VENTILATION MEASUREMENTS IN HOUSING

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Despite the fact that the majority of buildings, particularly in the domestic sector, are naturally ventilated, natural ventilation and infiltration remain amongst the most intractable aspects of building design. The need for improved guidance has become of increasing importance with the need for energy conservation.

As a first step to providing a better understanding of natural ventilation in housing this paper presents results of recent measurements of ventilation rates and air leakage characteristics in dwellings. These are used to show typical magnitudes of ventilation rates and the way in which they are influenced by meteorological parameters, such as wind speed and direction, and air temperature, and the characteristics of the fabric and form of the building.

1 INTRODUCTION

Natural ventilation is one of the most intractable features of building design. Despite the fact that the majority of buildings, particularly in the domestic sector depend upon natural ventilation to maintain internal air quality and, in summer, to limit the incidence of thermal discomfort, current knowledge of the rates of ventilation which occur in practice and the way that these are related to design parameters is very limited. In the past when heating fuel was relatively cheaper, excessive ventilation was comparatively unimportant, provided that it did not give rise to discomfort. The current need to reduce energy consumption has provided an impetus to reduce ventilation rates to the minimum levels necessary to ensure health, safety and comfort. This has lead to the demand for improved guidance on design and the development of methods for readily assessing the ventilation performance of buildings.

The purpose of this paper is to present the results of recent measurements in housing in order to illustrate typical magnitudes of ventilation rate and the way in which these are influenced by meteorological parameters and the characteristics of building fabric and form. Examples are taken from a recent survey by the Building Research Establishment of ventilation rates in unoccupied housing, a fuller report of which will be published in due course.

2 FACTORS WHICH INFLUENCE NATURAL VENTILATION RATES

It is proposed to review the theoretical principles of natural ventilation only briefly as these have been dealt with in many published papers, of which references (1, 2 and 3) are examples. In respect of natural ventilation a building may be considered to consist of a number of individual 'cells' connected to each other and to the outside air by openings through which air can flow. In a house these 'cells' may represent rooms or other spaces such as those beneath suspended floors, under the roof or even wall cavities. The connecting openings may be large and well-defined, such as doors, open windows, air-bricks and flues, or small, and not always immediately apparent, such as gaps around the opening lights of windows and cracks at the junction of floors and walls or where electrical fittings and other services penetrate the fabric. Air will flow through these openings when a pressure difference is created across them. This may be due to the action of the wind or to differences between the temperature of the air within the house and outside. It has been conventional in the past to consider only mean pressures but recent studies have indicated the importance of the fluctuating component of wind-generated pressures where the mean pressures difference across an opening in the external fabric is small(4,5). In addition, for large openings such as open windows, mechanisms dependent upon the local air speed, rather than the applied pressure difference, may be the dominant cause of air exchange between inside and outside(6).

The natural ventilation rate of a house therefore depends upon the following factors:

a) The meteorological variables - wind speed and direction and air temperature.

b) The shape of the house and the nature of its surroundings. These determine the distribution of wind-generated pressure at the external surfaces.

c) The positions and airflow characteristics of all openings and flow paths.

In addition, some openings, in particular windows and doors, may be controlled by the occupants. Dick(7) and, more recently, Brundrett(8) have demonstrated that window opening behaviour in dwellings can be correlated closely with external air temperature. A further factor which should therefore be added to those given above is the behaviour of occupants.

It is the wide range and the difficulty in determining the effects of some of these parameters which make the prediction of natural ventilation rates and the interpretation of field measurements so difficult.

3 MEASUREMENT TECHNIQUES

3.1 Air flow characteristics of openings

(i) Theoretical considerations

The relationship between the flow rate through an opening and an applied pressure difference depends upon Reynolds Number and the geometry of the opening. For large openings such as open windows, which approximate to a sharp-edged orifice the following simple relationship applies:

$$Q = C_d . A . \sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

where, Q is the volume flow rate resulting from the applied pressure difference Δp; A is the area of the opening, ρ is the density of air and C_d the discharge coefficient. For other types of opening it is necessary in general to determine the relationship empirically. It is convenient to fit the measured values to a simple expression and the following power law is generally used

$$Q = K . \Delta p^n \qquad (2)$$

More complex expressions, which can be more readily justified theoretically, have been developed, notably by Etheridge(9). These cannot, however, be easily used where the shape and dimensions of an opening are not known and this is generally the case in real situations.

The value of the exponent, n, will lie between 0.5, for flows which are independent of viscosity, and 1.0, for flows which are dominated by viscosity. For any given range of applied pressure the smaller the cross-stream dimension of the opening, the closer n will approach to 1.0.

(ii) Measurement techniques

Laboratory 'pressure box' techniques have been used for many years for testing the air leakage characteristics of building components such as windows. Van Gunst and den Ouden(10) extended the method to field use by developing a portable pressure box for measuring the in situ performance of windows in experimental houses. The technique is essentially simple. An enclosure is sealed around the component of interest. Air is extracted at a known rate and the pressure difference developed across the component measured with a manometer.

More recently the measurement of the leakage performance of individual components has been extended to measuring the 'whole house' leakage characteristics. Development of suitable equipment by Skinner(11) in the United Kingdom was accompanied by similar developments in Canada, Denmark, the USA and Sweden. Although the techniques used by various experimenters differ in detail, the essential method is the same. A large fan unit is sealed into a suitable opening in the external fabric of the house, usually an open doorway or window. The flow rate through the fan and the applied pressure difference are measured. In some cases the equipment is designed so that the flow can be reversed and the leakage measured for both positive and negative pressure differences.

Large openings whose equivalent areas can be determined by alternative methods are sealed during testing. Progressive sealing of chosen components and repetition of the measurements allows the distribution of leakage to be determined.

Provided a variable speed fan unit is used, results may be presented as a curve of volume flow rate against applied pressure difference and a simple power law expression, of the form given in equation (2), may be fitted. In fact this expression will represent the aggregate of the various flow paths through the fabric:

$$Q = K . (\Delta p)^n = \Sigma K_i . (\Delta p)^{n_i} \qquad (3)$$

A simpler alternative which is also used is to give the leakage at a fixed pressure difference, usually 50 Pa. The two approaches may be readily combined, by writing equation (3) in the following form, which has the additional merit of being dimensionless:

$$Q/Q_T = \left[(\Delta p)/(\Delta p_T)\right]^n \qquad (4)$$

where Q_T is the flow rate at the applied pressure, Δp_T.

The technique has achieved considerable interest because of its simplicity and ease of use on site and because of the possibility that it could be used as an indicator of the general natural ventilation performance of a dwelling. To determine the validity of this proposal it is necessary to compare the results obtained using this pressurisation technique with the results of tracer gas measurements of ventilation rates and this will be discussed further in a following section. In this context it is worth noting the following points:

a) Pressures generated by wind and stack effect are not uniformly applied across the building envelope, as they are in the pressurisation test.

b) Relatively high pressure differences are used, usually in the range 20 to 60 Pa, in comparison with typical pressures generated across the fabric at average wind speed, which are of the order of 1 to 5 Pa. (In an attempt to overcome this limitation, techniques using alternating pressures are under development(12) but have not reached the stage when they can be used with confidence.)

3.2 Ventilation rate measurements

(i) Tracer gas methods

Because the air flow paths in a naturally ventilated building are not well defined conventional anemometric techniques cannot be used to measure the volume flow rate of air entering a space. The only satisfactory techniques employ the use of a tracer substance, usually a gas. Two methods of operating may be employed:

a) the exponential decay method, and
b) the constant injection rate method.

These may be illustrated by considering a single 'cell' of volume V. Air enters and leaves the cell at a rate Q. If tracer gas is introduced into the cell at a constant rate, q, its concentration after a period of time, t is given by:

$$c = q/Q \left[1 - e^{-\frac{Qt}{V}}\right] \qquad (5)$$

After a sufficiently long period the concentration tends to an equilibrium level, c_e, given by

$$c_c = q/Q \qquad (6)$$

If c_e and q are measured then the ventilation flow rate, Q, may be determined. This is the basis of the constant injection rate method. If the injection of tracer is stopped then the concentration rate decays exponentially according to the following equation:

$$c = c_o . e^{-Qt/V} \qquad (7)$$

The ventilation rate R(= Q/V) is readily determined. Both methods require that the tracer gas should be uniformly mixed within the space.

A recent development of the constant injection technique(13) employs a microprocessor in a feedback loop from the measuring instrument to the injection device and maintains the concentration of tracer gas constant, while monitoring the amount of tracer injected. The average ventilation rate of the space under consideration is obtained by dividing the total volume of tracer gas injected over a given period by the value at which the concentration is held constant.

(ii) Tracer gas characteristics

To be suitable as a tracer gas must possess the following characteristics:

a) It should neither be created or removed from the space under test, other than by ventilation (ie it should be stable and not absorbed or emanated by surfaces within the space).

b) It should be capable of being readily mixed with air.

c) It should be non-toxic.

d) It should be capable of being measured over an appropriate range of concentration.

A number of gases have been employed as tracers including carbon dioxide, hydrogen, helium, ethane and krypton-85. The two gases most commonly used at present are sulphur hexafluoride and nitrous oxide. These may be measured in concentrations as low as 10^{-4} and 10 parts per million respectively using an electron capture chromatograph in the first case and an infra red gas analyser in the second case.

(iii) Measurements in dwellings

The type of tracer gas measurements to be made in dwellings depend upon the reason for which the ventilation rate is required. If the concern is with energy consumption, and temperatures are reasonably uniform throughout the house, then whole house ventilation rates are of interest. If substantial temperature differences are likely to occur then concern is the fresh air entering a particular room. The constant concentration technique is most useful in this case since it allows the air entering each room to be separately determined. Alternatively the major concern may be the movement of some contaminant, such as water vapour, from one part of the house to another, in which case it is necessary to know the rate of air exchange between rooms, which is obscured in the constant concentration method. A second tracer using the exponential decay method is required. Individual room measurements, made by injecting tracer gas into a single room are less easy to interpret since the incoming air may come from elsewhere within the house as well as from outside. However this may be overcome in part by observing the points of entry and exit of the air using smoke filament indicators. Although such measurements obscure the origin of the air entering the room they are useful;

(i) for comparison with theoretical predictions, and

(ii) in situations where a contaminant is produced in the room in question only. This is often the case in housing because of the diversity of use of rooms and the range of contaminants that need to be controlled.

4 MEASUREMENTS IN DWELLINGS

4.1 BRE measurements

In order to provide basic data on the ventilation of dwellings in practice a programme of air leakage and ventilation rate measurements has been carried out in 25 dwellings. In addition measurements in a further 13 houses of ventilation rates and component characteristics have been carried out under contract by the Building Services Research and Information Association. Full sets of leakage characteristics and ventilation rates were made in nineteen of the houses and brief details of these are included in Table 1.

Where possible the ventilation rate measurements were carried out over a period of three to four weeks in order to obtain a range of wind speeds and directions, and, generally less successfully, temperatures. In order to limit the range of variables the measurements were carried out with windows and doors closed, although in a few of the houses a limited number of additional measurements were made with windows and other controllable ventilation openings set to particular positions of opening. All measurements were made in unoccupied dwellings. A full analysis of the results referred to in the following sections will be published in due course.

4.2 Air leakage measurements

(i) Method

Whole house air leakage measurements were made using the pressurisation equipment described by Skinner(11). This allowed measurements to be made with both positive and negative pressure differences. The measurements were carried out during periods of low wind speed in order to reduce any interference by wind generated pressures.

Air leakage through individual items was determined separately using a portable rig consisting of an adjustable frame capable of being set up to fit over any component up to the size of a double door. Polythene sheet was sealed over this to form an airtight enclosure from which air was extracted using a small fan. The pressure difference applied across the component and the rate of flow of the extracted air were measured.

(ii) Whole house air leakage measurements

Measurements were made of whole house air leakage for both positive and negative applied pressure differences for each of the nineteen dwellings listed in Table 1. Power law curves were fitted to each set of results and the mean values K and n from the positive and negative results calculated for each dwelling. Using the form given by equation (4), Table 1 lists the values of air leakage, Q_T in m^3/h, at an applied pressure difference of 50 Pa, and of the exponent, n. As expected the values of n lie within the range 0.5 to 1.0. The maximum value is 0.69 and the minimum 0.53. The mean value is 0.60, with a standard deviation of 0.04. Table 1 also

TABLE 1 - Whole House Air Leakage Characteristics

House data				Air leakage characteristics at 50 Pa					Ventilation rates at mean wind speed for the site
No.	Date	Type	Volume m^3	Q_T m^3/h	(Q_T/V) ach	(Q_T/A_p) m^3/hm^2	n	Percentage background leakage	ach
1	1971	2 B	197	2310	11.7	12.4	0.57	64%	0.44
2	1957	2 B	254	2205	9.7	11.9	0.69	52%	-
3	1957	2 B	249	2910	11.7	16.6	0.55	64%	0.45
4	1976	2 C	196	3090	15.8	23.3	0.64	67%	0.58
5	1976	2 C	196	2810	14.4	21.2	0.57	69%	0.77
6	1956	2 D	164	2210	13.5	22.2	0.67	42%	0.72
7	1975	2 D	200	2440	12.4	22.6	0.66	57%	0.70
8	1977	2 D	77	1330	17.3	40.2	0.58	60%	0.72
9	1947	2 A	195	3530	18.1	19.3	0.61	-	-
10	1978	2 D	179	1760	9.9	13.9	0.58	72%	0.49
11	1977	2 C	196	4130	21.8	31.5	0.64	72%	1.27
12	1960	2 B	261	3782	14.5	22.3	0.58	69%	0.50
13	1960	2 B	261	3990	17.4	23.5	0.58	67%	0.58
14	1977	2 C	247	3570	14.5	16.6	0.63	76%	-
15	1976	1 E	148	1350	9.1	16.1	0.55	48%	-
16	1976	2 F	169	1620	9.6	16.7	0.54	57%	-
17	1976	2 G	179	3400	19.0	39.2	0.53	54%	-
18	1977	3 D	220	3240	14.7	32.6	0.63	56%	-
19	1970	2 C	221	2310	10.4	17.3	0.58	70%	0.36

House type_ 1, 2, 3 - Number of storeys:

A - detached
B - semi-detached
C - end terrace
D - mid-terrace
E - flat
F - maisonnette
G - quad.

shows the air leakage flow rate scaled by the house volume (Q_T/V), and scales by the permeable area (Q_T/A_p). For this purpose the latter is defined as the sum of the areas of the external walls of the house together with the area of the ground floor, provided that this is permeable to air flow, and the area of the surface between the house and the roof space. (Q_T/A_p) is an index of the overall permeability to air flow of the building envelope.

It is of interest to compare these results with those obtained in typical dwellings in other countries. The mean of the results for the nineteen houses, together with similar results obtained in Canada(14), Sweden(15,16), Denmark(17) and the United States(18) are shown in Table 2. The air leakage rates at 50 Pa for the British house compare favourably with all but the Swedish houses which have much lower values. However when a comparison is made taking into account the different average volumes for each data set the British houses are clearly considerably less tight than those in Canada and Sweden. This is further reflected in a comparison of fabric permeability - (Q_T/A_p), which shows Swedish houses to be four times as tight as the United Kingdom sample.

(iii) Variation of air leakage rates with time

In order to determine whether any variation occurred in the air leakage characteristics, measurements were made in one of the dwellings (no 11, Table 1) and repeated at regular intervals over a period of eighteen months. The results are shown in Figure 1 in the form of the whole house leakage rate, Q_T, at 50 Pa, subdivided between leakage through the windows and doors, and background leakage. The house concerned was unoccupied during the test period, but was heated to normal temperatures during the heating season. Figure 1 indicates a very substantial seasonal change in overall leakage with a maximum in winter and a minimum in the summer months. In view of the

TABLE 2 - A Comparison of Air Leakage Characteristics of Dwellings in Different Countries

Author	Country	Sample size	Average house volume (m^3)	Air leakage characteristics at 50 Pa Q_T (m^3/h)	Q_T/V (ach)	Q_T/A_p (m^3/m^2h)	n	Applied pressure direction
Present results	United Kingdom	19	200	2740	13.9	22.1	0.60	Mean
Grimsud et al (18)	United States (California)	13	378	3330	9.4	-	-	Mean
Colet et al (17)	Denmark	6	303	2730	8.6	-	0.70	Positive
Holmgren et al (16)	Sweden	10	307	1580	5.1	-	0.71	Positive
Kronvall (15)	Sweden	25	317	1360	4.5	5.0	0.77	Negative
Beach (14)	Canada (Ottawa)	63	553	2420	4.4	8.4	0.66	Positive

fact that the house was not occupied internal relative humidities were relatively low during the winter, there being no moisture input, and, in consequence, drying out of the timber in the structure may be a contributory factor to the observed change in tightness. The measurements will be repeated during the coming heating season when typical moisture levels will be maintained in the house.

Recent measurements in Swedish houses(19) indicated a very substantial change in air leakage characteristics in the first year of occupation of new houses. Leakage rates measured in five houses increased on average by 70%. Measurements made a further year later showed no significant change. Similar measurements were made in the present series of tests on three identical British houses. The mean leakage at 50 Pa at completion was found to be 1870 m^3/h. Approximately one year after the houses had been occupied the leakage rate had increased to a mean value of 3420 m^3/h, an increase of 83%. Possible reasons for this include drying out of the fabric, settling of the structure, changes carried out by the occupants and general wear and tear during use, particularly of the doors and windows.

Before any general conclusions can be drawn from these results they will need to be substantiated by further work and if possible related to form of construction. Nevertheless there is a clear indication that the interpretation of whole house air leakage measurements should take into account the time when the measurements are made.

(iv) Distribution of airleakage between components

A useful indication of the distribution of leakage between components may be obtained by expressing, at a common applied pressure of 50 Pa, the leakage of each component, obtained either by individual measurement or selective sealing during whole house tests, as a proportion of the total leakage at the same pressure. Figure 2 shows a typical example obtained for House 18. The proportions of the air leakage at 50 Pa attributable to background air flow paths, ie not through identifiable flow paths such as gaps around windows and doors, have been measured for the houses in Table 1 and are included as percentages in the Table. The average value is approximately 60% with a range from 40 to 80%.

Although expressing air leakage in this way emphasises the importance of background leakage some care should be taken in placing too much importance on detailed figures, bearing in mind the qualifications concerning the technique expressed in Section 3.1. The overall air leakage is an aggregate of many individual leakage paths with different values of the exponent, n. Components with higher values of n will be more dominant at the higher end of the pressure difference range. This is illustrated in Figure 3 which shows the percentages of the overall air leakage flow attributable to windows, doors, and background flow paths over a range of applied pressure difference from 5 Pa to 50 Pa, for House 17 in Table 1. Whereas at 50 Pa the background areas contribute 54% of the leakage, at 5 Pa the proportion is reduced to 27%.

4.3 Tracer gas measurements

(i) Method

Measurements were made of whole house and individual room ventilation rates using the exponential decay technique described in Section 3.2. Nitrous oxide was used as the tracer gas and its concentration was measured using an infra-red gas analyser. Simultaneously with the tracer gas concentration wind speed and direction, were measured using a lightweight cup anemometer and wind vane mounted on a 10 m high mast at a suitable position near the house under test, and together with internal and external air temperatures were recorded and automatically logged on to paper tape. This was subsequently processed on an ICL 1905 mainframe computer to calculate the ventilation rate, R, and the mean wind speed, U , wind direction, ϕ, and average temperature difference between inside and outside air, ΔT, for each test.

The whole house ventilation rates were obtained by the expedient of artificially mixing the air within the house using fans mounted in the open doorways, thus effectively reducing the house to a single 'cell'. The results are therefore representative of conditions of use when internal doors are normally kept partly open, or present very little resistance to flow. The results are likely to slightly overestimate the actual rates in occupied house in which the internal doors are kept closed. Individual room rates, determined by the decay rate technique, must be interpreted with care since, as noted in Section 3.2(iii) the incoming air may enter from other parts of the building as well as from outside.

(ii) Whole house ventilation rates

In order to indicate the general magnitude and range of whole house ventilation rates found in practice the results of 430 measurements in 25 different houses have been aggregated and presented in the form of a histogram in Figure 4a. The mean ventilation rate is 0.7 ach. Additional information is obtained from the cumulative frequency diagram, Figure 4b which shows that the median value is 0.6 ach and that a ventilation rate of 1.3 ach is exceeded only on 10% of occasions. In view of the substantially lower air leakage in Swedish housing it is of interest to compare these results with a similar analysis of results reported by Kronvall(20) of 97 measurements in 70 different houses. These lead to a mean value of 0.16 ach, a median of 0.14 ach and a rate of 0.3 ach exceeded on 10% of occasions.

Aggregating the results, however, obscures the effects of the individual factors, outlined in Section 2, which influence natural ventilation rates. The results for individual houses may be characterised by fitting regression lines to the data. Various combinations of the main meteorological variables, U , ΔT, and ϕ have been considered by previous workers. In general wind speed has been found to be the dominant variable and for present purposes the results for each house have been fitted to wind speed by simple regression analysis. Cases with significance levels less than 5% were rejected. The resulting regression equation enables the ventilation to be determined for any chosen wind speed and the values at the mean wind speed for each site have been calculated. These are listed in Table 1 for comparison with the leakage measurements. For the full sample of houses which satisfied the significance criterion, the mean value was found to be 0.74 ach with a range from 0.36 to 1.70 ach.

Another approach to the analysis of the results which yield more information is to isolate the results for each house which are dominated by wind or by stack effect. Using a simple single cell model it is shown in reference (21) that this may be achieved by plotting the results in the form $(Q/\Delta T^n)$ against $(U^{2n}/\Delta T^n)$. Those measurements which are substantially dominated by stack effect will lie in the range, for two storey houses,

$$0 \leqslant \left[\frac{U^{2n}}{\Delta T^n}\right] < 0.3$$

and those dominated by wind will lie in the range,

$$\left[\frac{U^{2n}}{\Delta T^n}\right] > 1.5$$

As an example of this approach the results of the whole house ventilation rate measurements for house 6 have been analysed and the wind dominated results identified. Since for any specific house these are a function of wind direction and wind speed only, plotting (Q/U^{2n}) against ϕ, will indicate the variation of ventilation rate with wind direction. This has been done and results shown in Figure 6. House 6 is in the centre of a row of terraced houses and the results give a clear indication of the effect of wind direction for this building arrangement. Ventilation rate, at a given wind speed, with the wind perpendicular to the row of houses is twice that when the wind is parallel to the row.

TABLE 3 - Room Ventilation Rates at Mean Wind Speed for Different Types of Room Use

Room description	Number of rooms in the sample	Ventilation rates (ach)		
		Mean value	Range	
			Minimum	Maximum
Living room	16	0.89	0.24 -	1.64
Kitchen	17	1.43	0.43 -	3.50
Bathroom	18	1.81	0.25 -	3.19
Large Bedroom (Volume $\geqslant$ 15 m^3)	29	0.65	0.25 -	1.19
Small Bedroom (Volume < 15 mm^3)	14	0.87	0.28 -	2.90

(iii) Room ventilation rates

Room ventilation rates may be analysed in the same way as for the whole house results. Figure 5a for instance shows a histogram for large bedrooms (defined as those with a volume greater than 15 m^3) based upon 290 individual measurements in 25 houses. The associated cumulative frequency diagram is shown in Figure 5b. The mean ventilation rate is 0.73 ach, but the skewed nature of the distribution results in a median value of 0.55. A rate of 1.5 ach is exceeded in only 10% of cases. As with the whole house results the ventilation rate measurements for each room were fitted to wind speed by a simple regression analysis. Results with a significance level of less than 5% were rejected and the subsequent regression lines were used to calculate the ventilation rate for each room at the appropriate site mean wind speed. The mean values of ventilation rate for each type of room are shown in Table 3.

4.4 Comparison of pressurisation and tracer gas measurements

Although the tracer gas technique provides a direct measurement of natural ventilation rate considerable effort is required to set up the associated equipment and to carry out the measurements. To obtain sufficient results to establish the variation of ventilation rate with the main climatic parameters takes a long time. The instrumentation is expensive and requires specialist knowledge to operate it. In contrast the equipment for whole house pressurisation measurements is relatively inexpensive, robust and requires little experience to use. Measurements can be made in a few hours. Its usefulness would be considerably enhanced if it can be demonstrated that the natural ventilation rate of a dwelling can be related to leakage characteristics. The measurements, using both types of equipment in a range of houses, which have been briefly described in this paper offer an opportunity for testing this proposition.

One possibility is to compare the whole house leakage rate, Q_T, measured at 50 Pa, with a suitably chosen ventilation rate. For this purpose the simple regression fit against wind speed may be used for those cases where the significance levels were better than 5%. Using this to obtain the ventilation rate correspondingly to a standard wind speed of 3.5 m/s (this is approximately the mean wind speed at 10 m for most inland suburban sites in the United Kingdom) for each house these have been plotted against Q_T in Figure 7. The corelation is sufficiently encouraging to proceed to a more detailed analysis based upon the simple theoretical model discussed in reference (21).

5 CONCLUSIONS

1) Measurements in typical modern British housing indicate that average ventilation rates, with windows and other controllable openings closed lie in the range 0.3 to 1.7 ach with a mean value of 0.7 ach. The distribution of aggregated data from all houses gives a similar mean value of 0.7 ach and also indicates a median level of 0.6 ach and an upper decile value of 1.3 ach.

2) In comparison with housing in countries with much more severe winter climates British housing is much less resistant to air flow through the fabric and components. Swedish dwellings for instance, are three to four times tighter. However the levels of natural ventilation found in British houses are close to the minimum air requirements for fresh air supply. Any general reduction in air leakage, without alternative provision for fresh air supply could lead to an increase in problems such as condensation.

3) Pressurisation measurements indicate that a substantial proportion of the infiltration of air into a dwelling may take place through paths other than the cracks around windows and doors.

4) A comparison of pressurisation and tracer gas measurements indicates that the possibility exists for using the simple pressurisation leakage test as an indicator of the ventilation performance of a dwelling. Further research and theoretical analysis is, however, required.

ACKNOWLEDGEMENTS

The authors wish to thank their colleagues who contributed to the measurements described in this paper, in particular to Mrs L Parkins who was responsible for the component tests and much of the analysis of the results.

The work described has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

REFERENCES

1 Dick J B, The Fundamentals of Natural Ventilation of Houses, JIHVE, Vol 18, June 1950, p133-134.

2 Jackman P J, Natural Ventilation Principles in Design Proceedings, CIBS Symposium - Natural Ventilation by Design, Garston, December 1980.

3 Principles of Natural Ventilation. Building Research Establishment Digest 210, February 1978.

4 Etheridge D W and Nolan J A, Ventilation Measurements at Model Scale in a Turbulent Flow, Building and Environment, Vol 14, 1979, p53-64.

5 Potter I N, The Effect of Fluctuating Pressures on Natural Ventilation Rates, ASHRAE Transaction, Vol 685, 1979, Part 2, p445 ff.

6 Warren P R, Ventilation of Spaces with Openings on One Side Only, Proceedings International Symposium on Heat and Mass Transfer in Buildings, ICHMT, Dubrovnik, September 1977, Publ. Hemisphere Press Inc, Washington, USA.

7 Dick J B, Ventilation Research in Occupied Houses, JIHVE, Vol 19, October 1951, p306-326.

8 Brundrett G W, Ventilation: A Behavioural Approach, Energy Research, Vol 1, 1977, p289-298.

9 Etheridge D W, Crack Flow Equations and Scale Effect, Building and Environment, Vol 12, 1977, p181-189.

10 Van Gunst E and den Ouden H Ph L, Metingen aan de ramen in de proefwoningen (Measurements on the Windows of Experimental Houses), Organisatiecommissie Gezondheidstechniek TNO, Netherlands, Report No 56, October 1949. BRE Library Communication No 461.

11 Skinner N P, Natural Ventilation Routes and their Magnitude in Houses - Part II, Symposium - Controlled Ventilation, its Contribution to Lower Energy Use and Improved Comfort, Aston University, 24 September 1975.

12 Sherman M H, Grimsrud D T and Sonderegger R C, The Low Pressure Leakage Function of a Building. LBL Report, 1980.

13 Gale R, Ventilation Heat Loss - Outside in Gas Engineering and Management, Vol 19, 1979, No 11, p563-572.

14 Beach R K, Relative Tightening of New Housing in the Ottawa Area. National Research Council of Canada, Division of Building Research, Building Research Note No 148, June 1979.

15 Hildingson O and Holmgren S, Byggnaders Lufttathet - Undersokning och Utveckling av Matmoder (Airtightness of Buildings - Investigation and Development of Measuring Methods), Lund Institute of Technology, Sweden, Division of Building Technology Report 4:76, November 1976.

16 Kronvall J, Testing Houses for Air Leakage using a Pressurisation Method, ASHRAE Transactions, Vol 84, 1978, Part 1.

17 Colet P F, Frederikson E, Hoffman T and Madsen G, Boligers Luftskifte (Air Change in Dwellings), Byggeteknik Teknologisk Institut, Tastrup, Denmark, July 1976.

18 Grimsrud D T, Sherman M H, Blomsterberg A K and Rosenfeld A H, Infiltration and Air Leakage Comparisons - Conventional and Energy Efficient Housing Design, Proceedings International Conference on Energy Use Management, Los Angeles, October 1979.

19 Elmroth A and Logdberg A, Well Insulated Airtight Buildings - Energy Consumption, Indoor Climate, Ventilation and Air Infiltration, Proceedings of the 8th CIB Congress, Oslo, June 1980.

20 Kronvåll J, Airtightness - Measurements and Measurement Methods, Swedish Council for Building Research Report F8:1980.

21 Warren P R and Webb B C, The relationship between tracer gas and pressurisation techniques in dwellings. To be published in the Proceedings of the 1st Air Infilitration Centre Conference, Bracknell, October 1980.

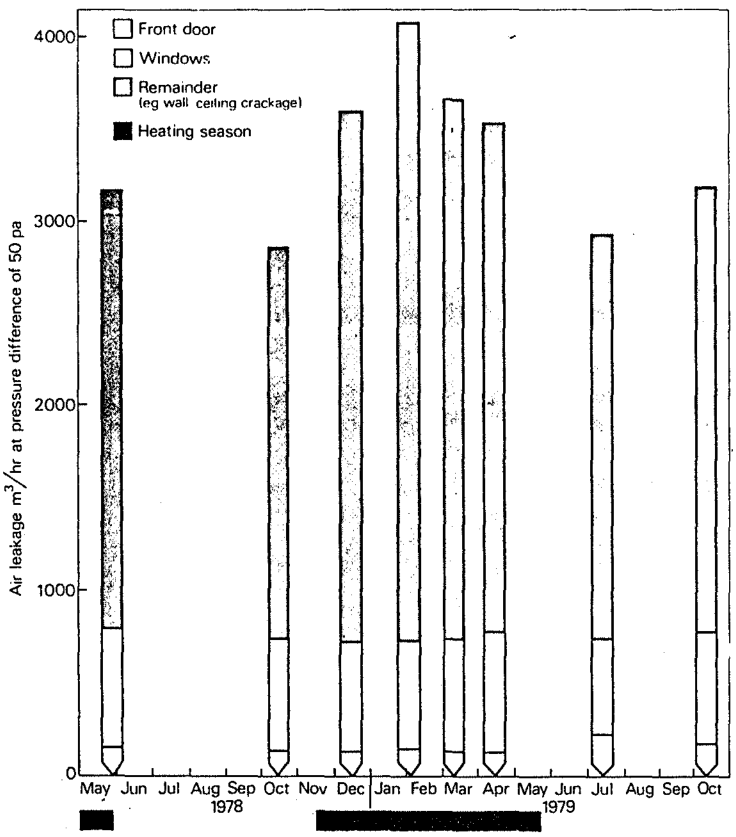

Figure 1. Seasonal Variation of Whole House Air Leakage at 50 Pa (House 11)

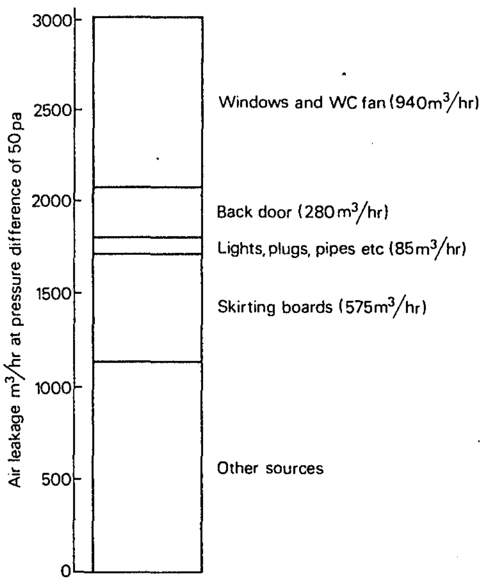

Figure 2. Distribution of Whole House Air Leakage between Components at 50 Pa (House 18)

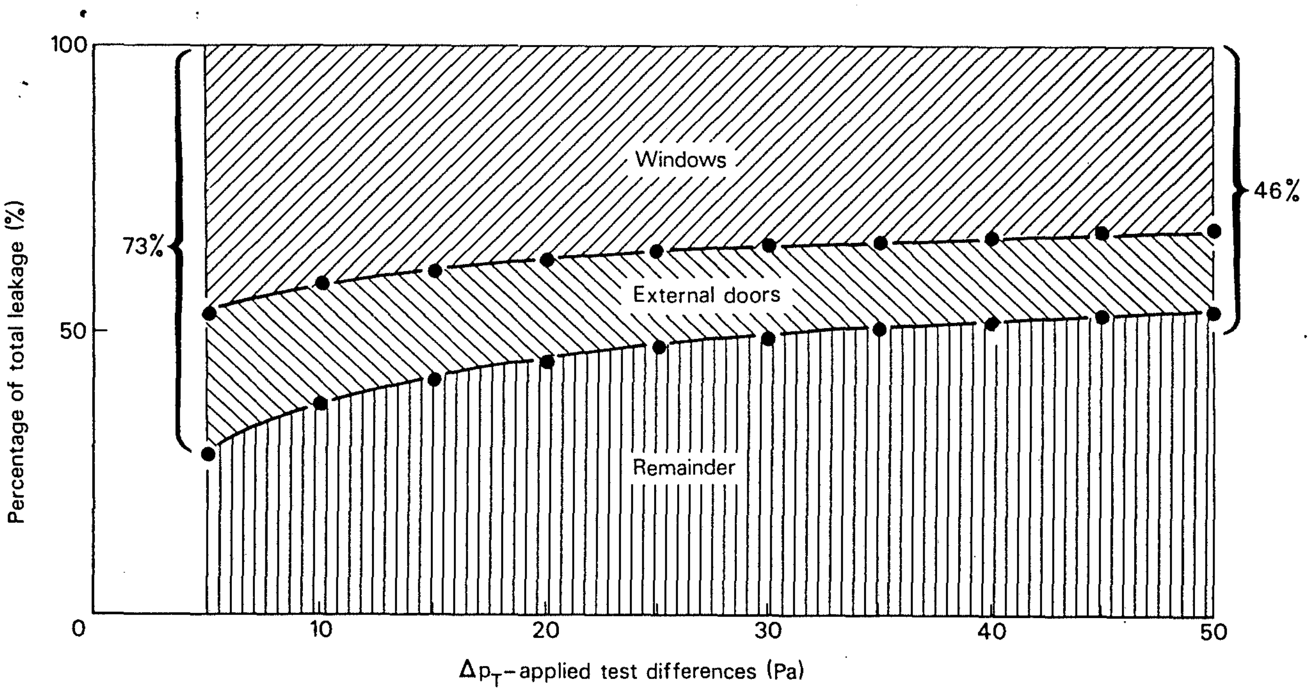

Figure 3. Variation of the Proportion of Whole House Air Leakage Attributable to Various Components with Applied Test Pressure (House 17)

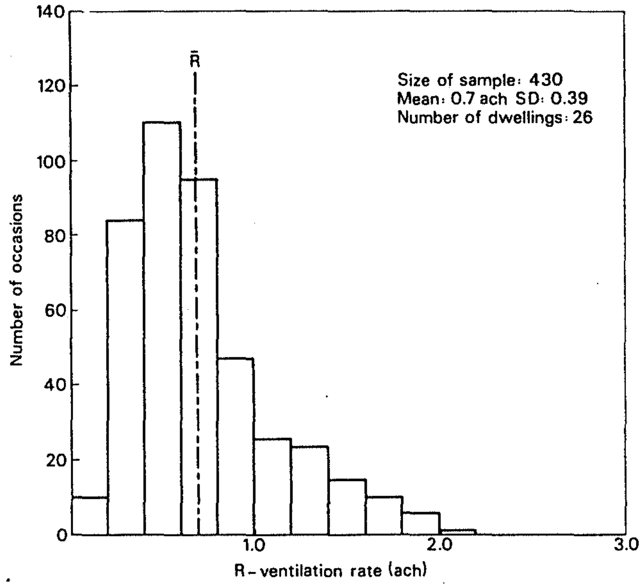

Figure 4a. Distribution of Whole House Ventilation Rates

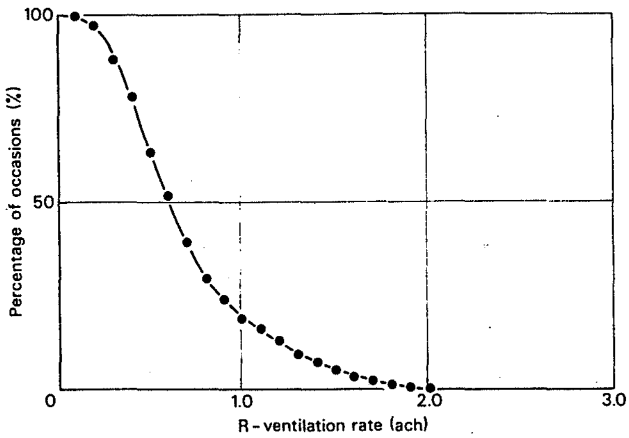

Figure 4b. Cumulative Frequency Diagram for Whole House Ventilation Rates

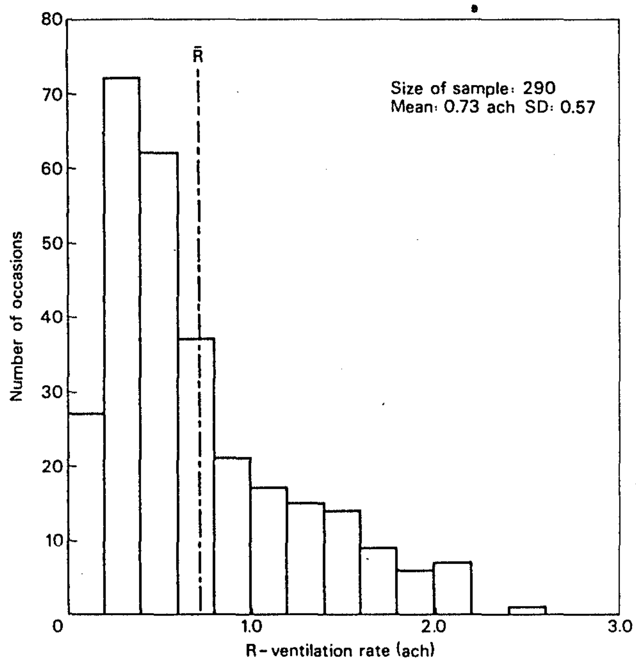

Figure 5a. Distribution of Ventilation Rates - Large Bedrooms

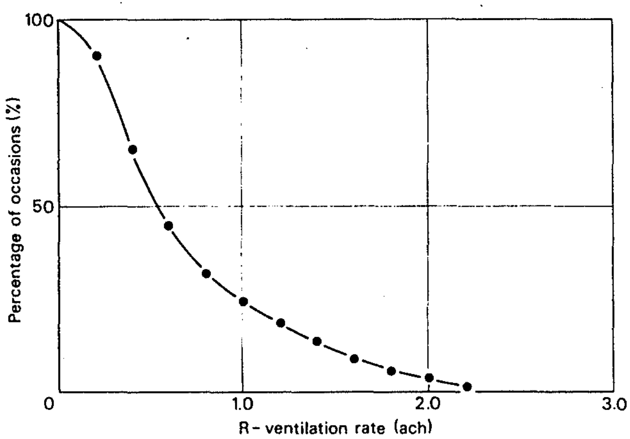

Figure 5b. Cumulative Frequency Diagram for Ventilation Rates in Large Bedrooms

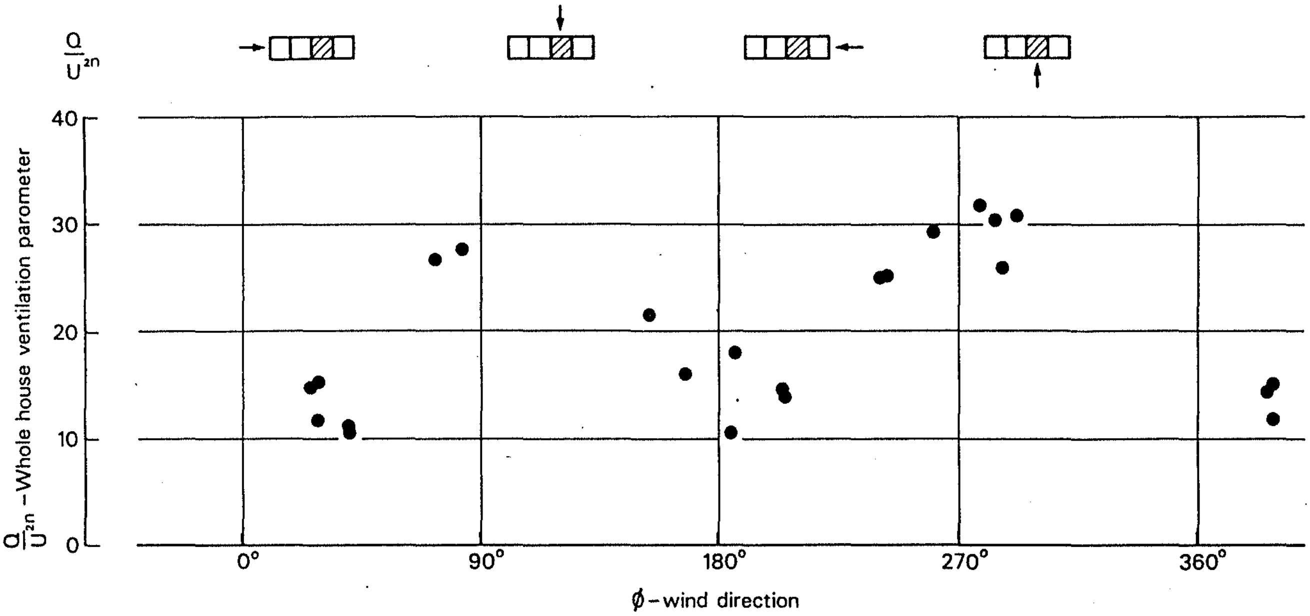

Figure 6. The Effect of Wind Direction on Whole House Ventilation Rate (House 6)

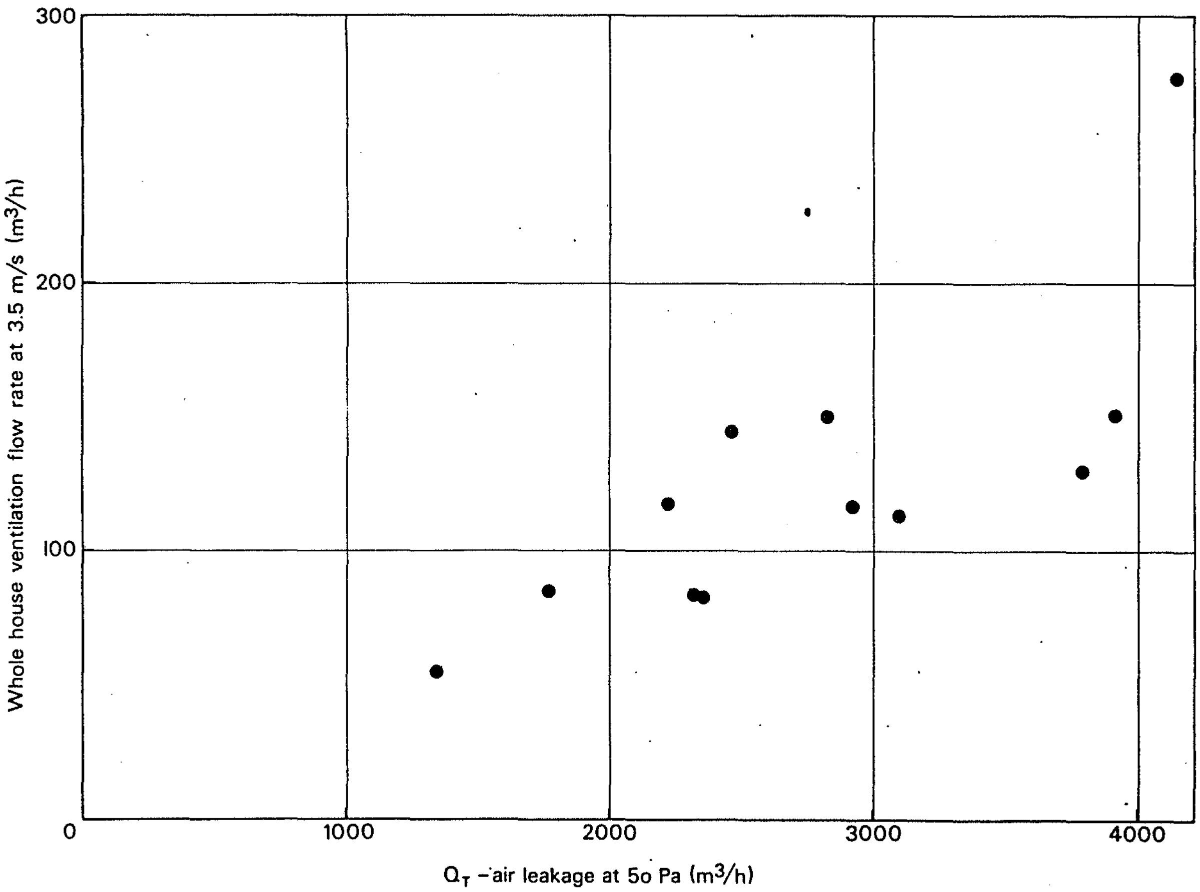

Figure 7. Variation of Whole House Ventilation Rate at a Wind Speed of 3.5 m/s with Air Leakage at 50 Pa