Principles of natural ventilation

Unless filtration is used, a supply of fresh air is needed in any habitable building to control the level of contaminants present; a method of determining the quantity of air required is given in Digest 206. A properly-designed mechanical ventilation system should be able to provide this quantity where and when it is required but has the disadvantages of initial capital cost and running and maintenance costs. The alternative, which is virtually without cost but suffers from the variability of meteorological conditions, is to use the natural movement of air through the building due to wind and to temperature difference. This digest discusses the mechanisms which govern natural ventilation and illustrates them with formulae for simple cases.

Meteorological factors

Wind

The wind is turbulent and its mean speed varies with height. The vertical profiles of wind velocity and the turbulence characteristics vary with the stability of the atmosphere and the roughness of terrain over which the wind is passing. Local topographical features such as hills and valleys can also affect wind profiles. All that is needed here is an outline knowledge of the variation of wind speed with height and a simple formula(1) can be used. For different types of terrain this describes the wind speed variation as a power-law profile:

$$\frac{U}{U_m} = Kz^a \qquad \text{..........(1)}$$

The wind speed (U_m) is measured at a large number of sites in the UK by the Meteorological Office, and is quoted for an equivalent height of 10 m, in open countryside. Using equation (1) it is possible to relate the wind speed at any other height and for any of the types of terrain to the wind speed U_m. The appropriate conversion factors are given in Table 1.

Definition of terms used

a	Exponent relating wind speed to height (allowing for terrain)	
A	Area of opening	m^2
A_b	Equivalent area for bouyancy-driven ventilation	m^2
A_w	Equivalent area for wind-driven ventilation	m^2
d	Width of crack or similar opening	m
g	Gravitational constant	m/s^2
H	Vertical distance between two openings	m
h	Height of opening	m
J	Function relating to window opening angle ϕ	
K	Coefficient relating wind speed to height (allowing for terrain)	
k	Leakage coefficient	
L	Length of crack or similar opening	m
n	Exponent for flow through small openings	
p	Pressure	Pa
p_o	Reference static pressure	Pa
Δp	Pressure difference	Pa
Q	Volume flow rate	m^3/s
U	Wind speed	m/s
U_m	Meteorological wind speed at height equivalent to 10m	m/s
U_{50}	Value of U_m which is exceeded for 50 per cent of the time	m/s
U_r	Reference wind speed measured at a height equal to that of the building in the free wind	m/s
z	Height	m
θ	Absolute temperature	°K
θ_i	Mean absolute temperature within building	°K
θ_o	Absolute ambient temperature	°K
$\bar{\theta}$	Mean value of θ_i and θ_o	°K
$\Delta\theta$	Difference between mean internal and external air temperatures	°C
ϵ	Ration of area of upper to lower opening	
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
ϕ	Angle of window opening	
C_d	Discharge coefficient	
C_p	Pressure coefficient $\left[\frac{p - p_o}{\frac{1}{2}\rho U_r^2}\right]$	
Re	Reynolds number $\frac{d}{\nu}\sqrt{\frac{2\Delta p}{\rho}}$	

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Technical enquiries arising from this Digest should be directed to Building Research Advisory Service at the above address.

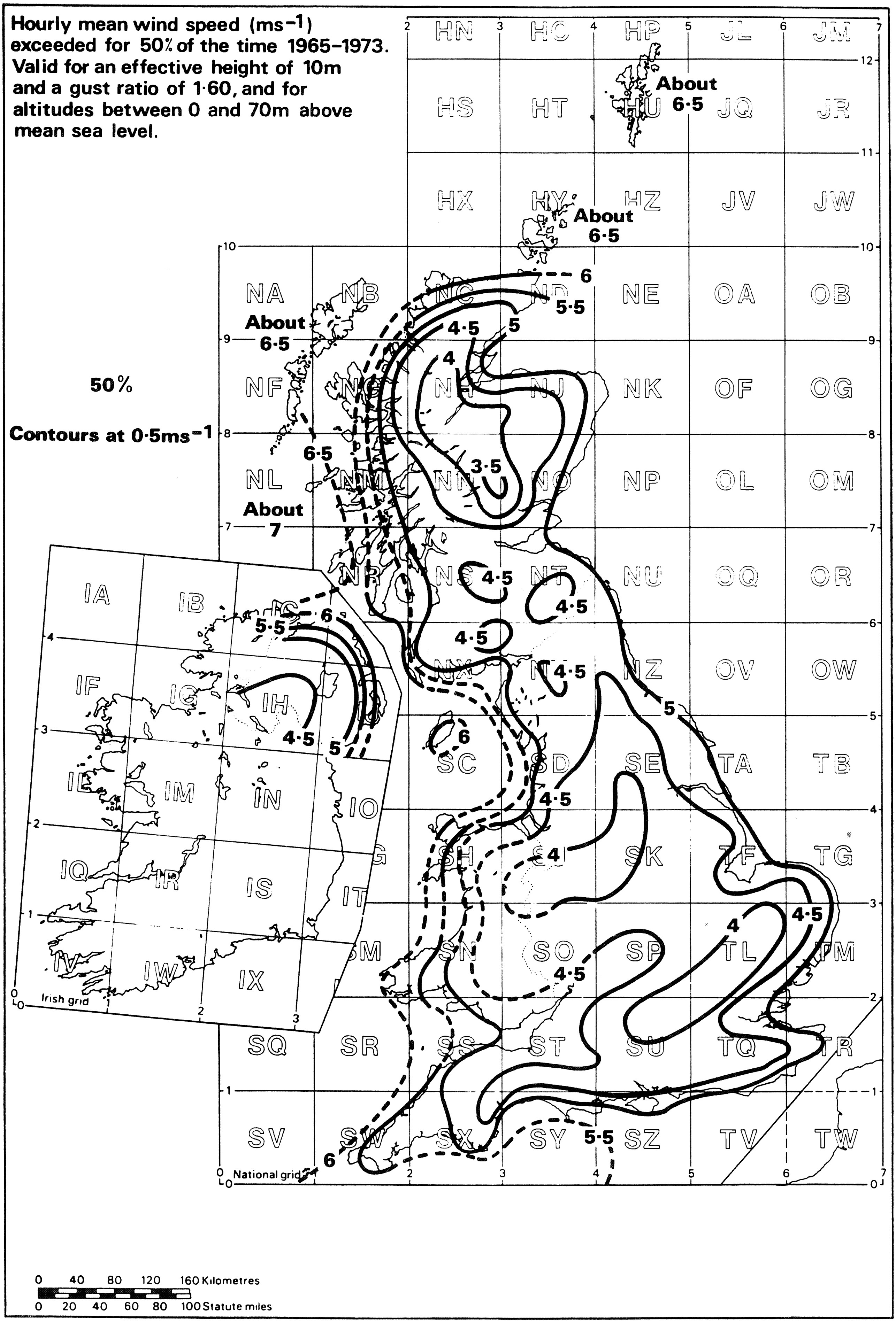


Fig 1 Contours of U_{50} for the United Kingdom

Data on mean wind speed has been condensed[2] to provide a description of the cumulative frequency of wind speed which is exceeded for 50 per cent of the time, U_{50}. Using Fig 1 and the data given in Table 2, the meteorological wind speed U_m exceeded for any chosen proportion of the time can be found for any site in the UK. It is then possible, using the data from Table 1, to determine the wind speed for a particular height and type of terrain exceeded for any given proportion of time. It is assumed that the cumulative frequency distribution is independent of wind direction, which varies considerably at most sites in the UK. The predominant directions may be determined from wind 'rose' maps [3].

Ambient atmospheric air temperature

Ambient air temperature varies during each day and from day to day, but may be characterised by monthly mean and a monthly mean diurnal variation for any particular site. Table 3 gives the monthly mean temperatures for five sites; further data can be obtained from ref 4 and 5. Daily mean variations for Heathrow are given in ref 3 together with standard deviations associated with these means.

Table 1 Factors for determining mean wind speed at different heights and for different types of terrain from Meteorological Office wind speed U_m measured at 10m in open country

Terrain	K	a
Open flat country	0·68	0·17
Country with scattered windbreaks	0·52	0·20
Urban	0·35	0·25
City	0·21	0·33

Table 2 Values of the ratio of mean wind speed exceeded for a given percentage of time to the 50 per cent mean wind speed U_{50} (from ref 2)

Percentage	Location	
	Exposed coastal	Sheltered inland
80	0·56	0·46
75	0·64	0·56
70	0·71	0·65
60	0·86	0·83
50	1·00	1·00
40	1·15	1·18
30	1·33	1·39
25	1·42	1·51
20	1·54	1·66
15	1·70	1·80
10	1·84	2·03

Table 3 Mean monthly temperatures (°C) for five sites in the United Kingdom 1941–1970 (from ref 4)

	Aberdeen	Aldergrove	Manchester	Kew	Scilly Isles
January	2·5	3·5	3·3	4·2	7·7
February	2·7	3·8	3·7	4·5	7·3
March	4·5	5·7	5·7	6·6	8·5
April	6·8	7·9	8·3	9·5	9·9
May	9·0	10·4	11·3	12·6	11·9
June	12·1	13·3	14·3	15·9	14·4
July	13·7	14·4	15·7	17·5	16·0
August	13·3	14·3	15·5	17·1	16·3
September	11·9	12·7	13·7	14·9	15·1
October	9·3	10·1	10·5	11·6	12·9
November	5·3	6·4	6·5	7·5	10·2
December	3·7	4·6	4·3	5·3	8·7
Annual	7·9	8·9	9·4	10·6	11·6

Flow characteristics of openings in buildings

A building may be regarded as a series of discrete 'cells' connected by air flow paths. Usually these cells will be rooms or circulation spaces, although floor, roof and wall voids might also need to be considered. Not all such cells will be inter-connected, and some may be joined by more than one flow path. The nature of these air flow paths will vary considerably from large openings such as doors and windows to very small cracks in components. When a difference in pressure is applied across an opening, a flow of air will take place through the opening. The magnitude of this flow depends upon the dimensions, shape and the Reynolds number. Using dimensional analysis to summarise this relationship, the flow rate, Q, is given by

$$Q = A.F(\text{Re, geometry of opening})\sqrt{\frac{2\Delta p}{\rho}} \quad \ldots\ldots (2)$$

The Reynolds number, Re, is defined for convenience in terms of pressure, as follows,

$$\text{Re} = \frac{D}{\nu}\sqrt{\frac{2\Delta p}{\rho}} \quad \ldots\ldots\ldots\ldots (3)$$

where D is a length scale appropriate to the cross-section of the opening, eg the diameter for a circular opening. For long, narrow openings, such as cracks, it is more convenient and conventional to replace A by d.L in equation (2) and D by d in equation (3). For openings with a typical dimension (ie that used in equation (3) in the calculation of Re) greater than about 10mm, which will include airbricks as well as open windows and doors, the function F may be regarded as a constant, and is usually referred to as the discharge coefficient C_d. Thus,

$$Q = A.C_d\sqrt{\frac{2\Delta p}{\rho}} \quad \ldots\ldots\ldots\ldots (4)$$

It has become conventional to give C_d a value equal to that for a sharp-edged opening, which at high Reynolds numbers is 0·61, and to refer to the area so defined for any particular opening as the 'equivalent' area. This will be close to the geometric area for openings such as windows and doors, but may be larger in the case of openings such as those in air bricks which are long in the flow direction in comparison with their width. Table 4 gives experimentally-determined values of equivalent area for various types of purpose-made openings.

For small openings, such as cracks around closed windows and doors, the form of the function F is much more complicated. Figure 2 shows the results determined experimentally for a range of typical metal window cracks. For high values of Re, F approaches a constant value and an equation of the form of (4) applies; for very low values, F is proportional to Re and the flow rate will be proportional to Δp. However, the expected operating region under normal conditions is as shown in Fig 2. This leads to a variation of flow rate with Δp expressed in the form

$$Q = L.k.(\Delta p)^n \quad \ldots\ldots\ldots. (5)$$

where $0{\cdot}6 < n < 0{\cdot}7$ and k is a constant for which typical values are given in Table 5.

Table 4 Equivalent areas of ventilation openings

	Overall size *mm*	Equivalent area *mm²*
Air brick, terra cotta, square holes	225 × 75	1 400
Air brick, terra cotta, square holes	225 × 150	4 300
Air brick, terra cotta, square holes	225 × 225	6 400
Air brick, terra cotta, louvres	225 × 150	2 000
Air brick, terra cotta, louvres	225 × 225	4 300
Air brick, cast iron, square holes	225 × 75	7 200
Air brick, cast iron, square holes	225 × 150	12 700
Air brick, cast iron, square holes	225 × 225	19 600
Air brick, cast iron, louvres	225 × 75	3 100
Air brick, cast iron, louvres	225 × 150	11 300
Air brick, cast iron, louvres	225 × 225	19 200
Typical internal louvres grille	225 × 75	2 400
Typical internal louvres grille	225 × 150	7 200
Typical internal louvres grille	225 × 225	10 700

Pressures generated at building surfaces

The effect of wind

It has been found that, for a particular wind direction, the pattern of air flow around a building is comparatively independent of wind speed, provided that the building has sharp corners. The surface pressure will vary with the wind speed squared whilst all other conditions, including wind direction, remain constant; in consequence the pressure, p, generated by the wind at a point on the surface may be defined in terms of a single coefficient, C_p, as follows:

$$C_p = (p - p_o)/\tfrac{1}{2}\rho U^2_r \quad \ldots\ldots\ldots. (6)$$

Once the distribution of C_p at the surface has been determined for a single wind-speed and a particular wind direction (probably from a scale wind-tunnel test), the pressure may be computed for any other wind speed. U_r is conventionally taken as the wind speed measured in the free wind at a height equal to that of the building. Pressures averaged over the surface for simple building shapes are given in Digest 119. For buildings which stand alone or are relatively much higher than surrounding buildings and obstructions, the difference in mean pressure coefficient between windward and leeward faces will typically be equal to 1·0. For buildings in sheltered situations, such as those shown in Fig 3[6], a difference in mean coefficient of the order of 0·1 can be expected.

The effect of temperature difference

Air density varies approximately as the inverse of absolute temperature. The weight of two vertical columns of air of different temperatures separated from each other by a vertical surface will differ and a pressure difference will be applied across the intervening surface. Thus, if the air temperature within a building is higher than that outside, pressure differences will create an air flow through openings in the intervening fabric.

Table 5 Values of k for windows (in l/s per metre of crack length for $\Delta p = 1$ Pa)

Window type	Value of k	
	Average	Range
Sliding	0·08	0·02 – 0·30
Pivoted	0·21	0·06 – 0·80
Pivoted (weather-stripped)	0·08	0·005 – 0·20

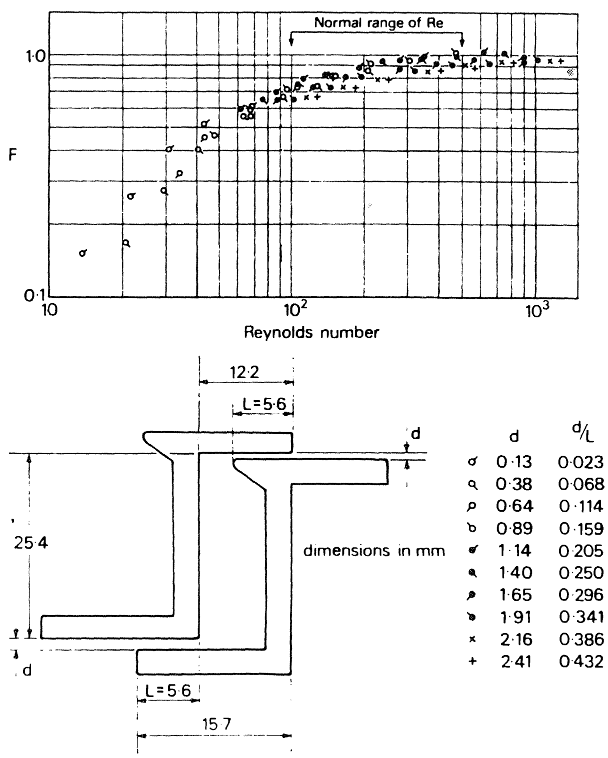


Fig 2 Flow of air through window cracks

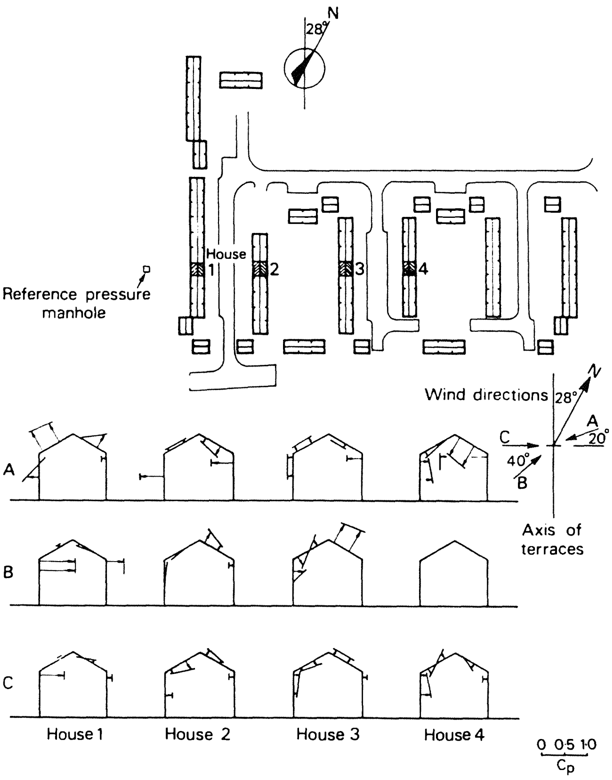


Fig 3 Effect of shelter on surface pressure coefficients

The general characteristics of natural ventilation can, however, be demonstrated by considering some simple cases. Figure 4 shows a simple, two-dimensional building; internal divisions are ignored and the building consists of a single cell with openings as shown. These will be considered to be large, and therefore flow through them is governed by equation (4). Table 6 shows schematically the approximate airflow pattern and gives the formulae from which the ventilation flow rate Q can be determined.

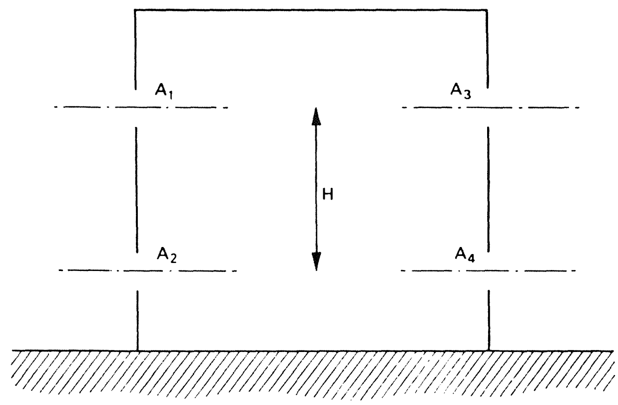


Fig 4 Arrangement of openings in simple buildings

The determination of natural ventilation rates

The airflow through a building and the ventilation rates of rooms within the building can be determined, for a given design wind speed and direction if the following are known:

(i) the position and flow characteristics of all openings;

(ii) the detailed surface mean pressure coefficient distribution for the wind direction under consideration;

(iii) the internal and external air temperatures.

However, it is difficult to obtain a solution in all but the simplest cases because of the large number of non-linear simultaneous solutions which require solution, and the only practicable method is to use a digital computer. A number of computer programs are under development and are at a stage when they are being compared with full-scale measurements to test their validity.

Such programs are only as accurate as the data from (i), (ii), and (iii) and it is very rare that these are known in detail for existing buildings, let alone those at the design stage. A comprehensive series of wind-tunnel tests may give the information required under (ii), but recent work shows that it is far from easy to predict the positions, let alone the flow characteristics, of all of the openings.

Wind effect only Due to the difference in mean pressure between windward and leeward faces, air flows in through the openings A_1 and A_2 and out through A_3 and A_4. A_w is the overall effective area of the four openings; it can be seen, therefore, that openings in parallel can be added together arithmetically whilst those in series must be obtained by adding the inverse of the squares. It can also be noted that ventilation rate is proportional both to wind speed and to the square root of applied pressure difference. Thus, a range of ΔC_p from 0·1 to 1·0 (ie sheltered to exposed) gives only an approximately 1 :3 difference in ventilation rate at the same reference wind speed.

Temperature difference only In this case air flows in through the lower openings A_2 and A_4 and out through A_1 and A_3. The equivalent area is now A_b. From the formula it can be seen that ventilation rate is proportional both to the square root of the temperature difference and to the square root of the vertical distance between openings.

Combined effect of wind and temperature For a fixed wind speed with small temperature differences the flow is similar to that for wind only, but as the temperature difference increases, the inflow of air at upper openings due to wind is reduced and outflow is increased; at lower openings the reverse occurs. Depending upon the relative values of the opening areas a point is reached when the flows are reversed at the upper windward opening, and as the temperature difference is further increased the flow approaches that for temperature difference only. A reasonable approximation of the combined flow rate can be made by taking the flow rates calculated for both conditions separately and taking the larger to apply to the combined case. For the case in Fig 4, this leads to an expression of $\frac{U}{\sqrt{\Delta\theta}}$, given in Table 6, which determines whether temperature or wind will dominate. The form of this expression indicates that taller, more sheltered buildings will have ventilation rates independant of wind speed for a large part of the colder months.

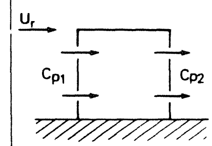
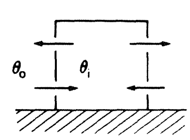
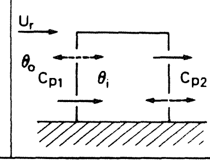
Conditions	Schematic	Formula
A) Wind only		$Q_w = C_D A_w U_r (\Delta C_p)^{1/2}$ $\frac{1}{A_w^2} = \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$
B) Temperature difference only		$Q_B = C_D A_b \left(\frac{2\Delta\theta g H}{\bar{\theta}}\right)^{1/2}$ $\frac{1}{A_b^2} = \frac{1}{(A_1+A_3)^2} + \frac{1}{(A_2+A_4)^2}$
C) Wind and temperature difference together		$Q_T = Q_B$ For $\frac{U}{\sqrt{\Delta\theta}} < 0{\cdot}26 \left(\frac{A_b}{A_w}\right) \left(\frac{H}{\Delta C_p}\right)^{1/2}$ $Q_T = Q_w$ For $\frac{U}{\sqrt{\Delta\theta}} > 0{\cdot}26 \left(\frac{A_b}{A_w}\right) \left(\frac{H}{\Delta C_p}\right)^{1/2}$

Table 6 Cross-ventilation of simple buildings

Other mechanisms

Single-sided ventilation

Wind only In summer, the ventilation rates needed to assist in maintaining comfortable internal conditions are at least an order of magnitude larger than those required in winter. These large rates can generally be obtained by cross-ventilation, except in the circumstance when large openings are available on one external wall only, eg in a school classroom or an office in which doors to any internal corridor are closed for reasons of privacy or noise. In these situations, the cross ventilation would be small since the small area of the internal openings would be the dominant factor. In fact, considerable exchange of air can take place through the openings in the external wall because of turbulent diffusion, by outward-opening lights interacting with the local airstream to give an exchange of air between inside and outside and, if there is more than one window, by pressure differences between the windows causing flows into the room.

The formula shown in Table 7 represents a minimum rate; this may be larger for certain wind directions and certain types of opening windows.

Temperature difference only It is clear that the mechanism for temperature-driven ventilation can apply in the 'single-sided' case with a number of openings at different heights within the room. When an equilibrium is reached, the outflow equals the incoming mass flow and the level at which the pressure difference across the dividing surface is fixed. This is the 'neutral level' and can be used as the reference height from which the flow rates through each of the openings can be calculated and hence the total ventilation flow rate determined. Table 7 shows a common example of two openings, eg a vertical sliding window. The formula is given in terms of A, which is the total open area and ϵ.

Another common case is the single plane opening. Air flows in at the lower part of the opening and out at the upper part. Table 7 shows the flow pattern and the simple formula which applies to it. Figure 5

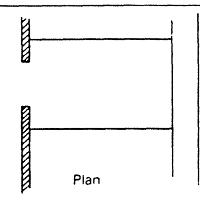
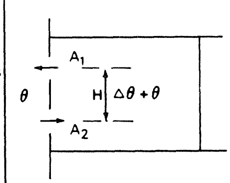
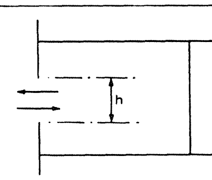
Conditions	Schematic	Formula
A) Due to wind		$Q = 0{\cdot}025 A U_r$
B) Due to temperature difference – two openings		$Q = C_d A \left[\frac{\sqrt{2}\,\varepsilon}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}}\right] \left(\frac{\Delta\theta g H}{\theta}\right)^{1/2}$ $\varepsilon = \frac{A_1}{A_2}$; $A = A_1 + A_2$
C) Due to temperature difference – one opening		$Q = C_d \frac{A}{3} \left(\frac{\Delta\theta g h}{\bar{\theta}}\right)^{1/2}$ If an opening light is present $Q = C_d \frac{A}{3} J(\phi) \left(\frac{\Delta\theta g h}{\bar{\theta}}\right)^{1/2}$ Where $J(\phi)$ is given in figure 5

Table 7 Spaces with openings on one wall only

shows how the presence of an outward opening side-mounted casement or a centre-privoted window modify the flow rate as a function of opening angle.

Given a fixed area of opening light, the largest rate of ventilation is obtained, in the case of single opening, by making it tall and narrow, and for more than one opening by separating them by as large a vertical distance as possible. Increasing the angle of opening for side-mounted casement and centre-pivoted windows has little effect beyond an angle of approximately 50°.

Combined effect of wind and temperature As in the case of cross-ventilation, the ventilation rate due to both effects acting together can be taken as the larger of the two individual values.

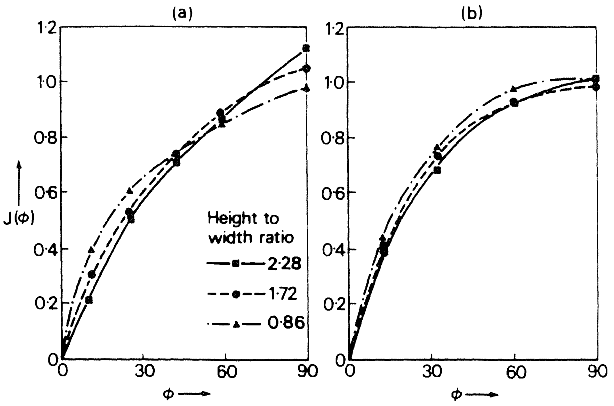


Fig 5 Variation of J (ϕ) with angle of opening ϕ for
(a) side-mounted casement windows
(b) centre-pivoted windows

Pressure fluctuation

The pressures generated by wind at the surface of a building fluctuate. This is due to the turbulent nature of the wind and to the interaction of the building and the wind which creates regions of flow separation and a wake. The use of mean pressures in the preceding section is therefore technically incorrect, but the error is small unless the difference between mean pressures is small. This can be due to shelter or to the configuration of the building relative to the wind direction. Considering, for example, a terraced house with the wind parallel to the terrace, the mean pressures on each face would be expected to be approximately equal, giving rise to a zero or very low ventilation rate if the formula in Table 6 is used. In practice, instantaneous pressure differences between the two sides of the house can be quite large and will give a flow into the house, alternately from each side. As far as the house is concerned, however, the ventilation rate is not dependent on the direction of flow and a higher than expected rate is achieved. At present, there is limited information concerning this mechanism, but the available experimental results indicate that, all other factors being equal, the ventilation rate can be approximated by giving a value for ΔC_p of 0·2 in the formula in Table 6.

Measurement of ventilation rates

Under natural conditions, there are many paths for the air to enter and leave a room or building and so it is not possible to use conventional anemometric techniques to measure volume flow rates. Instead, methods based on a tracer gas are generally used. The gas can be considered as an artifical contaminant and the equations for variation of contaminant concentration given in Digest 206 apply. Two methods can be used.

The continuous flow method A tracer gas is introduced into the space at a known rate and the measurement of the equilibrium concentration gives the volume flow rate at which air is leaving the space.

The decay method This is the more commonly used, in which a limited quantity of gas is introduced into the space and, provided good mixing occurs, the concentration within the space decays exponentially with time. From this, the ventilation rate can be determined. A number of tracer gases are used, their requirements being that they should be stable, non-toxic, not react with other materials within the space and that their concentration can be measured easily using suitable instruments. The most commonly used tracer gases and their methods of detection are:

Nitrous oxide	Infra-red gas analysis
Helium	Katharometer
Hydrogen	Katharometer
Carbon dioxide	Infra-red gas analysis
Krypton-85	Geiger-Muller Tube

References and further reading

1 Davenport AG; 1963 Proceedings of the conference on wind effects on buildings and structures, Vol 1, 1965, HMSO
2 Caton PGF; Maps of hourly mean wind speed over the United Kingdom 1965–1973, Meteorological Office, Climatology Memorandum, August 1976
3 Institute of Heating and Ventilating Engineers Guide, Book A, 1970
4 Maps of mean and extreme temperature over the United Kingdom 1941–1970, Meteorological Office, Climatology Memorandum No 73, August 1975
5 The climate of the British Isles; ed Chandler TJ and Gregory S, Longman, London 1976
6 The measurement of wind pressures on two-storey houses at Aylesbury; BRE Current Paper CP 70/74.

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