons of predicted and measured fresh air flow rates for lounge and kitchen with two different arrangements of floor background areas. Distribution DC. Natural ventilation, unsealed house.

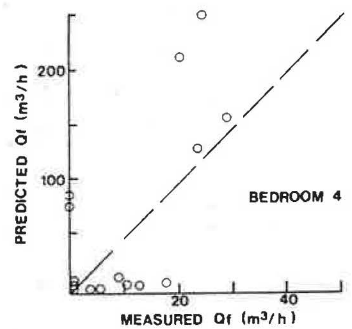

Fig. 13. Direct comparison of predicted and measured fresh air flow rates for bedroom 4. Distribution DC. Natural ventilation, unsealed house.

house lies downstream of large gasholders (see Fig. 1). Very sharp peaks occur in the wind tunnel pressure coefficients and these are unlikely to be experienced at full scale over the complete time period of the ventilation measurement. Consequently, some overestimation by the prediction method is to be expected. However, even when calculations were made with a smoothed peak, the overestimations were still apparent so this is probably not the complete explanation.

When a correction for turbulence is made to the predictions with DB (Fig. 7) the agreement becomes relatively poor. Much better agreement is obtained with distribution DC (Fig. 6) and it is worth noting that the westerly wind results are considerably improved. This indicates that distribution DC is closer to reality than DB. To a certain extent this seems reasonable, because a visual inspection of the house indicates that its floor and ceiling are more leaky than the walls, despite the extensive sealing measures on the floor. On average there is little to choose between DB and DC. For individual points there are, however, large differences between the predictions.

Turning to the predictions for the mechanical systems (Figs 8 and 9), it can be seen that the agreement with the measurements is quite good for both DB (no turbulence correction) and DC. On average the best agreement is found for the calculations with DC. It is particularly good for the extract system, for both unsealed and sealed cases.

The overall performance of the method with the two distributions can be judged from the plots of predicted against measured values of R given in Figs 10 and 11. For the DB calculations, the standard deviation of the ratio (predicted to measured) is 0·50. For the DC calculations, it is 0·39. Bearing in mind the wide range of ventilation conditions and magnitudes ($0{\cdot}5 < R < 2{\cdot}5$) included in the comparisons, both these results are considered very encouraging.

3.2. Room ventilation rates

The ventilation rate of a room is defined as the flow rate of fresh (i.e. outside) air entering the room, Q_{F_i}. As noted in reference 1, the measurement technique adopted for the full-scale tests allowed values of Q_{F_i} to be obtained, but these are likely to be subject to larger errors than the values of R. This is reflected in the comparisons between the predicted and measured values of Q_{F_i}, which exhibit much less agreement than the comparisons for R.

The predictions with distribution DC for three rooms (kitchen, lounge and bedroom 4) are compared with the measurements for natural ventilation (unsealed) in Figs 12 and 13. Points which lie on either of the axes correspond to the case where no fresh air is entering the room. For these points there is not only a difference in the magnitudes of the predicted and measured flow rates, but also in their directions.

The predicted Q_{F_i} will be highly dependent on the exact placement of the background areas. There is, for instance, uncertainty in the locations of the areas in the flooring. Figure 12 shows the comparisons of two arbitrary, although reasonable, choices: (i) all background areas located in the kitchen and (ii) background areas divided equally between the kitchen and the lounge–dining room. The latter is seen to produce better agreement.

Overall the prediction of the room air flow rates is not as good as could be hoped. Nevertheless, in view of the possibly large errors in the measurement, even this agreement is encouraging. It is worth noting that the agreement improves when comparisons are made with the total flow to each floor, and improves again when the whole house air flow is considered. This, again, indicates the importance of the location of the background areas.

4. FURTHER COMPARISONS WITH RECENT MEASUREMENTS

More accurate measurements have recently been made in the test house using the new measurement technique described in reference 7. This is a constant concentration technique and gives room fresh air entry rates explicitly.

The comparisons which have been made for these tests are very encouraging. For the whole house air change rates there is improved agreement, although it must be noted that the range encountered is less (see reference 12). For the room rates the agreement is very much improved, as can be seen by comparing Fig. 14 with Figs 12

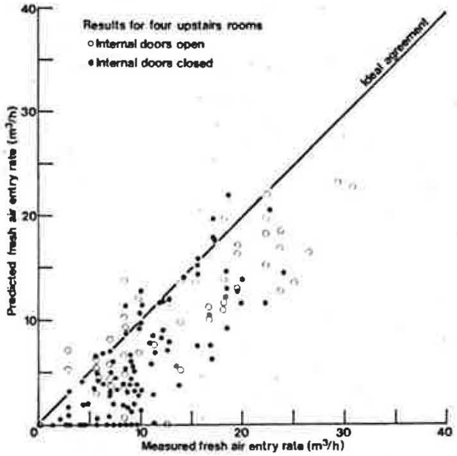

Fig. 14. Comparisons between predicted and measured room fresh air entry rates using data obtained with the new measurement technique. Distribution DC.

and 13. Figure 14 shows some of the recent comparisons which have been made for four upstair rooms. It seems clear that much of the scatter in Figs 12 and 13 is due to errors in the measurements, rather than to limitations of the prediction method.

5. CONCLUSIONS

There are four main conclusions to be drawn from the present comparisons.

First, the method is apparently capable of giving good agreement with measurements for a very wide range of ventilation conditions. These cover cases where stack effect, wind effect and/or mechanical systems are operating, and cases where component cracks are either sealed or unsealed. Although it must be remembered that the accuracy of the measurements is not high, the agreement which has been obtained is very encouraging.

Secondly, good agreement has been obtained by selecting distributions for the background leakage areas from many possible distributions. To make proper use of the prediction method, a means of measuring the background distribution must be found so that it can form a true part of the data input. The calculations which have been carried out indicate that it is important for accurate predictions that account be taken of this spatial distribution, even if a distinction is only made between floors, walls and ceilings. For houses with low background leakage good agreement should be easier to obtain. Thirdly, the agreement for the individual rooms is not as good, but is still encouraging. The background area distribution is more important and needs to be known for each room.

Fourthly, similar agreement has been found with and without accounting approximately for turbulence. This has, however, only been achieved with different background area distributions. The predicted effect of turbulence is often large and background distributions which gave good agreement when turbulence was neglected must presumably be considered fortuitous. This is another good reason for investigating background distributions. Further work must be done to determine more about the effects of turbulence on ventilation. Several assumptions have been made in accounting for turbulence in the prediction method. Although certain approximations will always have to be made (at least in our method where quasi-steady flow is a basic assumption) there is definitely scope for improvement.

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