PAPER 15

THE RELATIONSHIP BETWEEN TRACER GAS AND PRESSURIZATION TECHNIQUES IN DWELLINGS

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by P R Warren and B C Webb

1 INTRODUCTION

Two main methods are currently in use for measuring the infiltration performance of dwellings, tracer gas techniques for determining infiltration rate and pressurisation techniques for measuring the leakage characteristics of the envelope. The infiltration rate is of most interest since it enables the related heat loss to be calculated, and, since the majority of dwellings are naturally ventilated, it also enables possible levels of internal airborne contaminants to be determined. Pressurisation techniques are limited to providing data on the magnitude and the distribution of airflow paths through the building envelope. However pressurisation techniques possess certain advantages; the necessary equipment is relatively cheap, robust and easily operated and the time required on site is short. In contrast, tracer gas measurements require considerable expertise, expensive equipment and are time-consuming, if the full range of variables which affect infiltration are to be included.

The usefulness of pressurisation techniques could be considerably enhanced if a method of linking the results achieved with their use to infiltration rates could be identified and established. The purpose of this paper is to propose such a method, based upon a simple theoretical model of infiltration, and to discuss its validity using whole house pressurisation

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and infiltration measurements made as part of field survey of infiltration rates in British dwellings.

2 FIELD MEASUREMENTS

2.1 Pressurisation measurements

Table 1 includes brief details of fifteen houses in which whole house pressurisation measurements were made as part of a larger survey of infiltration and natural ventilation in dwellings. These are labelled A to P for purposes of easy reference. In addition published data on two other dwellings have been taken from references (1) and (2). These dwellings are labelled R and S respectively.

Pressurisation measurements of the air leakage through the envelope of each house was made using the equipment developed and described by Skinner(3). Measurements were made for both positive and negative applied pressure difference across the dwelling envelope, over a range of 10 to 60 Pa. 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 an applied pressure difference Δp. Q_T is the flow rate at a chosen reference pressure Δp_T. This may be arbitrarily chosen, but for present purposes the value 50Pa will be used to conform with current Swedish practice(4). The values of Q_T and n are listed in Table 1. Also listed for comparison with other published results are the corresponding values of (Q_T/V) and (Q_T/A_p) where V and A_p are the volume and permeable area of each dwelling.

The permeable area is defined as the sum of the areas of the exposed walls, the ground floor, provided that this is not solid, and the area of the ceiling between the topmost floor and the roof space. Party walls in semi-detached and terraced houses are assumed to be impermeable. For all of the results given in Table 1 windows, doors and other controllable openings were fully closed. Extract fans were switched off and their openings sealed.

It is interesting to note that values of (Q_T/V) are substantially larger than the average values found in recent Swedish(5) and Canadian(6) surveys which were 3.5 ach and 4.4 ach respectively.

2.2 Tracer gas measurements

Whole house tracer gas measurements were made in all of the listed houses. In houses A to R nitrous oxide was used as the tracer gas and its concentration monitored using an infra-red gas analyser. All internal doors were set open and fans placed in the open doorways in order to mix the tracer gas throughout the house. The ventilation rate measured is the ratio of the flow rate of air entering the house to the volume of the house. This should be typical of the ventilation rate under normal occupied conditions provided that internal doors are either kept open or present little resistance to flow in comparison with the air leakage paths in the external envelope.

On average approximately twenty measurements of whole house ventilation rate were made. Wind speed and direction were monitored throughout each test period using a lightweight anemometer and windvane mounted on a 10 m high hydraulic mast, situated close to, but not in the immediate flow field of, the house under test. Air temperatures were measured in each room, as well as externally, using calibrated thermocouples. The output from each of the instruments was recorded, via a data logger, on paper tape for subsequent analysis by mainframe computer. The resulting output consisted of the ventilation rate during the test period (usually of the order of thirty minutes), the average wind speed and direction and the average temperatures as well as measures of the variation of each of these quantities over the period.

3 PROBLEMS IN RELATING TRACER GAS AND PRESSURISATION MEASUREMENTS

3.1 Limitations of pressurisation techniques

(i) The magnitude of the pressure differences used in the pressurisation tests is necessarily higher than those normally generated by the wind and stack effect. The extrapolation of the applied pressure - flow rate relationship defined by equation (1) to lower applied pressures than those to which it was fitted currently lacks experimental validation.

(ii) The pressure differences generated across the building envelope by stack and wind effects are not applied uniformly as they are in the pressurisation technique.

(iii) The simple determination of Q_T and the exponent, n, does not define the distribution of Q_T. The same results would be obtained whether Q_T were lumped together on one external wall or whether it were evenly distributed over the whole envelope. Repeated measurements with chosen components sealed up gives additional information on the magnitudes and distribution of the openings, but removes some of the simplicity and ease of use which makes the technique attractive.

3.2 Choice of characteristic quantities

Further to the problems outlined above there is a difficulty in comparing pressurisation results for a given house with the results of the measurements of infiltration because of the number of variables involved. The results of the pressurisation tests are defined by two parameters, Q_T and n. Any measured value of infiltration rate, R, is a function of wind speed U, wind direction, ϕ, and the difference between internal and external air temperature, ΔT.

Clearly any method which aims to relate Q_T and Q_V, the infiltration flow rate, must also include the other variables if it is to be used as a basis for predicting the infiltration performance of a given dwelling. The following section outlines a simple theoretical model which aims to accomplish this.

4 A SIMPLE THEORETICAL MODEL FOR INFILTRATION

4.1 Assumptions made in setting up the model

The following assumptions are made in setting up the infiltration model:

(i) The building envelope is represented by a rectangular parallelipiped of height, h. This does not preclude the presence of a pitched roof, but is intended to define the volume of interest from the point of view of infiltration. The maximum overall height of the building, for instance to the top of a pitched roof, is H and is used to specify the air speed 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 (7). Reference (7) 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.

4.2 Infiltration rate functions F_V, F_W and F_B

The derivation of the model is summarised in Appendix 1. Three relationships are obtained. The first concerns the infiltration flow rate Q_V which is given by

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

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

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

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(8).

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

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

The Archimedes number combines the two main meteorological variables U and ΔT, as well as the height, h, defined previously.

(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:

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

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

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

F_B is a constant for any given building and F_W is a function of wind direction only.

4.3 Typical values of F_V, F_W and F_B

In order to demonstrate the variation of the function F_V, F_W and F_B derived above with building characteristics values have been calculated for three typical housing types;

(a) Detached

(b) Semi-detached

(c) Centre terrace

The dimensions of the houses are shown in Table 2, together with appropriate pressure coefficients for a selection of wind directions obtained from reference (8). All three functions will vary with n. The calculations have therefore been carried out for three values of n - 0.5, 0.6 and 0.7, in order to cover the range found in practice (see Table 1). The leakage, Q_T, was assumed to be distributed uniformly over the whole of the exposed surface of the envelope in each case. The ground floor is assumed to be impermeable, except for the value of n = 0.6, where for purposes of comparison calculations were also made with a permeable floor.

The calculated values of F_W and F_B are given in Table 3(a). F_V is shown in Figures 1(a), (b) and (c). The axes have been chosen to give identical asymptotes for each set of values of F_V. Inspection of the results for F_W and F_B shows a negligible variation of F_B with house arrangement. There is some variation with n; a reduction of approximately 10% when n is raised from 0.6 to 0.7, and an increase of approximately the same amount when n is reduced from 0.6 to 0.5. There are substantial variations in F_W with wind direction ϕ for each house type.

5 COMPARISON OF FIELD MEASUREMENTS WITH MODEL PREDICTIONS

As a first step to comparing the results of the field measurements with the predicted values from the model only F_W and F_B will be considered. The aim here is to determine how well values of F_W and F_B derived from the field measurements agree with those given in Table 3(a).

In order to do this it is necessary to isolate those results which are dominated by either stack or wind effect. It is very rare to obtain measurements in the field where either effect is completely absent and it is necessary to establish some form of criterion by which to judge each set of results for a given house to determine whether it may fall into either of the categories required. An indication of a method of achieving this is contained in Figures 1(a) to (c). The ordinate in these figures is, in fact, (Q_V/Q_B) and the asymptote as $(F_W/F_B.Ar^n)$ tends to infinity is, $Q_V = Q_W$. A reasonable proposal is to set the limit for stack dominated infiltration as

$$\frac{Q_V}{Q_B} \leqslant 1.1$$

and for wind dominated infiltration,

$$\frac{Q_V}{Q_W} \leq 1.1$$

On rearrangement these lead to the following approximate criteria based upon the measured climatic variables,

Stack dominated infiltration: $U^{2n}/\Delta T^n \leq 0.3$

Wind dominated infiltration: $U^{2n}/\Delta T^n \geq 1.5$

On examining each set of results for the houses listed in Table 1 those sets which fulfil these criteria were extracted and used to calculate the following:

For stack dominated infiltration:

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

and, for wind dominated infiltration:

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

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, the quantities given above for each house have been plotted against Q_T in Figures (3) and (2) 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. Of the houses which lie outside the expected band it is suspected that the values of Q_T for K and J include some leakage through the party wall. This will be checked in a future series of measurements.

The results in Figure(2),for wind,are more scattered. This is,however, to be expected because of dependence of F_W on ϕ as well as n. Figure (4) shows the variation of F_W with ϕ for House F which is a centre-terraced house. It is interesting to note that the infiltration rate with the wind perpendicular to the terrace is considerably greater than when the wind is parallel.

Despite the scatter there is a trend for the values of F_W to lie below the region containing the expected range predicted by the theoretical model. However the pressure coefficients used, as given in Table 2, apply to buildings in isolation. All of the houses in which measurements were made had other buildings, as well as other forms of shelter such as trees and fences in their vicinity. Although detailed data on pressure coefficients other than for isolated buildings is sparse there is evidence, from both full scale(9) and model studies(10) of pressure distributions on low rise buildings, that the values for surface pressure coefficients are substantially reduced by the presence of other buildings of a similar height. Lee et al(10) have demonstrated that reductions of 50% in wall and roof pressure coefficients may be expected in housing of moderate density. The values of F_W given in Table (3a) have therefore been recalculated with the surface pressure coefficients arbitrarily reduced to half of their original value. The new range of predicted values of F_W is given in Table (3b) and shown on Figure (5). In place of the mean of the measured values of F_W the range is indicated by plotting the maximum and minimum value for each house. The agreement is very much better.

It should be noted that the theoretical results are limited to the house types and dimensions set out in Table 2, and not specifically matched to the dimensions of the houses tested. Further, the leakage area has been assumed to be uniformly distributed over the exposed surfaces of the envelope. Further analysis will be undertaken to compare each set of measured results with predicted values specific to each site. A major problem exists however in the lack of data on pressure coefficients for typical housing arrangements.

6 THE PREDICTION OF INFILTRATION RATES

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 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 F_B and F_W may be calculated and the larger of the two predicted ventilation rates taken. Another possibility which lies between these alternatives is to note that the following simple function fits the predicted results shown in Figures (1a), (1b) and (1c) with a reasonable degree of accuracy

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

On rearrangement this leads to

$$F_V = \left[(F_B . Ar^n)^2 + F_W^2 \right]^{\frac{1}{2}} \qquad (8)$$

7 CONCLUSIONS

The agreement demonstrated between the theoretical model and the data from measurements in seventeen houses gives confidence that the simple theoretical model may provide a means of estimating house infiltration rates using leakage data obtained from whole house pressurisation measurements. In addition, however, surface pressure coefficients for typical house shapes, arrangements and surroundings are also required but, at present, there is a dearth of data of this type.

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REFERENCES

1 Guillaume M, Ptacek J, Warren P R and Webb B C, Measurements of ventilation rates in houses with natural and mechanical ventilation systems. Proceedings of Meeting of CIB Steering Group S 17, Holzkirchen, September 1977

2 Dickson D J. Ventilation with open windows. Electricity Council Research Centre Memorandum ECRC/M1329, April 1980

3 Skinner N. Natural infiltration routes and their magnitude in houses - Part 2. Proceedings of Conference - Controlled Ventilation. Aston University, September 1975

4 Standard Method Description SP 1977:1. National Swedish Authority for Testing Inspection and Metrology

5 Kronvall J. Airtightness - measurements and measurement methods. Swedish Council for Building Research Report D8:1980

6 Beach R K. Relative tightness of new housing in the Ottawa area. National Research Council of Canada, Division of Building Research, Building Research Note No 149, June 1979

7 Principles of natural ventilation. Building Research Establishment Digest No 210, February 1978

8 Code of basic data for the design of buildings. Chapter V. Loading Part 2. Wind loads. British Standard CP3 : Chapter V : Part 2 : 1972

9 Eaton K J and Mayne J R. The measurement of wind pressures on two-storey houses at Aylesbury. Building Research Establishment Current Paper CP 70/74. July 1974

10 Lee B E, Hussain M and Soliman B. A method for the assessment of the wind-induced natural ventilation forces acting on low rise building arrays. Building Services Engineering Research and Technology (CIBS Series A), Vol 1, No 1, 1980

11 Blomsterberg A K, Sherman M H and Grimsrud D T. A model correlating air tightness and air infiltration in houses. Lawrence Berkel Laboratory Report, November 1979

12 Sherman M H and Grimsrud D T. Infiltration-pressurisation correlation: simplified physical modelling. Presented at ASHRAE Semi-annual Meeting, Denver, Colorado, June 1980

13 Cole J T, Zawacki T S, Elkins R H, Zimmer J W and Macriss R A. Application of a generalised model of air infiltration to existing homes. Presented at ASHRAE Semi-annual Meeting, Denver, Colorado, June 1980

14 Shaw C Y. Wind and pressures induced pressure differentials and an equivalent pressure difference model for predicting air infiltration on shcools. ASHRAE Translations, Vol 86, Part 1, 1980

15 Lindquist T and Bergenstjerna A. Vardering av lufttathet hos fonster (Assessment of airtightness of windows). Chalmers Tekniska Hogskola, Goteborg. Department of Building Construction, Report 1979:12

16 Warren P R. Natural ventilation routes and their magnitude in houses - Part 1. Proceedings of Conference - Controlled Ventilation, Aston University, September 1975

17 Warren P R. Ventilation of spaces with openings on one side only. Proceedings of International Conference on Heat and Mass Transfer in Buildings, Dubrovnik, September 1977. Publ Hemisphere Publishing Corporation, Washington DC

18 Mattingley G E, Harrje D T, Heisler G M. The effectiveness of an evergreen windbreak for reducing residential energy consumption. ASHRAE Transactions, Vol 85, Part II, 1979

NOMENCLATURE

A	Area
a	Substitution function (= $(C_{pi} - C_{pI})$)
b	Substitution function (= 2Ar)
C_p	Pressure coefficient
F	Infiltration function (suffices B, V and W)
g	Acceleration due to gravity
H	Height (suffix r)
h	Height of ventilated space
m	Number of vertical surfaces
n	Exponent of building leakage characteristic
p	Pressure (suffices i, I, L, U)
T	Absolute temperature
U	Wind speed (suffix r)
Q	Infiltration flow rate (suffices B, V and W)
V	Volume of ventilated space
w	Width of vertical surface
Z	Dimensionless vertical co-ordinate (= z/h)
z	Vertical co-ordinate
Ar	Archimedes No (= $\frac{\Delta T.gh}{T_I U^2}$)
α	Exponent for wind velocity profile
ρ	Density of air (suffices o, I)

Prefix:

Δ	Difference between two values of the same quantity

Suffices:

B,V,W	Relate to stack effect, combined effect and wind effect respectively
i	Number of a vertical surface
L,U	Relate to lower and upper surface respectively
o,I	Relate to inside and outside of the ventilated space
T	Relates to test reference condition for pressurisation tests
r	Relates to reference wind speed and height

TABLE 1 BASIC DETAILS AND LEAKAGE CHARACTERISTICS OF TEST HOUSES

HOUSE DATA				AIR LEAKAGE CHARACTERISTICS AT 50 Pa			
House	Date	Type	Volume m^3	Q_T m^3/h	n	(Q_T/V) ach	(Q_T/A_p) m^3/hm^3
A	1971	2 B	197	2310	0.57	11.7	12.4
B	1957	2 B	254	2210	0.69	9.7	11.7
C	1957	2 B	249	2910	0.55	11.7	16.6
D	1976	2 C	196	3090	0.64	15.8	23.3
E	1976	2 C	196	2810	0.57	14.4	21.2
F	1956	2 D	164	2210	0.67	13.5	22.2
G	1977	2 D	77	1330	0.58	17.3	40.2
H	1947	2 A	195	3530	0.61	18.1	19.3
I	1978	2 D	179	1760	0.58	9.9	13.9
J	1977	2 C	196	4130	0.64	21.8	31.5
K	1960	2 B	261	3780	0.58	14.5	22.5
L	1960	2 B	261	3990	0.58	15.3	23.5
M	1976	2 E	179	3400	0.53	19.0	39.2
N	1977	3 D	220	3240	0.63	14.7	32.6
P	1970	2 C	221	2310	0.58	10.4	17.3
Q*	1977	1 A	229	2640	0.63	11.6	14.9
R**	1977	2 A	260	1710	0.66	6.6	8.7

Notes: House type: 1, 2, 3 - number of storeys.
A - detached; B - semi-detached; C - end terrace;
D - centre terrace; E - quad.

* Reference (1). ** Reference (2).

TABLE 2 SURFACE PRESSURE COEFFICIENTS USED WITH THE INFILTRATION MODEL

Surface		Area m^2	House type: Detached		Semi-detached			Centre-terraced	
			0^owind	90^owind	0^owind	90^owind	270^owind	0^owind	90^owind
Wall	1	33.5	+0.70	-0.60	+0.70	-0.50	-0.50	+0.70	-0.50
	2	33.5	-0.60	+0.70	-0.70	+0.70	-0.10	--	--
	3	33.5	-0.25	-0.60	-0.30	-0.50	-0.50	-0.30	-0.50
	4	33.5	-0.60	-0.25	--	--	--	--	--
Roof		45.0	-0.35	-0.80	-0.35	-0.80	-0.80	-0.35	-0.80
Floor		45.0	-0.25	-0.25	-0.10	-0.10	-0.35	+0.20	-0.50

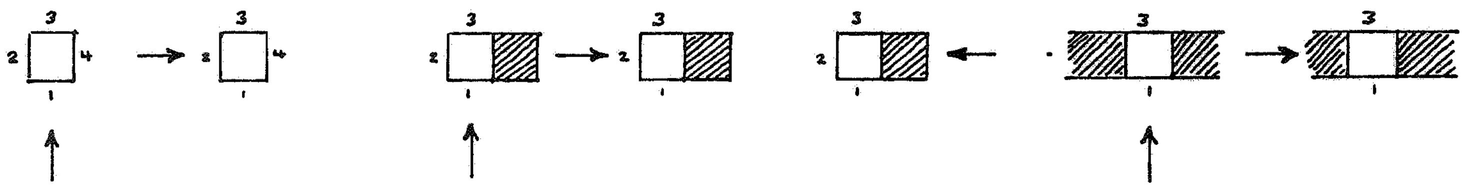

TABLE 3(a) VALUES OF F_B AND F_W CALCULATED USING THE PRESSURE COEFFICIENTS LISTED IN TABLE 2

House type	n	F_B (i)	F_B (ii)	F_W (0^o wind) (i)	F_W (0^o wind) (ii)	F_W (90^o wind) (i)	F_W (90^o wind) (ii)	F_W (270^o wind) (i)	F_W (270^o wind) (ii)
Detached	0.5	0.26	--	0.17	--	0.20	--	--	--
	0.6	0.23	0.26	0.15	0.13	0.18	0.16	--	--
	0.7	0.20	--	0.13	--	0.16	--	--	--
Semi-detached	0.5	0.26	--	0.16	--	0.18	--	0.12	--
	0.6	0.23	0.27	0.15	0.15	0.16	0.18	0.10	0.10
	0.7	0.20	--	0.14	--	0.15	--	0.08	--
Centre-terraced	0.5	0.26	--	0.20	--	0.13	--	--	--
	0.6	0.23	0.27	0.18	0.18	0.10	0.08	--	--
	0.7	0.20	--	0.16	--	0.08	--	--	--

TABLE 3(b) VALUES OF F_B AND F_W CALCULATED USING MODIFIED PRESSURE COEFFICIENTS

House type	n	F_B (i)	F_B (ii)	F_W (0^o wind) (i)	F_W (0^o wind) (ii)	F_W (90^o wind) (i)	F_W (90^o wind) (ii)	F_W (270^o wind) (i)	F_W (270^o wind) (ii)
Detached	0.5	0.26	--	0.12	--	0.14	--	--	--
	0.6	0.23	0.26	0.10	0.08	0.12	0.11	--	--
	0.7	0.20	--	0.08	--	0.10	--	--	--
Semi-detached	0.5	0.26	--	0.12	--	0.13	--	0.09	--
	0.6	0.23	0.27	0.10	0.10	0.11	0.12	0.06	0.07
	0.7	0.20	--	0.08	--	0.09	--	0.05	--
Centre-terraced	0.5	0.26	--	0.14	--	0.09	--	--	--
	0.6	0.23	0.27	0.12	0.12	0.07	0.05	--	--
	0.7	0.20	--	0.10	--	0.05	--	--	--

* (i) - impermeable ground floor ; (ii) - permeable ground floor

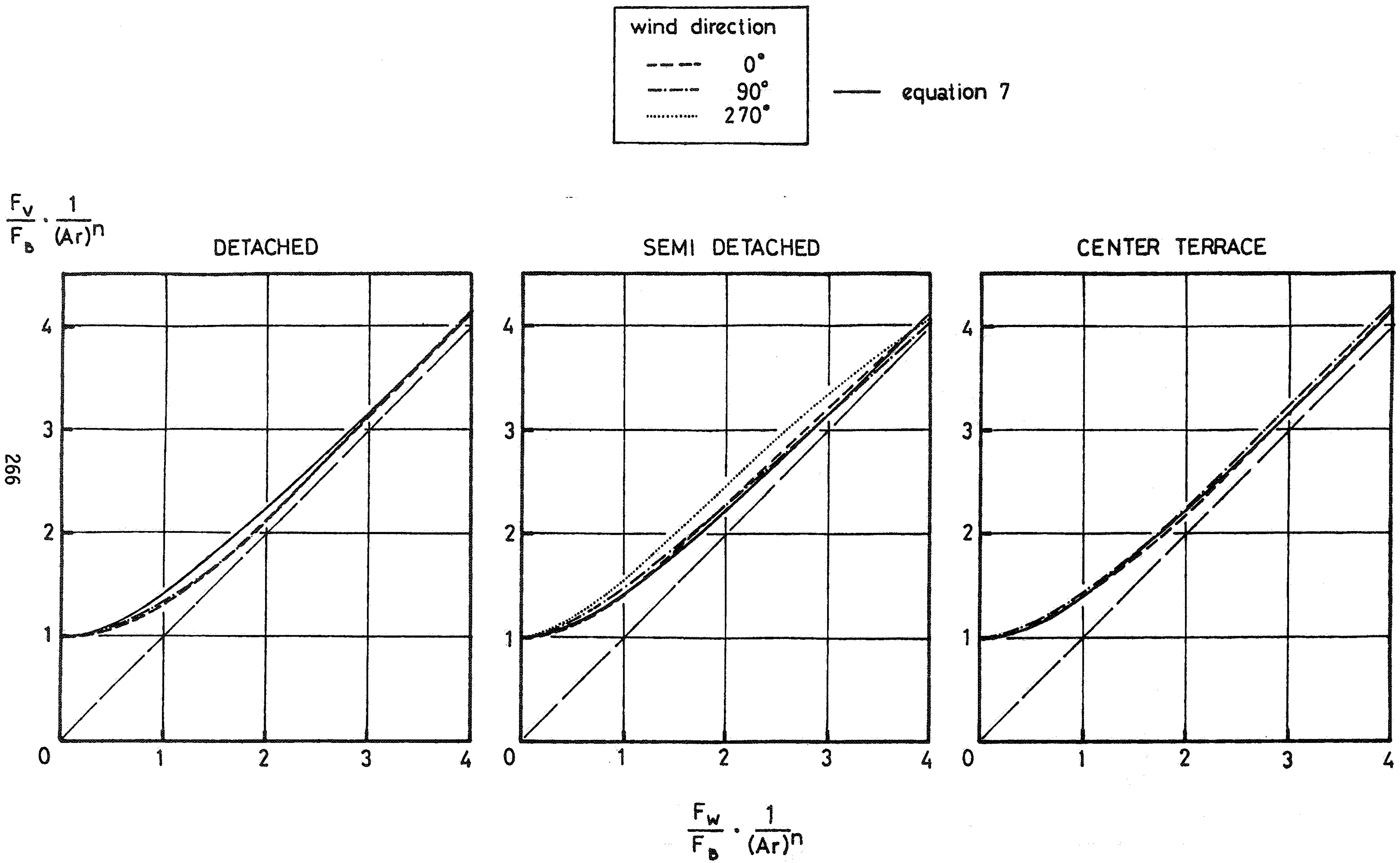

Figure 1 Variation of $(F_V/F_B Ar^n)$ with $(F_W/F_B Ar^n)$ and wind direction, ϕ, for three house types, ($n = 0 \cdot 6$) .

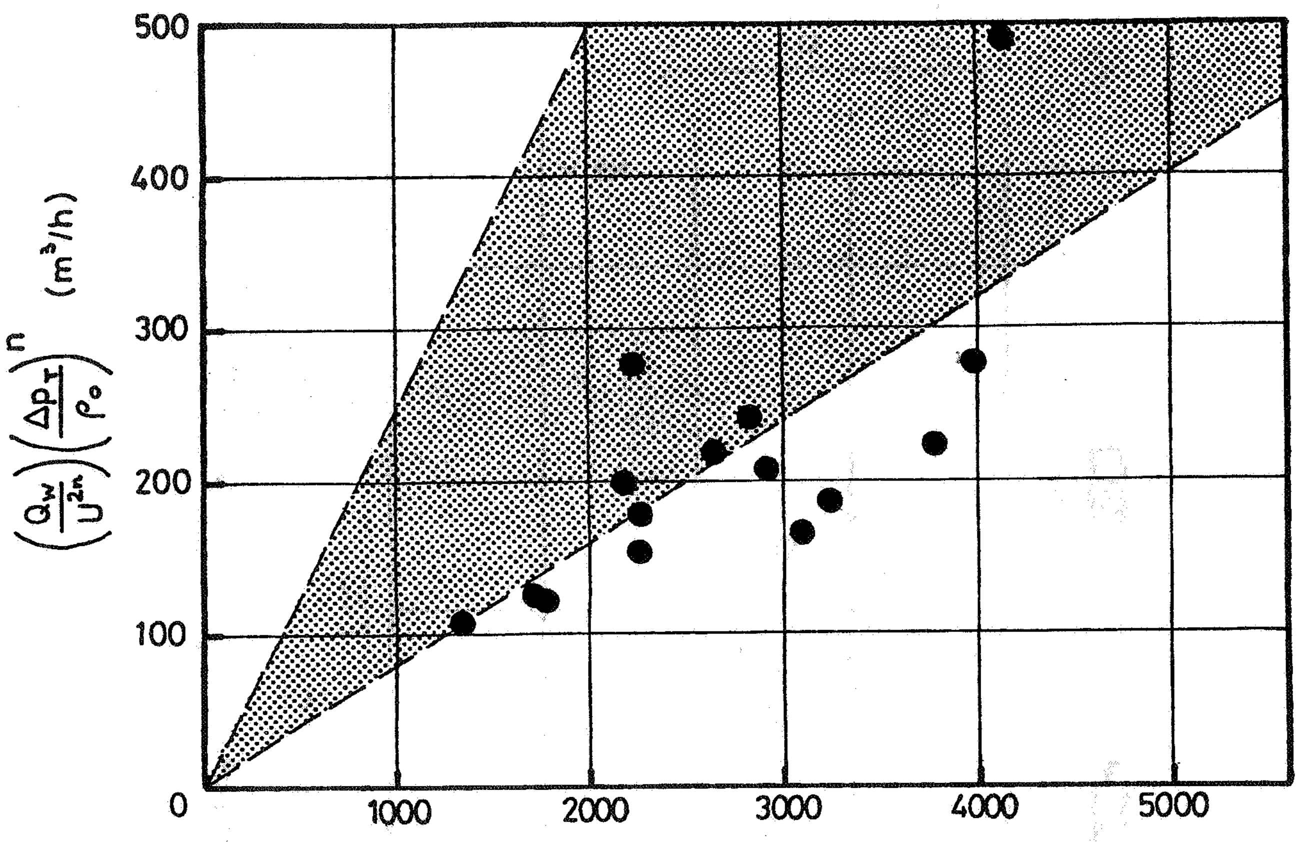

Figure 2 Determination of F_W - wind effect only

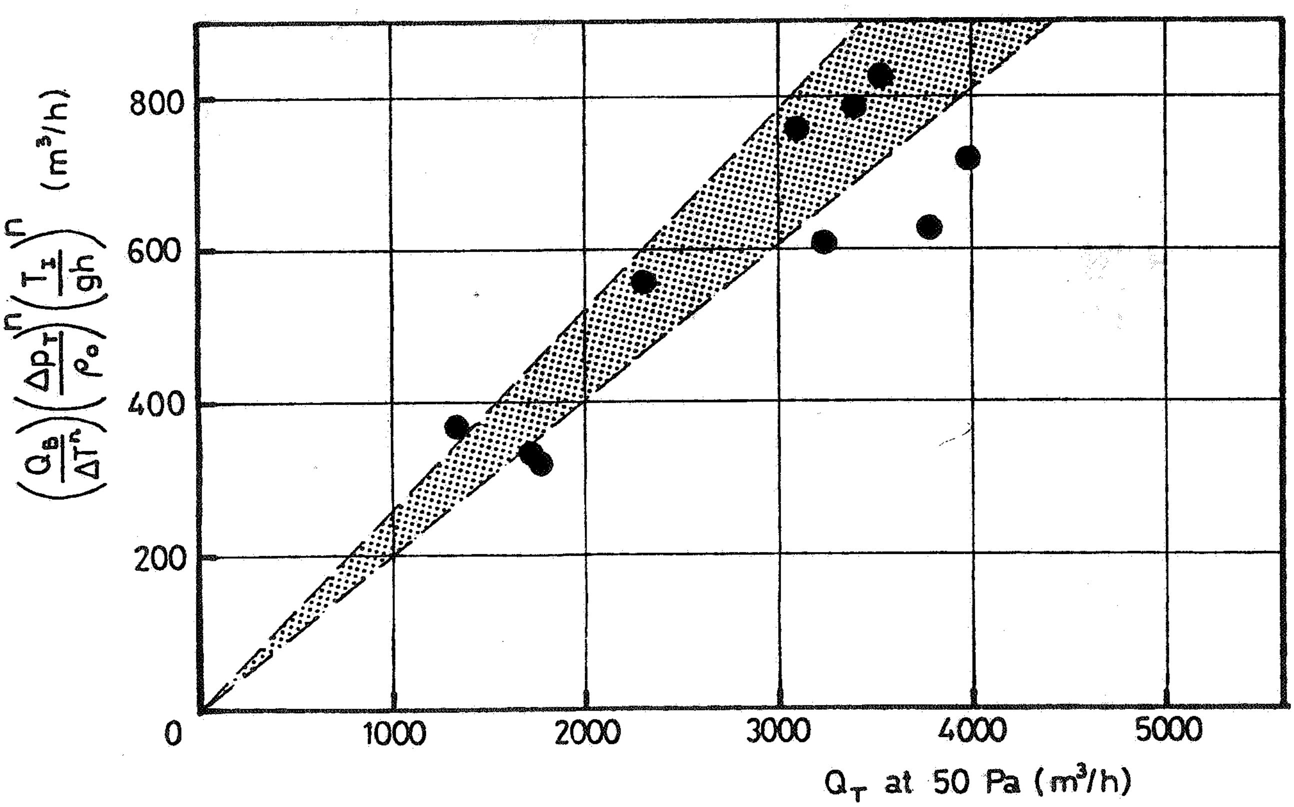

Figure 3 Determination of F_B - stack effect only

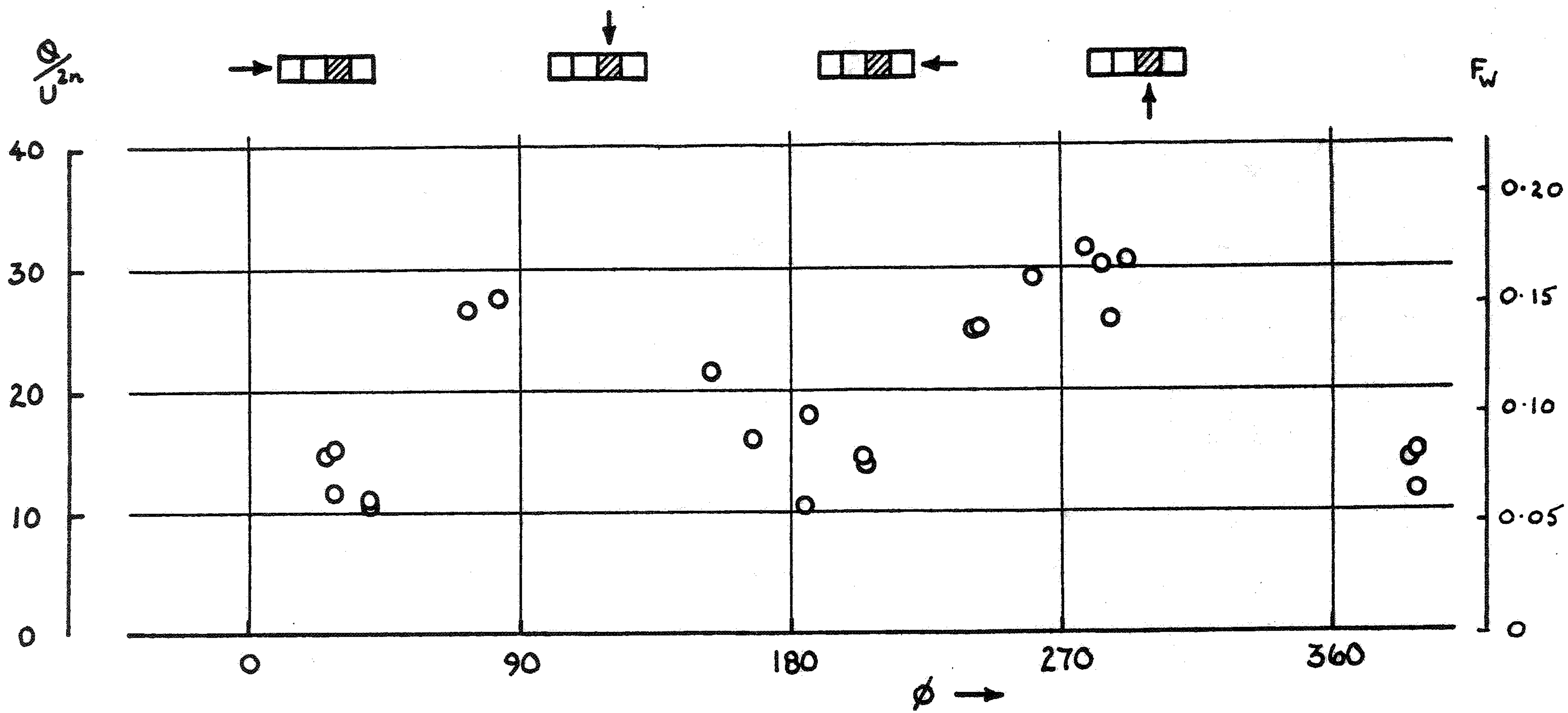

Figure 4 Variation of (Q/U^{2n}) and the infiltration function F_W with wind direction (O) for House F .

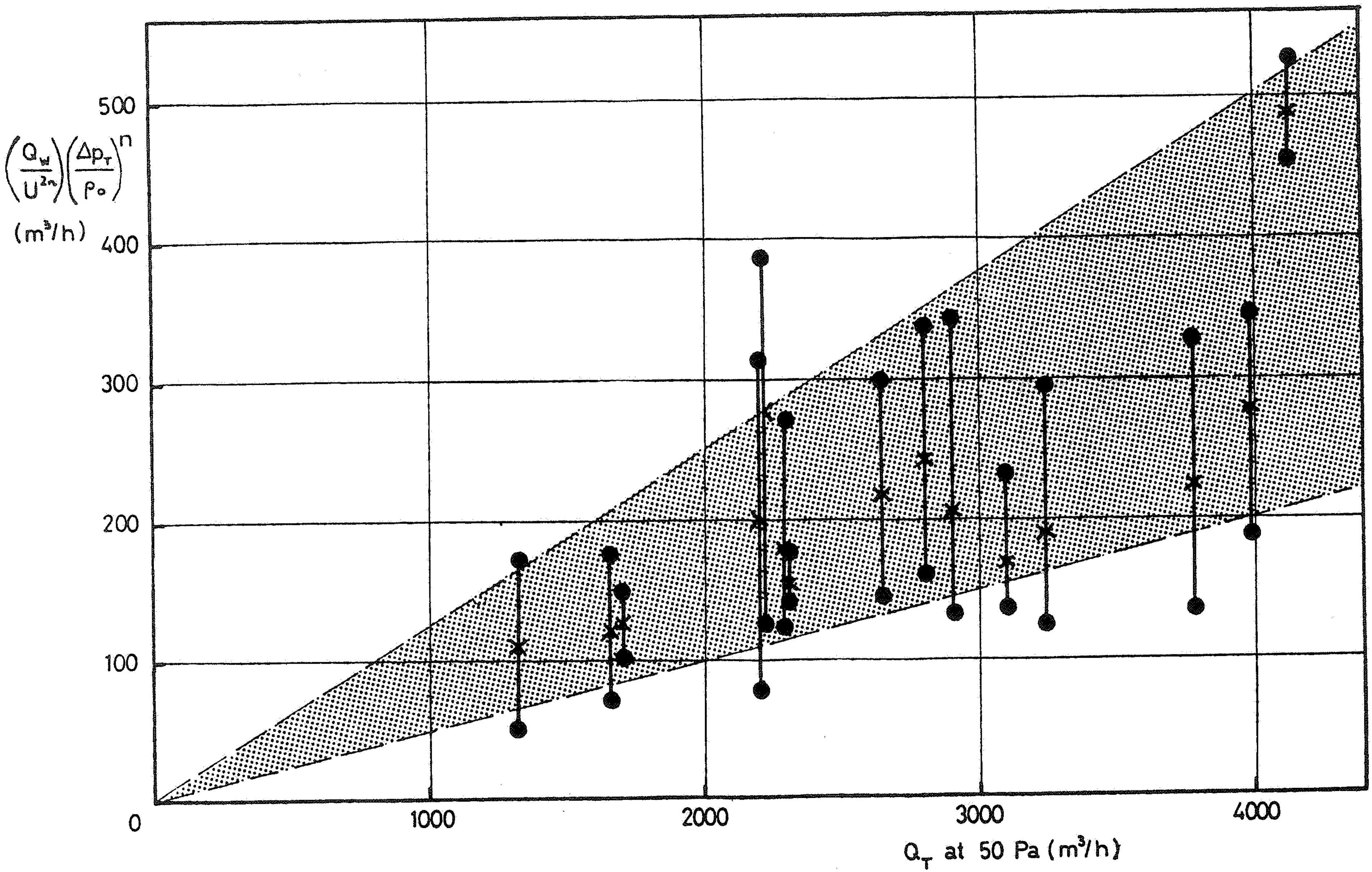

Figure 5 Comparison of the variation of F_W with predicted variation

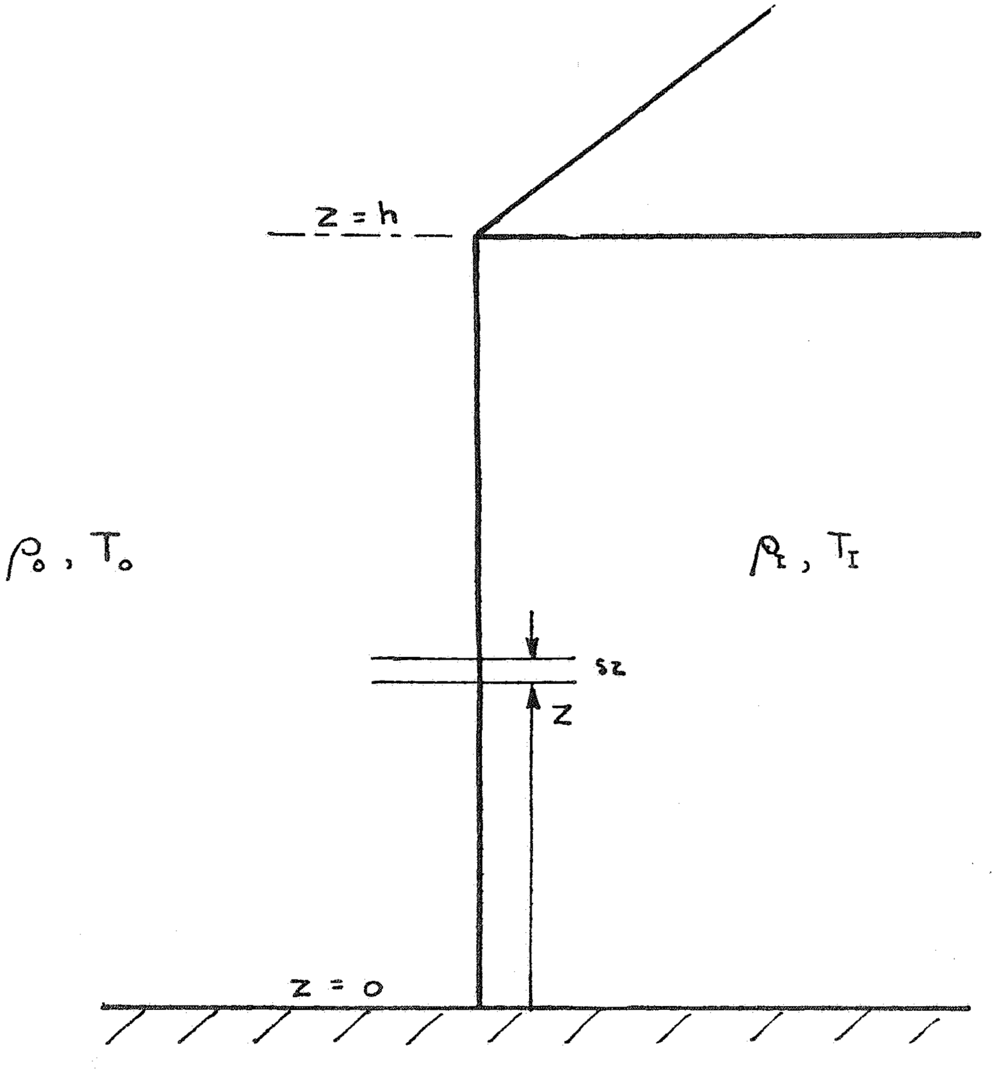

Figure 6 Schematic diagram for flow through vertical surfaces

APPENDIX 1

THE INFILTRATION MODEL

Introduction

The purpose of the model is to provide a method for relating infiltration rate at any given combination of wind speed, direction and difference between internal and external air temperatures to the leakage characteristics of a house, derived from pressurisation tests. The model assumes that the house can be represented as a single 'cell' and ignores any internal subdivisions of the space into rooms. A number of other single cell models have been developed, in particular by Blomsterberg et al(11), Sherman and Grimsrud(12), Cole et al(13), Shaw(14) and Lindquist(15). The present model differs from these in the set of assumptions made. For the present case these have been set out in Section 4 of the main text. In particular, unlike most of the other single cell models, no a priori assumptions concerning internal pressure or the position of neutral layers are made. The characterisation of the combined effect of stack and wind by the use of the dimensionless parameter, Ar, the Archimedes number, follows from its earlier use to illustrate the combined effect of stack and wind on heat losses in a naturally ventilated house(16) and in the analysis of data from field measurements of ventilation of spaces with openings on one side only(17). It is similar to the parameters, M, used by Mattingley et al(18) in the analysis of infiltration measurements, and the parameter, σ, used in a theoretical model by Sherman et al(12).

Derivation of the model equations

The flows through vertical and horizontal surfaces are considered separately:

(i) Vertical surfaces

Referring to the diagram shown in Figure (6), the pressure difference across the i^{th} wall, at a height z from the base of the dwelling, Δp_i, is given by the following equation,

$$\Delta p_i = \left(C_{pi}.\tfrac{1}{2}\rho_o U^2 + p_o - \rho_o gz\right) - \left(p_I - \rho_I gz\right) \qquad A(1)$$

p_I is the static pressure, at z = 0, within the house. p_o is the reference static pressure at z = o in the free wind. For convenience p_I may be expressed as a pressure coefficient,

$$p_I = C_{pI}.\tfrac{1}{2}\rho_o U^2 + p_o,$$

whence,

$$\Delta p_i = \tfrac{1}{2}\rho_o U^2 (a_i - b.Z) \qquad A(2)$$

Where,

$$a_i = C_{pi} - C_{pI}; \quad b = \frac{(\rho_o - \rho_I)gh}{\tfrac{1}{2}\rho_o U^2} = 2Ar$$

and $Z = \frac{z}{h}$.

Following from assumptions (iii) and (iv) in Section 4 of the main text, the volume flow rate δQ_i through a section of vertical surface δz is given by

$$\delta Q_i = \frac{Q_{Ti}.w_i}{A_i} \left\{\frac{|\Delta p_i|}{\Delta p_T}\right\}^n . \text{ sign } (\Delta p_i) \ . \ \delta z \qquad A(3)$$

It is necessary to specify the modulus of Δp_i since this may take either positive or negative values and because $n < 1$. The term $\text{sign}(\Delta p_i)$ is positive for flow into the building and negative for flow out. A_i is the area of the i^{th} vertical surface; Q_{Ti} is the total flow through the i^{th} surface at an applied pressure difference, Δp_T; w_i is the width of the i^{th} surface. Substituting for Δp_i from equation A(2) into equation A(3) gives, on rearrangement,

$$\delta Q_i = K_i.(|a_i - b.Z|)^n.\ \text{sign}(a_i - bZ).\delta Z \qquad \text{A(4)}$$

On integrating over Z = 0 to Z = 1, this yields an expression for the net flow through the i'th wall;

$$Q_i = \frac{K_i}{b(n + 1)} \left[(|a_i|)^{n+1} - (|a_i - b|)^{n+1}\right] \qquad \text{A(5)}$$

where

$$K_i = Q_{Ti} \left[\frac{\frac{1}{2}\rho_o U^2}{\Delta p_T}\right]^n$$

(ii) Horizontal surfaces

There are two horizontal surfaces, at Z = 0, and at Z = 1, specified in the following equations by the suffices $(\ )_L$ and $(\ )_U$ respectively. The total flow through each is readily derived from equation A(4):

$$Q_L = K_L.(|a_L|)^n.\ \text{sign}(a_L) \qquad \text{A(6a)}$$

$$Q_U = K_U.(|a_U - b|)^n.\ \text{sign}(a_U - b) \qquad \text{A(6b)}$$

(iii) Determination of C_{pI}

Ignoring small density changes, the principle of continuity requires that,

$$Q_L + Q_U + \sum_{i=0}^{m} Q_i = 0 \qquad A(7)$$

where m is the number of vertical surfaces.

Equation A(7) contains only one unknown when the original quantities are resubstituted. This is the dimensionless internal pressure coefficient C_{pI}. Equation A(7) may be solved by simple numerical procedures for C_{pI}, providing that the following are given:

(a) The leakage characteristics, Q_T and n.

(b) The value of Q_{TL}/Q_T, Q_{TU}/Q_T etc.

(c) The values of C_{pL}, C_{pU}, and C_{pi} (for i = 1 to m).

(d) The Archimedes number, Ar.

(iv) The determination of the infiltration flow rate

Let Q_V be the infiltration flow rate. Once C_{pI} is known, Q_V is given by

$$2Q_V = \left\{ \frac{1}{b(n+1)} \sum_{i=1}^{m} \left\{ (|a_i|)^{n+1} \cdot \mathrm{sign}(a_i) - (|a_i - b|)^{n+1} \cdot \mathrm{sign}(a_i - b) \right\} \cdot K_i + K_L \cdot (|a_L|)^n + K_U \cdot (|a_U - b|)^n \right\} \qquad A(8)$$

For any given house, items (a) and (b) above are fixed, and the pressure coefficients are determined by the wind direction, ϕ, only. Q_V may therefore be written in the form,

$$Q_V = Q_T \cdot \left[\frac{\rho_o U^2}{\Delta p_T}\right] F_V(Ar,\ \phi) \qquad A(9)$$

The Archimedes number may be expressed in terms of the temperature difference, ΔT, between internal and external air:

$$Ar = \left[\frac{\Delta T . g . h}{T_I . U^2}\right] \qquad A(10)$$

where T_I is the absolute temperature of the air within the house.

(v) Wind acting alone

Q_W, the infiltration flow rate when the internal and external temperatures are equal, may be obtained using the preceding derivation, and setting $\Delta\rho = 0$. This leads to the equivalent of equation A(9) where,

$$Q_W = Q_T \cdot \left[\frac{\rho_o U^2}{p_T}\right]^n \cdot F_W(\phi) \qquad A(11)$$

F_W is given by;

$$F_W = \frac{1}{2^{n+1}}\left\{\sum_{i=1}^{m}\left[\frac{Q_{Ti}}{Q_T}\right] \cdot |a_i|^n + \left[\frac{Q_{TL}}{Q_T}\right] \cdot |a_L|^n + \left[\frac{Q_{TU}}{Q_T}\right] \cdot |a_U|^n\right\}$$

(vi) Stack effect acting alone

Q_B the infiltration flow rate when the wind speed is zero may be obtained in a similar way by setting $U = 0$ in equation A(1) and preceding as before, but without putting the unknown quantity, p_I, into pressure coefficient form.