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THE PREDICTION OF VENTILATION RATES IN HOUSES
AND THE IMPLICATIONS FOR ENERGY CONSERVATION

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THE PREDICTION OF VENTILATION RATES IN HOUSES AND THE IMPLICATIONS FOR ENERGY CONSERVATION

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SUMMARY

The paper describes a ventilation prediction method which is under development and which is considered to have the potential to be an advance over currently available methods. The importance of an accurate knowledge of wind-generated pressure distributions and of background leakage areas is demonstrated quantitatively. Preliminary comparisons between field measurements and predictions are presented and show encouraging agreement. The implications of the work for energy conservation are discussed.

THE PREDICTION OF VENTILATION RATES IN HOUSES AND THE IMPLICATIONS FOR ENERGY CONSERVATION

1. INTRODUCTION

Ventilation heat losses are an important factor in the energy balance of houses, particularly low-energy houses, and it is desirable to be able to predict ventilation rates accurately. Other reasons stem from the important role that ventilation plays in determining the indoor environment.

The objective of the work described was to develop an accurate and reliable prediction method which could be used for carrying out generalised investigations of ventilation with a reasonable degree of confidence. The available prediction methods[1,2] were not considered to be sufficiently accurate because of three major shortcomings. Firstly they did not describe the flow through cracks in a physically acceptable manner. Secondly they made use of generalised values of external pressure distributions taken from guidebooks; such distributions generally apply to buildings in isolation and make no allowance for the geometry of the site in question. Thirdly, they did not account for background leakage areas. These are basically the residual open areas through which ventilation occurs when all cracks around doors and windows have been sealed (and purpose-provided openings have been closed). Work done by Building Research Establishment[3] and by British Gas Corporation at Watson House (see below) have shown that it is essential to account for the background leakage areas.

The manner in which the above shortcomings have been resolved in the present method is briefly described in Section 2. Section 3 describes preliminary field measurements which have been carried out to test the method and the comparisons between prediction and measurement are given in Section 4. In Section 5 the further development of the method is described. It must be stressed that the method is in its infancy and further work is required before it could be considered for use as other than a research tool. In particular it will be seen that detailed information is needed as basic data for the predictions. Whether or not the method could be used as a design aid depends on whether or not this data can be sufficiently generalised.

Although the main aim of this paper is to describe the prediction method, some aspects of the work have implications for energy conservation and these are briefly discussed in Section 6.

2. DEVELOPMENT OF PREDICTION METHOD

2.1. Basic Method

The basis of the method is a solution of the simultaneous equations describing the flow of air through cracks in the dwelling, coupled with the continuity equation. By supplying data about the geometry of the cracks and data from which the pressures acting on the cracks can be determined, the equations can be solved by an iterative procedure. In view of the large number of flow equations corresponding to the large number of cracks, the solution has to be carried out by a digital computer.

The crack flow equations used are those described by Etheridge[4]. For simplicity the doors and windows are not divided into their component cracks, but each door and window is treated as a single crack, which it is often permissible to do[4]. Similarly each background leakage area is represented by a single type of crack (see section 2.2.3. below).

Natural ventilation arises from the pressures generated across open areas by the action of the external wind (wind effect) and by differences between the internal temperature of the dwelling and ambient (stack effect). It will be seen below that it is necessary to include stack effect in the prediction method. This is achieved in the present method by adding the pressure difference across a given crack due to stack effect, Δps, to that due to wind effect, Δpw. If the height between the centres of the two windows is h, say, then the neutral axis is assumed to be midway between the centres, so that Δps is given by:-

$$\Delta ps = \pm 1731 \times h \left[\frac{1}{T_o} - \frac{1}{T_i} \right] \quad N/m^2$$

where To and Ti are the absolute external and internal temperatures respectively.

To be able to solve the above equations, a considerable amount of data about the building under investigation and about the meteorological conditions has to be supplied. In the following, the nature of this data and the way it has been obtained for one particular dwelling are described.

2.2. Data required

All of the following information relates to a ten-roomed detached house situated in a built-up area. This house has been available for experimental purposes and is unoccupied. Figure 1 shows the layout of the two floors.

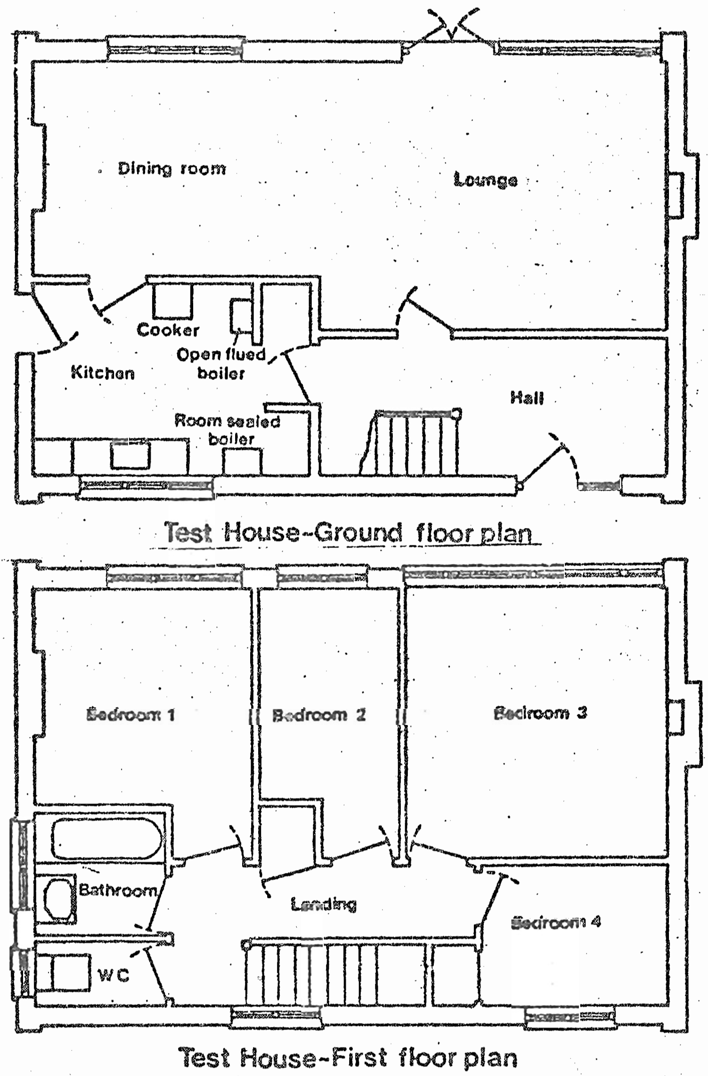


FIGURE 1. Floor plans of test house

2.2.1. External Pressure Distributions

The pressure distributions generated by the wind on the external surfaces of the house are often a major factor in determining the pressure difference across each crack. It is impractical to measure these distributions on the actual house, and so it was decided to obtain them from wind tunnel tests. Accordingly a 1/50th scale model of the house complete with the immediately adjacent buildings was built and was mounted on a turntable in a 2m x 1m wind tunnel. It is essential for such tests to simulate the atmospheric boundary layer [5] and this was achieved in this instance by a combination of a large-scale turbulence grid and roughness elements. Plate 1 shows the model installed in the tunnel.

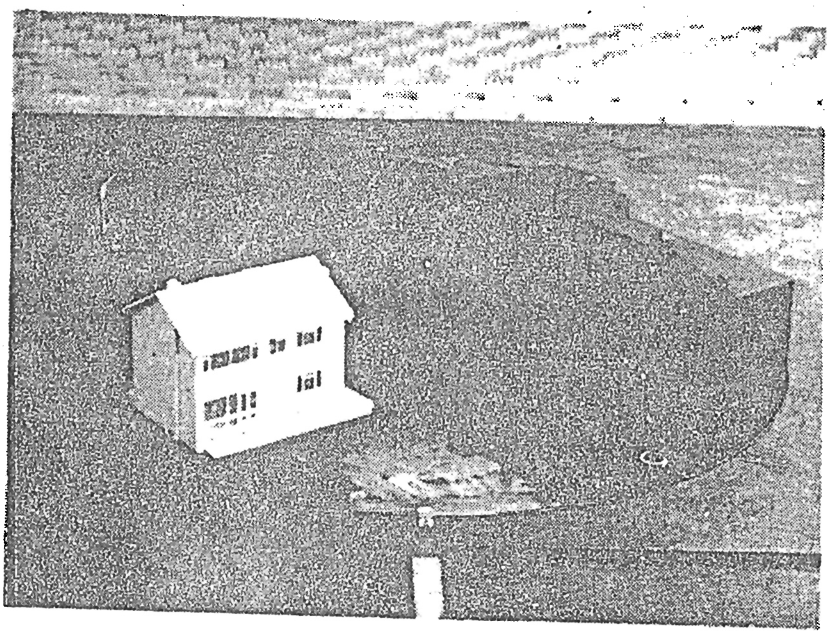
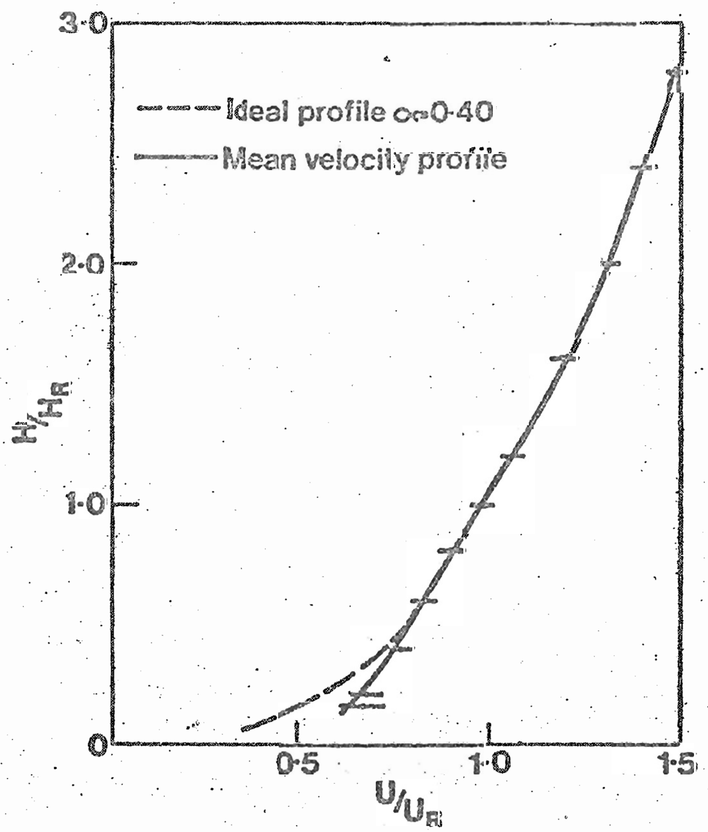
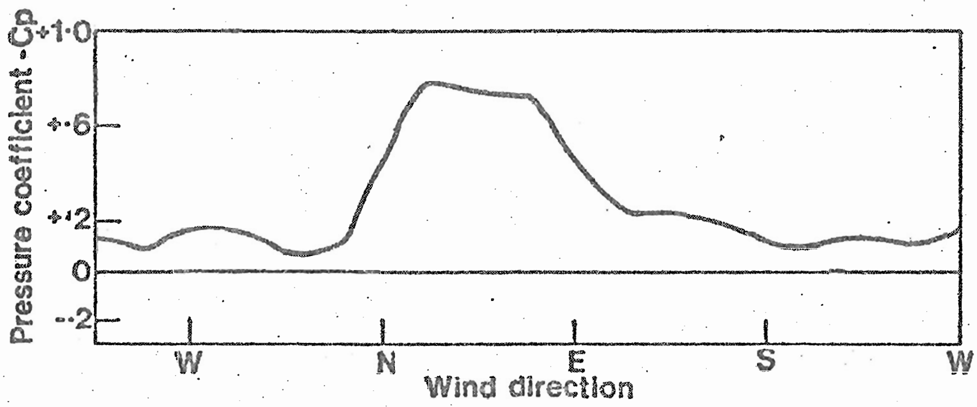


PLATE 1. Test house model and outbuildings



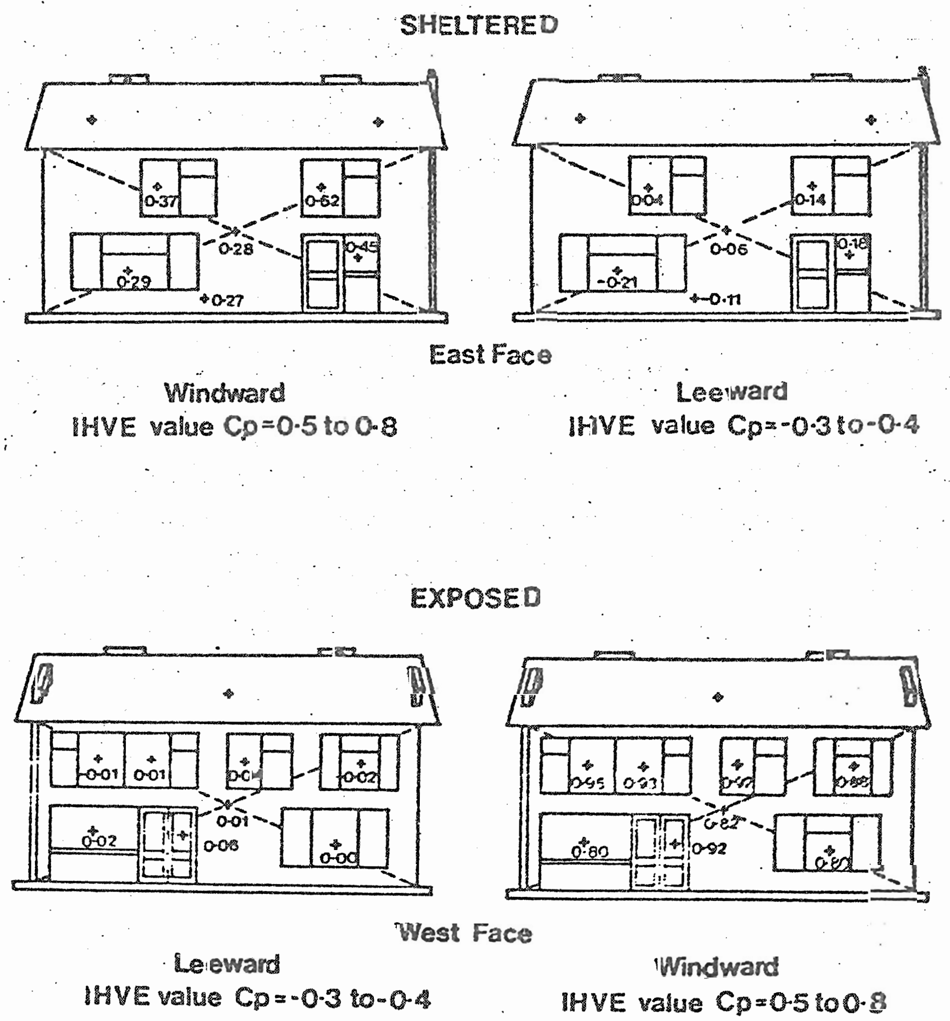
<u>FIGURE 2.</u> Mean velocity profile in working section

Fig. 2 shows the mean velocity profile obtained in the working section. The model was equipped with static pressure tappings at the centres of all the doors and windows and at other points on the external surfaces. Fig. 3 shows some typical results in the form of the variation of the pressure coefficient, Cp, with wind direction of a door on the east face. The pressure coefficient is defined in terms of the static and dynamic pressures recorded by a pitot-static tube mounted on one of the outbuildings. This reference position corresponds to the position at which wind speed and direction are recorded at the actual test site.



<u>FIGURE 3.</u> Pressure variation for door on East face

The importance of using pressure distributions which are peculiar to the particular site rather than distributions presently given in guidebooks is demonstrated in Fig. 4. Values taken from a guidebook (6) are compared with wind tunnel values and large differences are apparent.



<u>FIGURE 4.</u> Comparison between measured Cp values and IHVE values for a sheltered East face and an exposed West face.

2.2.2. Open Areas

The open areas, A, of all of the doors and windows of the test house have been measured by the pressure/extract method and by making use of the crack flow equations [4]. Briefly, the technique is to measure the flow rates through the component for a range of known pressure differences applied across the component. For each applied pressure difference a value for the open area can be calculated using the crack flow equations, once the crack type and certain of its dimensions have been specified. Fig. 5 shows typical results obtained for a landing window and it can be seen that the estimated open areas do not vary greatly with flow rate. This shows that the crack flow equation describes the flow characteristics of this particular components. Similar results were obtained for all the other components.

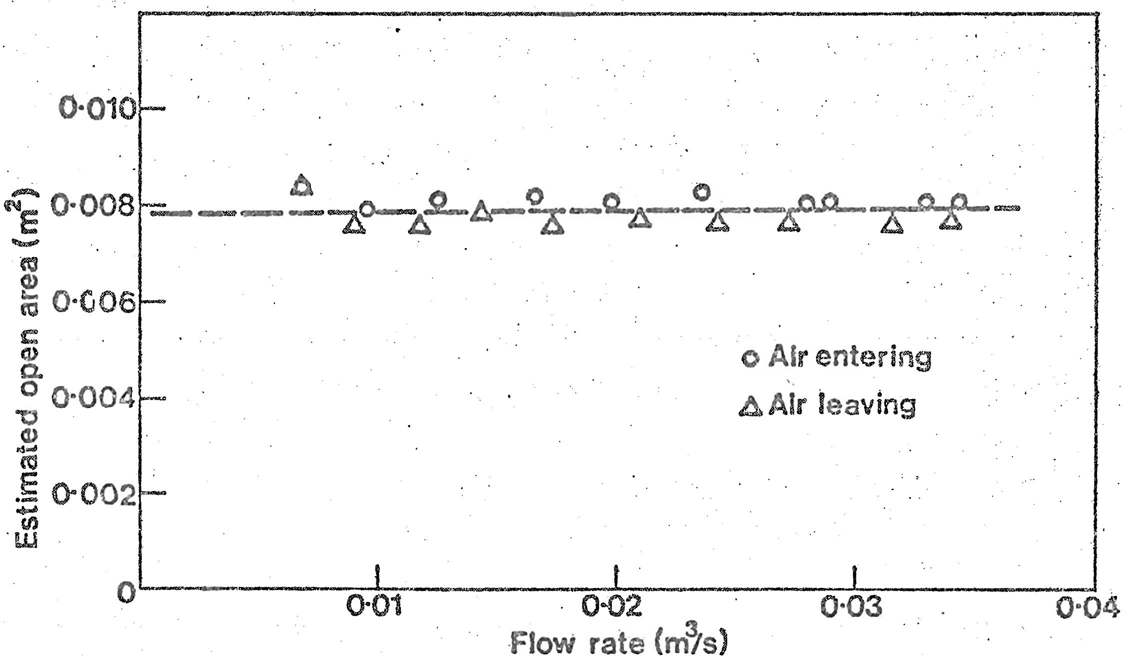


FIGURE 5. Estimates of open area for a window of the test house

Table 1 shows the estimated values for A of all the windows and external doors. In the Table, L denotes the length of the crack and Z the width of the crack. The crack type can be chosen from three types, i.e. straight-through, L-shaped and double-bend. A certain amount of latitude is permissible [4] when specifying these crack parameters.

a) WINDOWS Room	Crack Type	L Crack Length (m)	Z Distance through Crack (m)	Open Area (m^2) A	
				Air entering room	Air leaving room
Bedroom 1	Double bend	8.3	.041	.0124	.0114
Bedroom 2	" "	4.9	.041	.0063	.0063
Bedroom 3	" "	8.6	.073	.015	.013
Bedroom 4	" "	4.9	.041	.0064	.0064
Bathroom	" "	4.5	.053	.010	.0085
W.C.	" "	1.4	.043	.0038	.0032
Landing	" "	4.9	.041	.008	.0076
Kitchen	" "	8.7	.042	.011	.010
Dining room	" "	8.3	.041	.0094	.010
Lounge(double glazing open)	L-Shaped	17.7	.015	.0174	.0174
Lounge(" " closed)	"	17.7	.015	.0156	.0156
b) DOORS					
Bedroom 1	L-Shaped	5.48	.043	.0116	.0116
Bedroom 2	"	5.51	.039	.0131	.0132
Bedroom 3	"	5.44	.043	.0127	.0120
Bedroom 4	"	5.51	.045	.0157	–
Bathroom	"	5.47	.043	.0135	.0125
W.C.	"	5.48	.043	.016	.013
Kitchen(to outside)	"	5.48	.043	.0058	.0051
Kitchen(to hall)	"	5.48	.043	.025	.025
Hall(to outside)	"	5.48	.043	.0107	.0096
Lounge(to hall)	straight-through	5.34	.035	.023	.0268
Lounge(to outside)	L-Shaped	7.34	.068	.0116	.0112
Dining room (to kitchen)	"	5.48	.043	.012	.011

TABLE 1. Open areas of room components

The open areas of the components could have been obtained by direct measurement, with a feeler gauge and a ruler, say. This is probably what would have to be done under normal circumstances. However, higher accuracy is likely to be obtained from the pressure/extract technique and therefore this was used for the present estimates.

2.2.3. Background Leakage Areas

Work carried out by the Building Research Establishment[3] has shown that the flow of air into a house is not due solely to cracks around doors and windows. Therefore it was decided to obtain estimates of the background leakage areas of each of the rooms during the course of the pressure/extract tests. The background leakage area of a room is here defined as the open area which remains when all of the doors and windows in the room (and purpose-provided openings) are sealed.

There are many candidates for background leakage areas. Amongst these are the following:-

Porosity of walls, ceiling and floor (e.g. invisible hairline cracks.
Light switches and other electric fitments.
Cracks near pipes, for example due to central heating systems, mains water and gas.
Cracks under the window-sill and around the window-frame, as opposed to the windows themselves. Similarly for door frames.
Cracks hidden by skirting boards.

The background leakage areas were estimated in the same way as those of the doors and windows. Fig. 6 shows a typical set of results.

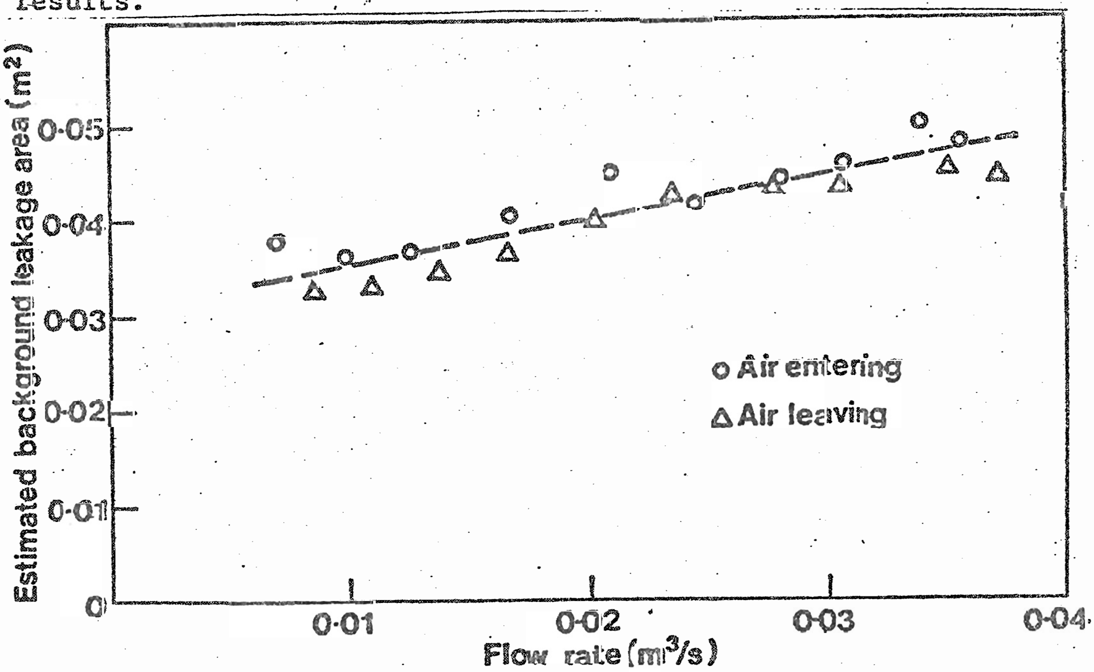


FIGURE 6. Estimates of background leakage area of a bedroom.

Since the small cracks which constitute the background leakage area cannot generally be defined, the choice of the crack parameters for calculating the open area is necessarily rather arbitrary. Nevertheless it was found that the crack flow equations could give a reasonable description of the flow characteristics (see Fig. 6) and for convenience it was decided to describe the flow through the background leakage areas in this way. Table 2 shows the estimated values of A and the chosen crack parameters for the background leakage areas. It can be seen that the background leakage areas are appreciable in relation to the component areas given in Table 1.

ROOM BACKGROUNDS	Crack Type	L Crack Length (m)	Z Distance through Crack (m)	Open Area (m^2) A	
				Air entering room	Air leaving room
Bedroom 1	Double Bend	8.30	.041	.039	.035
Bedroom 2	L-Shaped	10.62	.025	.033	.029
Bedroom 3	"	14.15	.035	.037	.035
Bedroom 4	Double Bend	13.75	.025	.032	.032
Bathroom	Straight through	6.60	.025	.026	.024
W.C.	"	4.83	.050	.005	.003
Kitchen	L-Shaped	19.55	.043	.039	.027
Lounge & Dining Room	"	23.0	.035	.034	.028

TABLE 2. Background leakage areas of the rooms of the test house

Having estimated the background areas of individual rooms, the next problem is to estimate the distribution of the areas within the rooms. We need to know not only the magnitudes of the areas, but also the spaces between which they communicate. This problem is considerably simplified if we restrict our attention to the case of the house with all internal doors open. (It is intended to consider the more general case (some or all internal doors closed) at a later date). For predicting the ventilation rate of the house in this state we need to know only the proportion of the background areas which communicate from the interior to the exterior. This information was obtained for the test house by carrying out a fairly simple test followed by "trial and error" calculations, as described in the following.

2.2.4. Background Leakage Area Test

For the background leakage area test, all of the internal doors of the house were opened, and a large electric fan was used to blow air into the house at a known rate. The static pressures on three outside walls of the house were then measured relative to the pressure in the hall inside the house. The fan pressurised the house to such an extent as to make contribution to the ventilation by both wind and stack effect almost negligible.

Calculations were then carried out with the prediction method with various percentages of the total measured background leakage areas communicating directly between the inside and outside.

Table 3 compares the measured pressures with those calculated using different distribution of background leakage area. It is easily seen that if the backgrounds are ignored the effect is to make the house much too tight, and hence a very high pressure difference is predicted. If all of the backgrounds are assumed to communicate to the outside, then the house becomes too leaky.

FACE	MEASURED (N / m²)	THEORETICAL (N / m²)			
		-a-	-b-	-c-	-d-
WEST	-13.72	-53.7	-5.3	-13.2	-13.2
EAST	-14.70	-54.5	-6.1	-14.8	-14.8
SOUTH	-14.21	-54.5	-6.1	-14.8	-14.8

CONDITIONS

WIND: WEST 3.5 KNOTS

FAN ON: FLOW = 0.5732 m^3/s

ALL DOORS OPEN

-a- NO BACKGROUNDS CONSIDERED

-b- BACKGROUNDS DIRECT TO OUTSIDE

-c- DISTRIBUTIONS I AND II

TABLE 3. Pressure differences between the hall and external walls

Clearly the solution to the problem lies somewhere between these two extremes. Two possible distributions (denoted I and II) are described below. Both of these give good agreement with the measured pressures of Table 3. Probably many other distributions could be put forward, but we have chosen two simple ones. It is not possible simply on the basis of the one test described above to decide which of these distributions is the closest to reality. This will have to be done by comparing the predictions of the distributions with actual ventilation measurements. A preliminary attempt to do this is described in Section 4.

Distribution I represents approximately what is considered to be a likely distribution. One would expect that the background infiltration via the walls, both external and internal, would be the major source. Therefore assuming even distribution over the walls, half of this contribution would be through outer walls and half through inner ones. The ceiling and floors would also be expected to make a contribution to the total open area. For the downstairs rooms though, the floor was sealed with polythene sheeting and so should be tight.

There should also be very little exchange between the ground and upper floors via the ceiling. Only a very small pressure difference exists between the two and the partition itself is, of necessity, a fairly solid construction since it also forms the floor of the upper storey. For upstairs rooms however, there is only a thin ceiling layer, which is perforated in several places by electric light fittings. A large pressure difference exists across it and so this could be a major background source. Based on this argument the following distribution was found to satisfy the background test (See Table 3).

DISTRIBUTION I

Lower Floor

50% Through external walls
(50% internal).

Upper Floor

40% Through external walls
(35% internal).
25% Through ceiling into loft space

Distribution II is a more extreme case, and was chosen to show that background leakage area distributions are important and must be assigned correctly. In this case exfiltration through the ceiling of the upper storey was taken as the only source of background for upstairs rooms. The argument for the lower floor remained the same.

DISTRIBUTION II

Lower Floor

50% Through external walls
(50% internal)

Upper Floor

100% Through ceiling into loft space.

3. VENTILATION MEASUREMENTS IN TEST HOUSE

The first series of measurements of ventilation rates in the test house has recently been completed.

The technique adopted was to fill the house with helium tracer gas and to monitor the decay in as many rooms as possible. Since only one analyser was available, the decay could be monitored continuously in only one of the rooms. For the other rooms, samples of the room air were taken at discrete time intervals and stored in gas sampling bottles for subsequent analysis. In all of the tests the internal doors were kept open, and each door and window was investigated with a smoke tube to ascertain whether the air was entering or leaving the interior.

Four runs were carried out and the meteorological conditions corresponding to these are given in Table 4. For Run 3 the central heating in the house was switched off so that stack effect would be negligible. For the other three runs, stack effect was considerable, since it was found from the smoke tube tests that the path of the ventilation air was such that all of it entered through the downstairs components and left through the upstairs components. This has been taken account of in the estimation of the total air change rate of the house, R. That is, R is defined by:-

$$R = \frac{\text{total air flow rate into house}}{\text{total volume of house}}$$

$$R = \frac{Q_{TOT}}{V}$$

and Q_{TOT} is obtained by summing the flow rates for those rooms where the air enters. These flow rates are given by the product of the measured decay rate and the room volume.

Table 4 gives the values of R obtained for the four runs which ranged from 0.69 to 1.15.

	RUN 1	RUN 2	RUN 3	RUN 4
WIND DIRECTION	WEST $283^{\circ} \pm 14.0$	SOUTH $182^{\circ} \pm 11.6$	SW $228^{\circ} \pm 16.8$	SSW $195^{\circ} \pm 12.6$
WIND (m/s) SPEED	2.20 ± 0.45	3.05 ± 0.75	4.00 ± 0.90	3.86 ± 0.73
INTERNAL TEMP ($^{\circ}$C)	19.1 ± 0.1	19.1 ± 0.1	12.2 ± 0.1	19.7 ± 0.1
EXTERNAL TEMP ($^{\circ}$C)	1.7 ± 0.1	4.4 ± 0.1	11.1 ± 0.1	8.6 ± 0.1
R (hr^{-1})	1.15 ± 0.07	0.90 ± 0.05	0.75 ± 0.06	0.69 ± 0.05

TABLE 4. Ventilation measurements in the test house

4. COMPARISON BETWEEN MEASUREMENT AND PREDICTION

The comparison between the four field measurements and the predicted values are presented graphically in Figures 7 to 10 below. This form of presentation has been chosen, instead of a simple table of values, because it allows other features of the predictions to be demonstrated, i.e. the differences arising from the use of Distributions I and II and from the complete neglect of background leakage areas. Each of the four field measurements corresponds to one wind direction and one value of temperature difference, ΔT, between the interior and ambient. Accordingly the predictions are in the form of plots of fresh air change rate against mean wind speed. The measured values of fresh air change rate are indicated by a bar which gives an indication of the possible errors involves in the interpretation of the tracer gas decay records.

Run 1. (Figure 7). The diagram shows that the measured air change rate is nearly three times larger than that predicted if backgrounds are ignored. However, if the backgrounds are distributed as stated for Distribution I, then the predicted value is 82% of that measured. For Distribution II the predicted value lies within experimental error. This clearly demonstrates the effect of the backgrounds, particularly as regards the amount allowed to exfiltrate through into the loft space.

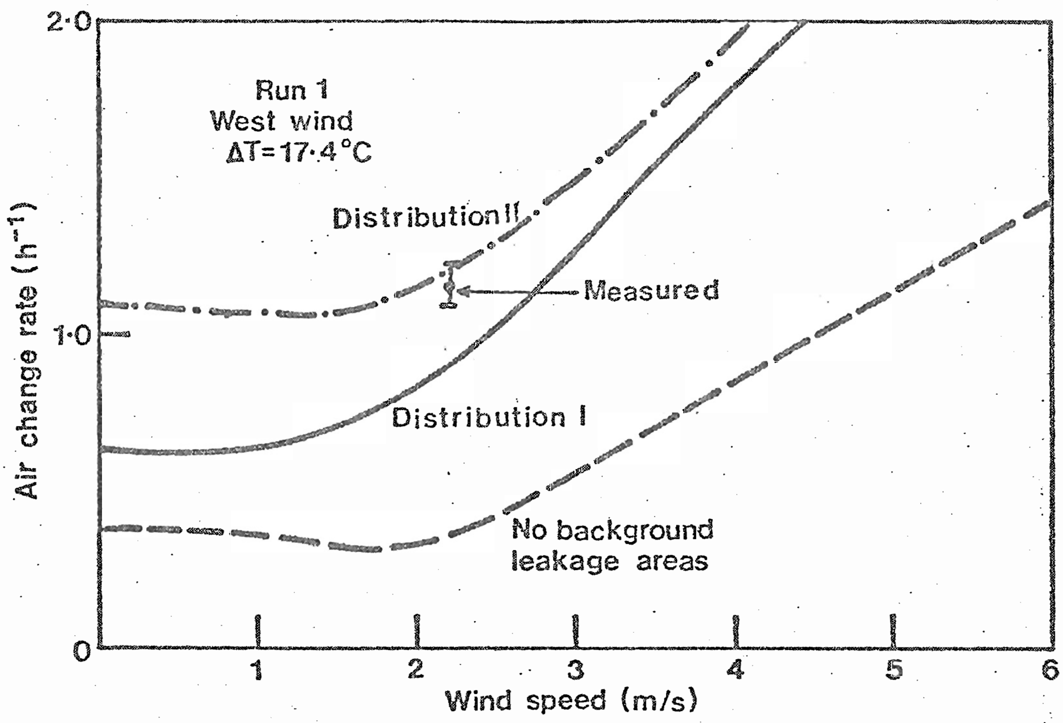


FIGURE 7. Comparison between predicted and measured air change rates

Run 2. (Figure 8). Predictions with no backgrounds are again shown, and are a factor of three less than the rate measured. Distribution I gives a value that is 61% of that recorded while Distribution II is well within experimental error.

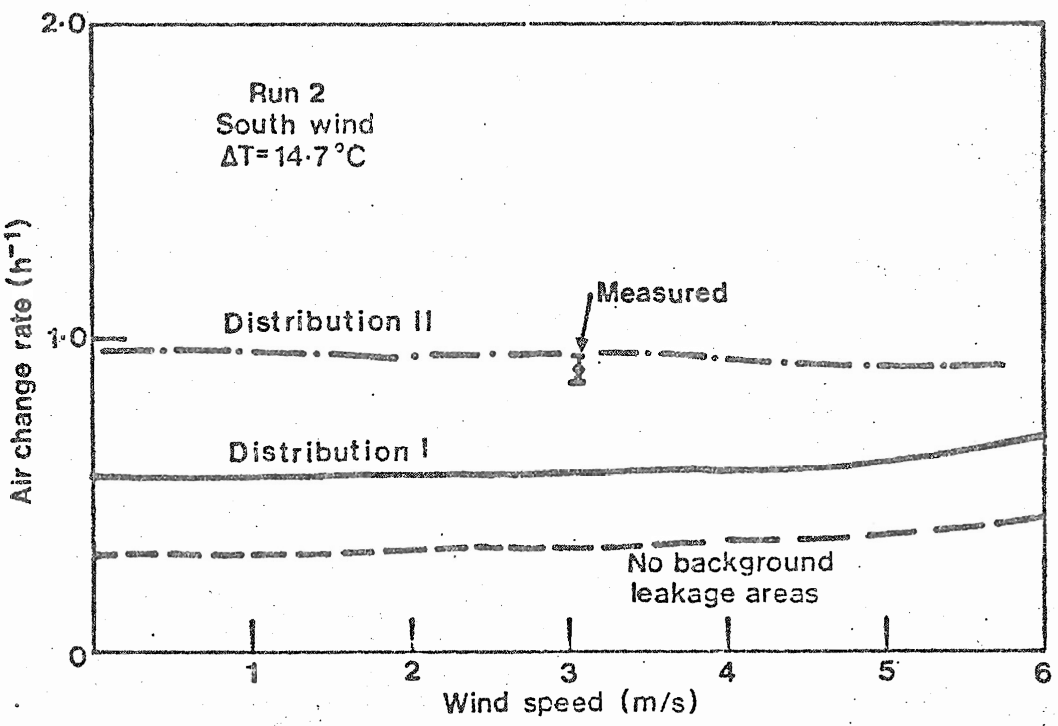


FIGURE 8. Comparison between predicted and measured air change rates.

Run 3. (Figure 9). Calculated values are only shown for Distributions I and II. Both are higher than that measured, with Distribution I the closer.

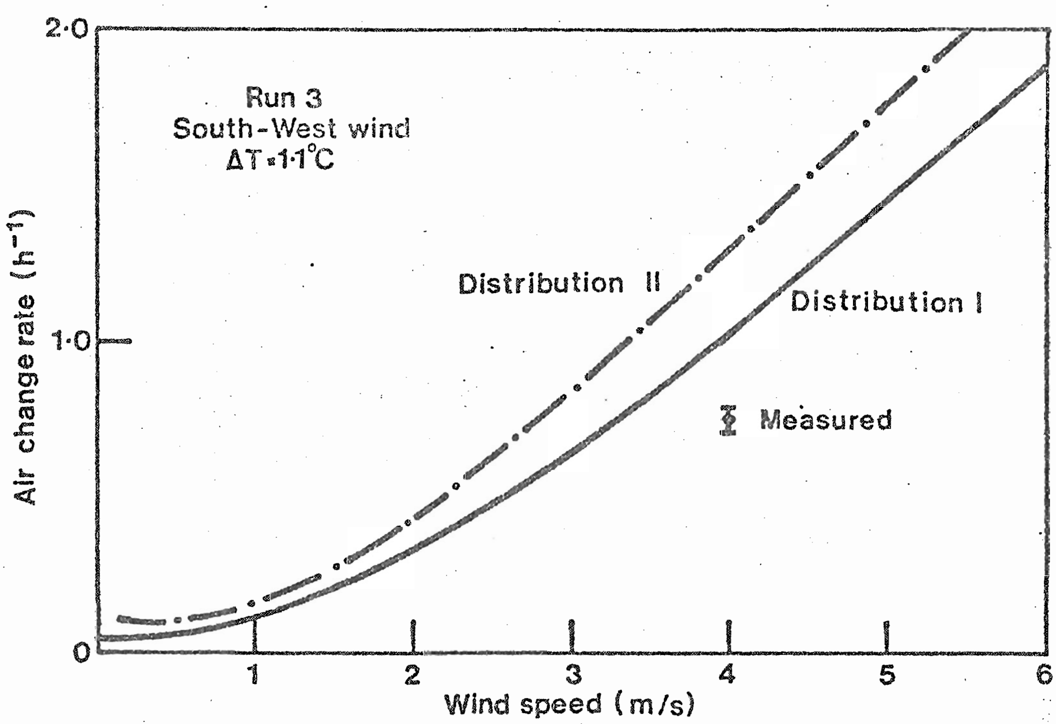


FIGURE 9. Comparison between predicted and measured air change rates

Run 4. (Figure 10). The most striking thing to be seen using Distribution I is the great difference in predicted ventilation rate caused by a small change in wind direction. This is due to the geometry of the site, allowing the house to pass rapidly from a sheltered state to one where it feels the full effect of the wind. This effect (which also applies to Distribution II) should be less pronounced in reality because of turbulent fluctuations in the wind direction (Table 4). If account were taken of these fluctuations both Distributions I and II would give predictions which are better than appears at first sight.

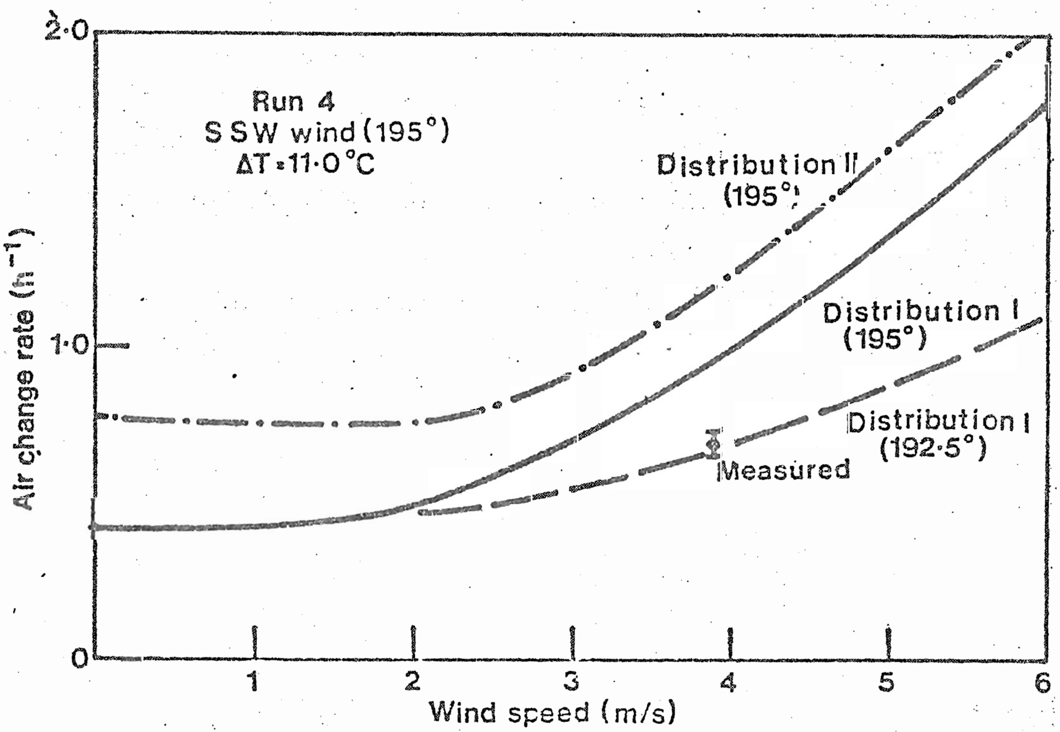


FIGURE 10. Comparison between predicted and measured air change rates

To summarise the above comparisons two main points can be made. Firstly, there are large differences between Distributions I and II, particularly when stack effect is dominant. This emphasises the importance of finding a satisfactory approximation for the distribution of background areas. Secondly, it is not possible to state with confidence that Distribution I is better than Distribution II, although on average the difference between measurement and prediction is smaller for Distribution I. Much more experimental data is required so that distinct trends can be identified. Nevertheless, bearing in mind the possible range of error inherent in the experimental measurements, the comparisons given above are considered to be encouraging.

5. FURTHER DEVELOPMENT OF MODEL

At the present time the model is in an early stage of development and further field tests are required to validate its use as a research tool. (Further development work is proposed, and should be reported at a later date).

If this can be achieved the method can be considered for use as a design aid. Whether or not it can be used for such purposes depends on whether or not simple means can be found for specifying the basic data requirements. Of these there are two main areas where further work is required.

Firstly, the distribution of background leakage areas needs to be more fully understood. For general purposes one would like to be able to relate the magnitude and the distribution of background leakage areas to the size and construction of dwellings. When one is concerned only with the overall air change rates of a dwelling, it is possible that enough information can be obtained from a test similar to that in use by BRE [3]. That is, the external doors and windows of the dwelling could be sealed and estimates obtained of the total background area by pressurising the house with a large fan with known flow rates. When one is concerned with the manner in which the ventilation air passes through the dwelling, much more detailed information about the distribution of background leakage areas is required. This would probably have to be obtained by measurements within rooms, as described in Section 2.2.2.

Secondly, it is necessary that handbook values of external pressure distributions should be improved. This means that pressure distributions obtained in wind tunnels which simulate the characteristics of the atmospheric boundary layer should be used. It should eventually be possible to derive a fairly simple classification of pressure distributions under such headings as dwelling shape, adjacent surroundings and distant surroundings.

6. IMPLICATIONS FOR ENERGY CONSERVATION

Both the predictions and the measurements described above have demonstrated the important contribution that background areas make to the total ventilation rate and hence to the total ventilation heat loss. Herein lies the main implication of the present work for energy conservation. Thus when deciding on the degree of ventilation sealing (weather stripping) which would be permissible in a given dwelling, it seems essential that account should be taken of the background leakage areas. Precisely how this should be done is not easy to specify at the present time. However it is possible that the whole-house pressure/extract technique as used by BRE[3] could provide useful information on background leakage areas.

In the same way account should be taken of background leakage areas when designing mechanical ventilation systems. For the test house used in the present work sufficient ventilation might occur through the background leakage areas alone (i.e. doors and windows sealed) with a mechanical extract system installed so that additional purpose provided inlet vents would not be necessary. Further investigation of this effect is required. In extreme cases the background leakage areas might be so large as to render it impossible to make the ventilation rate independent of meteorological conditions (i.e. independent of wind speed and ΔT). In such cases consideration would have to be given to sealing the background leakage areas (e.g. with special paints) or to ensuring that they are minimised during construction of the dwelling by paying special attention to details.

It can be seen from the predicted results for Distributions I and II that the greater the percentage contribution of the background leakage area assigned to infiltration into the loft space, the greater the overall ventilation rate is, and therefore the greater the ventilation heat losses will become. Hence it would appear that sealing the leaks into the loft could alone make worthwhile energy savings.

Another point to be considered, concerns the estimation of heat losses due to natural ventilation over the heating season. The manner in which the stack effect and wind effect combine leads to a virtually horizontal part of the predicted air change rate curve (see Fig. 7a for example). Thus below a certain wind speed the air change rate depends only on ΔT (and wind direction to a lesser extent) and this could prove to be a useful simplification in the estimation of integrated ventilation heat losses. Such estimates are necessary for the evaluation of potential energy savings arising from the use of mechanical ventilation systems.

7. CONCLUSIONS

The major conclusions to be drawn from the work described are as follows.

A mathematical model of ventilation in houses has been developed which is based on physically sound crack flow equations. It is important for predicting ventilation induced by the atmospheric wind that the external pressure distribution on the house be accurately known. Values of pressure coefficients given in handbooks are of little use when they are obtained from tests on isolated houses.

It is particularly important to take account of background leakage areas in the prediction of ventilation rates. Background leakage areas are of similar magnitude to the areas of cracks around doors and windows. The neglect of background leakage areas will lead to severe underestimation of ventilation rates. Because of their nature it is very difficult to determine the manner in which they are distributed about the house. Extensive measurements in a test house have led to the choice of two simple distributions which satisfy a pressure/extract test. Predictions carried out with these two distributions have demonstrated that it is essential to obtain a good approximation to the real distribution.

Comparisons between predictions and a very limited number of experimental ventilation rates obtained in a test house show on average encouraging agreement. Much more experimental data is needed however before a definitive assessment of the model can be made.

At low wind speeds it is important to include stack effect in the model because the pressures induced by buoyancy are large compared to those generated by the wind. A manifestation of this can be seen in the infiltration paths at low wind speeds - the air entering through the downstairs rooms and exhausting through the upstairs rooms.

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