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INTRODUCTION

The majority of buildings, particularly in the domestic sector are naturally ventilated, yet natural ventilation and infiltration are among the last understood aspects of building design. The need for improved guidance has been emphasised by the drive to reduce energy consumption. The saving in energy achieved by reducing air infiltration must, however, be balanced by the need to ensure that indoor air quality remains satisfactory.

As a first step to providing a better understanding of natural ventilation in housing, measurements have been made of infiltration rates and the air leakage characteristics of the building envelope in a number of dwellings built within the last twenty years and covering a range of construction types. In this context infiltration rate is taken as the natural ventilation rate with variable openings, such as windows and doors, closed; a condition typical of most dwellings during the colder winter months. This paper proposes a method based upon a simple theoretical model for predicting the infiltration rate of a dwelling under specified meteorological conditions, given its leakage characteristics, built form and immediate surroundings. The measured results are used to test this method.

MEASUREMENTS

Infiltration rate

Infiltration rates for the whole dwelling and for individual rooms were measured using conventional tracer gas techniques, employing nitrous oxide as the tracer and infra-red gas analysis for determining concentration. Measurements were undertaken in 38 dwellings, of which those in 13 were

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A Simple Method for Predicting Infiltration Rates in Housing

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ABSTRACT

This paper proposes a simple equation, derived using a more complex theoretical model, for use in the prediction of the infiltration performance of houses over a range of meteorological conditions. Initial comparisons have been made with the results from field measurements in a range of typical modern UK house types.

made under contract by the Building Services Research and Information Association. Wind speed and direction, and external and internal air temperatures were recorded for each test. In order to obtain a reasonable range of these variables measurements were made over a three to four week period.

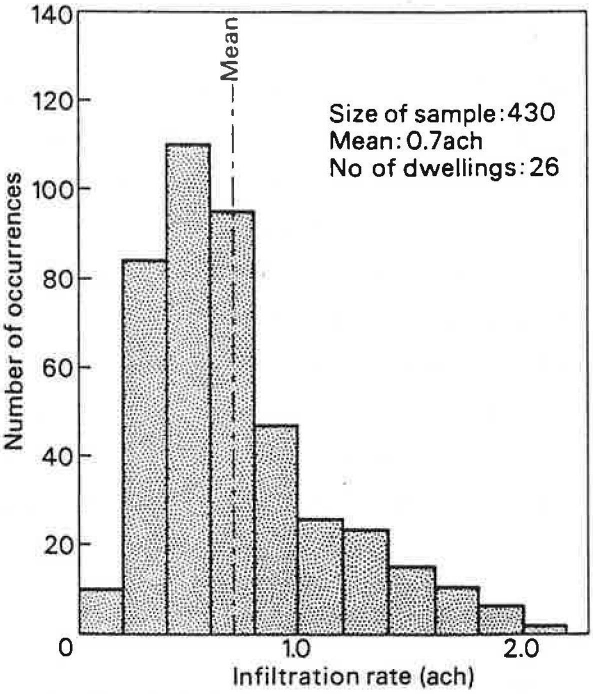

Figure 1 Distribution of whole house infiltration rates measured in 26 dwellings

To illustrate the general magnitude and range of whole house infiltration rates, the results of 430 individual measurements made in 26 of the houses have been aggregated and presented in the form of a histogram in Figure 1. The mean infiltration rate is 0.7 and the median 0.6 air changes per hour. An infiltration rate of 1.3 was exceeded in only ten percent of cases.

Further details of the measurements, results and their analysis are given in reference (1).

Leakage characteristics

A major factor which contributes to the magnitude of infiltration rate is the 'leakiness' of the building envelope. Air flows through a multiplicity of paths, some of which are recognisable, like the cracks around openable windows and doors, but many are not obvious and may be quite complex. The overall leakage characteristics can be determined by applying a uniform positive or negative pressure difference across the envelope using a large fan sealed into an external door frame, and measuring the total volume flow rate. Overall leakage measurements were made over a range of pressure differences from about -60 to +60 Pascals. A simple power law of the following form was fitted to the results:

$$Q = Q_T \left[\frac{\Delta p}{\Delta p_T} \right]^n \qquad (1)$$

Q is the volume flow rate of air at the applied pressure difference Δp. Q_T is the flow rate at an arbitrarily chosen reference pressure difference Δp_T. For present purposes a value of 50 Pascals has been used to conform with many other published results. Q_T is a convenient measure of the leakiness of a dwelling and Figure 2 indicates this leakage rate, expressed in air changes per hour by dividing by the volume of the dwelling, for 19 of the houses. Similar results obtained for Canadian (3) and Swedish houses (4), shown in Figure 2 are indicative of the relationship between building tightness and severity of climate.

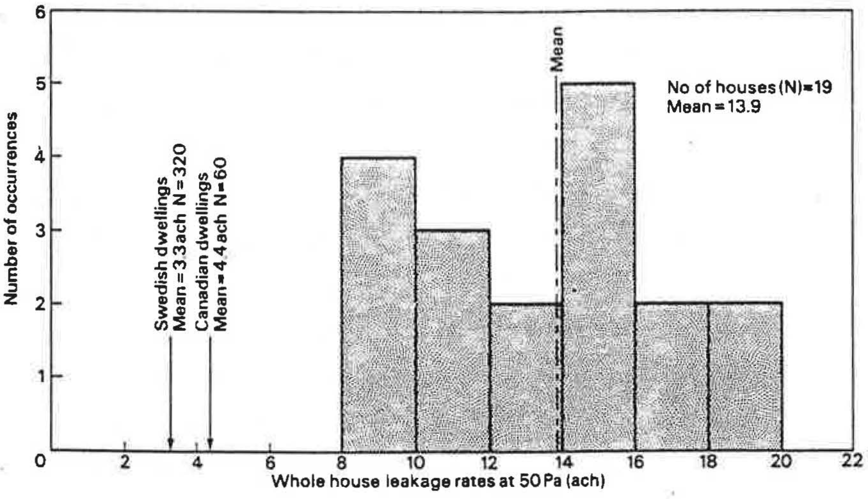

Figure 2 Distribution of whole house leakage rates in 19 of the dwellings

The fraction of the air leakage at any chosen pressure difference which may be attributed to particular components, such as windows and doors, may be determined from the individual leakage characteristics obtained either by selective sealing or by using a portable 'pressure box' rig. At 50 Pascals it was found that a relatively small proportion of the flow passed through the conventionally accepted leakage paths and on average approximately 60 per cent was attributed to 'background' leakage through less obvious paths.

required by convention for defining the surface pressure coefficients generated by the wind. The appropriate value of wind speed is given by

$$U = U_r \left[\frac{H}{H_r} \right]^{\alpha} \qquad (2)$$

where U_r is the reference site wind speed for the measurements and α depends upon the nature of the local terrain, as described in reference (5). Reference (5) also enables U to be calculated from standard Meteorological Office wind speeds for design purposes.

(ii) The pressure generated by the wind is uniform across each surface. The values for each surface will depend upon the building shape, its orientation to the wind and any surrounding obstacles, including other houses.

(iii) Air leakage through the envelope is assumed to be uniformly distributed across each surface, but the total leakage Q_T may be distributed in any chosen proportions among the surfaces.

(iv) The exponent, n, is assumed to apply to all leakage paths.

(v) Party walls and solid floors are assumed to be impermeable.

(vi) If the underfloor space is ventilated the assumed surface pressure is obtained by determining the area weighted mean of the pressures on exposed vertical walls.

Infiltration Rate Functions F_V, F_W and F_B

The derivation of the model is described in reference (2).
Three relationships are obtained. The first concerns the infiltration flow rate Q_V which is given by

$$Q_V = Q_T\left[\frac{\rho_o U^2}{\Delta p_T}\right]^n \cdot F_V\ (Ar,\phi) \tag{3}$$

F_V may be calculated if the following are known:

(i) The surface pressure coefficients as functions of ϕ. The surface pressure coefficient C_{pi} for any surface, i, is defined as

$$C_{pi} = \frac{(P_i - P_o)}{\frac{1}{2}\rho_o\ U^2} \tag{4}$$

Surface pressure coefficients are most accurately obtained from wind tunnel model studies of the building under consideration. Approximate values are available for simple building shapes, for instance in the British Standard Code dealing with Wind Loads (6).

(ii) The Archimedes number Ar. This relates buoyancy and inertial forces and in this contect is defined as

$$Ar = \left\{\frac{\Delta T.g.h}{T_I\ U^2}\right\}$$

(iii) The distribution of the leakage among the exposed surfaces.

Thus, given either measured or estimated values of the surface pressure coefficients and the distribution of leakage, F_V, and hence Q_V, may be obtained for any combination of values of U, ΔT and ϕ.

When the wind acts alone, the resulting infiltration flow rate, Q_W, may be derived from the model:

$$Q_W = Q_T\cdot\left[\frac{\rho_o U^2}{\Delta p_T}\right]^n \cdot\ F_W(\phi) \tag{5}$$

Similarly when stack effect acts alone, the resulting infiltration rate, Q_B, is given by

$$Q_B = Q_T \left[\frac{\Delta T . \rho_o \, gh}{T_I \Delta p_T} \right]^n . F_B \qquad (6)$$

Values of F_V, F_W and F_B

The function F_B is determined by the building shape and the distribution of leakage among the exposed external surfaces. F_W in addition depends upon the surface pressure coefficients which are determined by the shape of the building, its surroundings and the wind direction. F_V includes the effects of the major weather-dependent parameters U and ΔT, which are excluded from F_B and F_W.

In order to demonstrate the expected variation of F_B and F_W with building parameters and wind direction values have been calculated for three standard two-storey house types - (a) detached, (b) semi-detached and (c) centre terrace - using a standard square planform of area 45 m^2 and assuming an impermeable ground floor. In addition three values of n were used - 0.5, 0.6 and 0.7. (The range found for the 19 houses whose results are included in Figure 2 was 0.53 to 0.69, with a mean value of 0.60). With the further assumption that the leakage is uniformly distributed across the exposed external surface of the envelope, values of F_B have been calculated and are listed in Table 1. Additional information is required for F_W and for this purpose typical values of surface pressure coefficient have been taken from reference (6) for isolated buildings. These have arbitrarily modified by reducing them by 50% to account for

House type	n	F_B	$F_W(0^0$ wind)	$F_W(90^0$ wind)	$F_W(270^0$ wind)
Detached	0.5	0.26	0.12	0.14	----
	0.6	0.23	0.10	0.12	----
	0.7	0.20	0.08	0.10	----
Semi-detached	0.5	0.26	0.12	0.13	0.09
	0.6	0.23	0.10	0.11	0.06
	0.7	0.20	0.08	0.09	0.05
Centre-terrace	0.5	0.26	0.14	0.09	----
	0.6	0.23	0.12	0.07	----
	0.7	0.20	0.10	0.05	----

Table 1 Values of F_B and F_W for three house types

the presence of other local buildings, using wind tunnel data obtained by Lee et al (7). Values of F_W have been calculated for the three house types for wind directions parallel to the major building axes. Inspection of the results of the calculations indicate that F_B has a relatively small variation, whereas F_W shows a substantial variation, due to the effect of the variation of surface pressure coefficients, with built form and wind direction ϕ.

The calculated values of the function F_V have been plotted in Figure 4 for one example, the semi-detached house, in terms of F_B and F_W, using the dimensionless groups;

$$\left[\frac{F_V}{F_B} \cdot \frac{1}{(Ar)} n\right] \quad \text{and} \quad \left[\frac{F_W}{F_B} \cdot \frac{1}{(Ar)} n\right]$$

The variation with wind direction is small. Reference (2) shows that similar curves result for the other house types. Further, the following

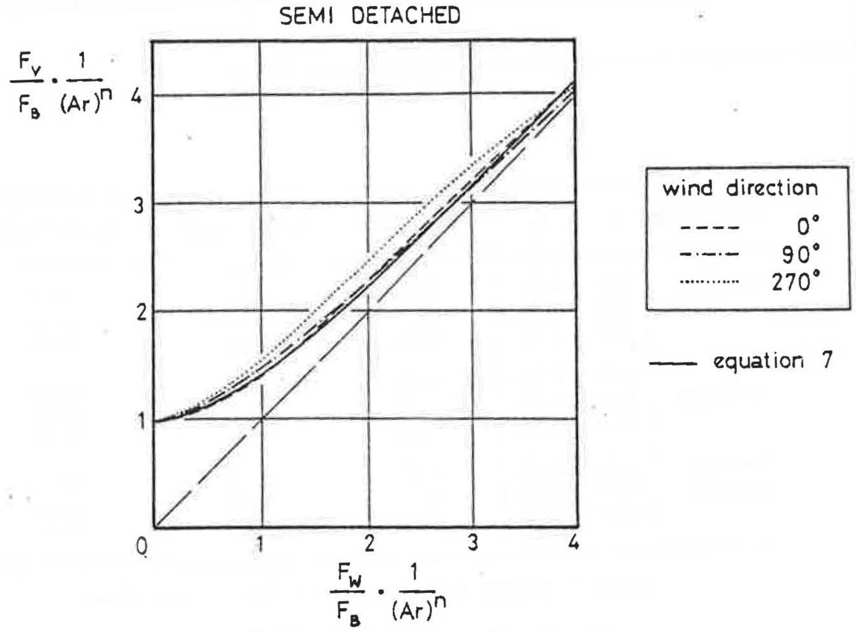

Figure 4 Variation of (F_V/F_BAr^n) with (F_W/F_BAr^n) for three wind directions relative to the front face; –0, 90 and 270°; detached house; $n = 0.6$

simple quadrature expression fits the results shown in Figure 4 with a reasonable degree of accuracy;

$$\frac{F_V}{F_B}\cdot\frac{1}{Ar^n} = \left[1+\left[\frac{F_W}{F_B}\cdot\frac{1}{Ar^n}\right]^2\right]^{\frac{1}{2}} \qquad (7)$$

PREDICTION OF INFILTRATION RATE

Given the leakage data for a house, together with its dimensions, the mean surface pressure coefficients for the expected range of wind directions and, if possible, the distribution of leakage among the exposed surfaces, then the infiltration rate may be calculated using F_V for any combination of wind speed, wind direction and temperature difference. The meteorological data can be presented either in statistical form or as a continuous series for a given period of time.

Alternatively the close correlation between the predictions given by the model and the expression given by equation (7) suggest that the latter could be used to provide a simpler approach. If equation (7) is expanded using the expressions defining F_V and Ar and rearranged the following equation for predicting Q_V is obtained;

$$Q_V = Q_T \cdot \left[\beta^2 . F_B^2 . (\Delta T)^{2n} + \gamma^2 F_W^2 . (U)^{4n} \right]^{\frac{1}{2}} \qquad (8)$$

where,

$$\beta = \left[\frac{\rho_o . g . h}{\Delta P_T . T_I} \right]^n ; \qquad \gamma = \left[\frac{\rho_o}{\Delta P_T} \right]^n$$

The advantage of this equation is that it separates the major weather-related variables, U and ΔT, from the building characteristics. Thus for a given house, β and γ may be readily calculated once and for all from the leakage characteristics and the height, h. F_B and F_W may be calculated from the distribution of leakage and variation of surface pressure coefficients with wind direction ϕ, when these are known. Alternatively tables of F_B and F_W could be constructed using the proposed theoretical model, or as will be seen subsequently from measured data. The user would choose values appropriate to the house under consideration, given its form, surroundings and expected leakage distribution. Substitution in equation (8) then allows the infiltration rate to be calculated for any given values of U and ΔT.

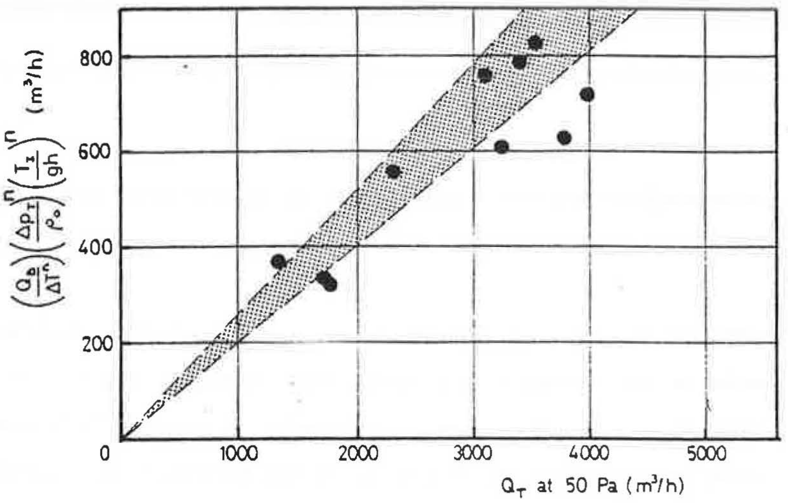

Figure 5 Comparison of measured values of F_B with the predicted range (shaded area)

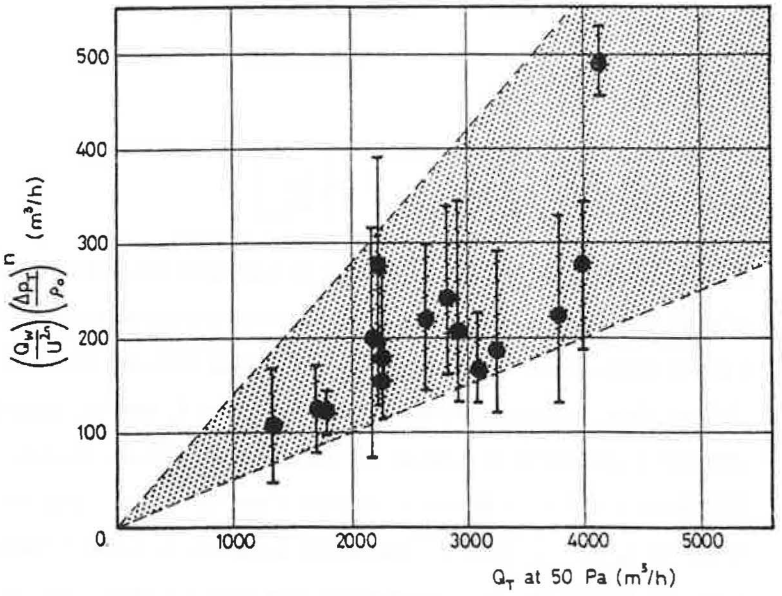

Figure 6 Comparison of measures ranges of F_W with the predicted range (shaded area)

The main bar to producing tabulated data lies in the current dearth of data on surface pressure coefficients for typical housing arrangements.

COMPARISON OF FIELD MEASUREMENTS WITH MODEL PREDICTIONS

As a first step to comparing the results of field measurements with the values predicted by the model only F_B and F_W will be considered. The aim is to determine how well the values of F_B and F_W derived from field measurements agree with those given in Table 1.

In reference (2) the criteria are derived for enabling measured results dominated either by stack effect or by wind to be isolated. Data sets which fulfilled the specified criteria were identified and values of the following groups calculated;

For stack dominated infiltration:

$$\left\{ \left(\frac{Q_V}{\Delta T^n}\right) \left(\frac{\Delta P_T}{\rho_o}\right)^n \left(\frac{T_i}{gh}\right)^n \right\}$$

and, for wind dominated infiltration:

$$\left\{ \left(\frac{Q_V}{U^{2n}}\right) \left(\frac{\Delta P_T}{\rho_o}\right)^n \right\}$$

From equations (5) and (6) it can be seen that when divided by Q_T these quantities should give values of F_B and F_W respectively. In order to compare these measured results with those calculated using the model, mean values for each house of the quantities given above have been plotted against Q_T in Figures (5) and (6) for stack effect and wind effect respectively. For comparison the expected spread of the results due to the variation of F_B with n, and of F_W with n and ϕ has been indicated by the shaded regions on each figure. The results for the stack effect comparison are very encouraging. For the values of F_W both the mean for each house and the range of values have been plotted. Again the range of experimental values falls within the region predicted by the model. It should be noted that the theoretical results are limited to the standardised house types given earlier and not specifically matched to each of the houses tested. Further, the leakage area has been assumed to be uniformly distributed over the exposed area of the envelope. Detailed analysis is being undertaken to compare the measured results with predicted values specific to each site.

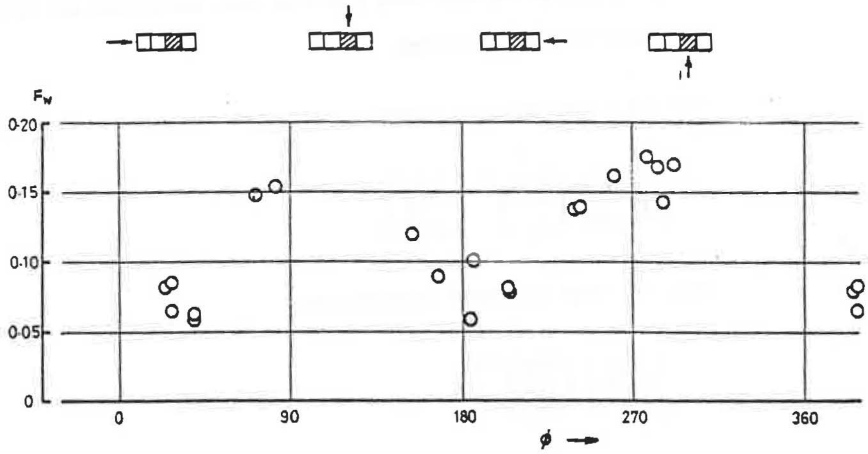

Figure 7 Measured variation of F_W with wind direction, ϕ, for a centre-terraced house

Where sufficient results exist it is possible to determine experimentally the form of F_W as a function of wind direction ϕ for a given house. Figure 7 illustrates such a case. The measuremnts were made in a centre terrace house and exhibit a substantial variation with wind direction. As expected, for a given wind speed, infiltration rate with the wind perpendicular to the terrace is substantially higher than with the wind parallel to the terrace.

CONCLUSIONS

On the basis of a theoretical model a simple method has been proposed for predicting the infiltration performance of houses. Initial comparisons with measured data are encouraging, but further more detailed comparisons are necessary and improved data on surface pressure coefficients on typical housing arrangements are required to give full confidence in its use.

ACKNOWLEDGMENTS

This paper is based upon two previous papers by the Author and listed as references (2) and (8) below.

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CHAIRMAN'S SUMMARY

Opening Remarks

As insulation levels increase and system design improves, the energy load due to infiltration becomes increasingly more important. Becuase of the inherent non-linearities, infiltration is much more difficult to predict than thermal performance, but it is, nevertheless, true that an increase in air tightness will decrease infiltration. An extreme reduction in infiltration, however, may cause undesirable indoor air quality problems, unless additional ventilation is supplied.

Current research in these areas of infiltration and ventilation divides itself into several identifiable topics:

- Direct measurement of infiltration for both single zone and multi-zone situations.
- Prediction of infiltration and ventilation using air tightness, weather and systems data.
- Occupancy and control effects.
- Indoor air quality assurance.
- Ventilation effectiveness.

The papers in this session will address all of these topics and should lead to informative discussion.

Summary and Closing Remarks

Several of the papers dealt with the prediction of ventilation in single zone situations. All of the models used some measure of air tightness, shielding and terrain factors, stack effect parameters, and wind and temperature differences. The consensus appeared to be that for most purposes ventilation could be adequately predicted using simple air tightness values and meteorological data. The superposition of infiltration flows from different sources (i.e. wind and stack effects) was discussed and it was felt that quadrature was the most appropriate.

The relatively new topic of local ventilation and ventilation efficiency provoked some discussion. These topics are especially important to the transport and removal of pollutants within the occupied space. The measurement technique of multiple tracer gases for multichamber infiltration is appropriate for these considerations. Particular examples of ventilation problems and solutions were presented in the papers from Finland, Sweden and U.K.

As evident from the discussion, international cooperation and sharing of information can be an extremely important part of any research programme. In the field of infiltration this effort is aided by the Air Infiltration Centre, which is a centre for the research and information on air infiltration and ventilation, operated by annex five of the International Energy Agency. The AIC also maintains bibliographic and numerical databases and many of their publications, including their quarterly newsletter, are available to non-participants. Such international forums as the AIC and this special session of the CIB have and will continue to have a positive impact on research in the fields of air infiltration and ventilation and energy conservation in the built environment.