A Study of the Natural Ventilation of Tall Office Buildings

by P. J. Jackman, B.Tech

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Nomenclature

C	air leakage coefficient	ft³/min ft in wg
C_1	coefficient of electrical resistance	
E	potential difference	
N	number of floors in building	
T	air temperature	°K
T_i	inside air temperature	°K
T_o	outside air temperature	°K
V	volume flow of air	ft³/min
V_T	total ventilation rate in building	ft³/min
V_x	ventilation rate at a given floor level	ft³/min
h	height above ground	ft
i	electrical current	
l	length of crack around openable window or door	ft
n	exponent	
p	pressure	in wg
v	wind speed	ft/sec or mile/h
v_a	wind speed at known height h_a	ft/sec or mile/h
v_g	gradient wind speed at height h_g	ft/sec or mile/h
v_m	meteorological wind speed	ft/sec or mile/h
v_x	wind speed at height h_x	ft/sec or mile/h
x	exponent	
ρ	air density	lb/ft³

1. Introduction

The knowledge of the amount of air passing into and out of a building is important, not only in the estimation of heating (or cooling) requirements, but also in the determination of the quality of the air within the building when such factors as relative humidity, CO_2 level, and contaminant concentration are significant criteria. The construction of a building is generally such that some ventilation due to natural causes will take place through cracks and apertures in the structural envelope. It is desirable at the design stage to be able to assess the amount of natural ventilation that will occur under specified conditions in order that its influence may be counteracted, supplemented or neglected, as required.

The prediction of rates of natural ventilation for buildings is a complex task and at present only the broadest of approximations are used. One method of estimation is based on measured leakage rates of building components such as windows and doors with respect to the pressure difference across them. This is known as the 'crack' method. Another procedure, known as the 'air change' method, involves the assumption of a certain number of air changes per hour for each room, depending on its location, number of exposed sides, window area or other similar criteria. The *ASHRAE Handbook*[1] gives information relating to both methods while the 'crack' method has been adopted in the German standard[2] and the 'air change' method is presented in the *IHVE Guide*[3]. The 'crack' method is generally regarded as the more accurate but its use depends on the knowledge of the leakage characteristics of various components and the relevant pressure conditions both inside and outside the building. In the detailed analysis of the ventilation of a complete building, such a method is too complex and laborious to warrant its general use by a designer. A simplified, yet accurate, design procedure is desirable.

A theoretical study of the natural ventilation process has been undertaken by the Association in conjunction with the Institute of Public Health Engineering TNO in Delft, Holland. Both analogue and digital techniques were used and the results so derived were analyzed with the aim of producing a design method suitable for the expeditious assessment of the natural ventilation of projected buildings.

As this was a joint project with the Dutch Institute metric units were used during the investigation, but for the purpose of this report all values are quoted in Imperial units. Where the Imperial equivalents have been approximated for convenience, the original value in metric units is given in brackets.

2. The basic parameters

The factors on which the process of natural ventilation is dependent, may be broadly divided into three categories, namely (1) the motive forces; (2) the external form and dimensions of the building; and (3) the resistance to airflow through the building. The basic parameters assumed for this study in each of these categories are stated below and outlines of the derivation of the specific values used in the calculations follow later in the report.

(1) The two motive forces primarily responsible for natural ventilation are caused by wind impingement and the difference of indoor and outdoor air temperature. The average value for the meteorological wind speed (i.e. the wind speed measured at or related to a specific height

above ground is an open level site) throughout the entire year was taken to be 10 mile/h (4·4 m/sec) and for this study values of 0, 10 and 20 mile/h were used. The winter design temperature of 32°F outside and 68°F inside were selected.

(2) The degree to which the natural forces produce ventilation is governed to a certain extent by the external shape and dimensions of the building. For instance, the height of a building affects both the influence of wind and air temperature differences. An elementary flat-roofed type of building was studied with a range of three building heights 50, 100 and 200 feet (15, 30 and 60 metres equivalent to 5, 10 and 20 storeys). Both long rectangular and square plan shapes were considered.

(3) The resistance to airflow through a building depends not only on the air tightness of the external structure but also on the internal layout and construction. The primary air leakage paths are through windows that can be opened and doors. It was assumed that all windows and doors remained closed, so that the passage of air was limited to the cracks around their periphery. The internal layouts selected for the rectangular and square plan buildings are shown on Fig. 1 and typify simple arrangements for office blocks.

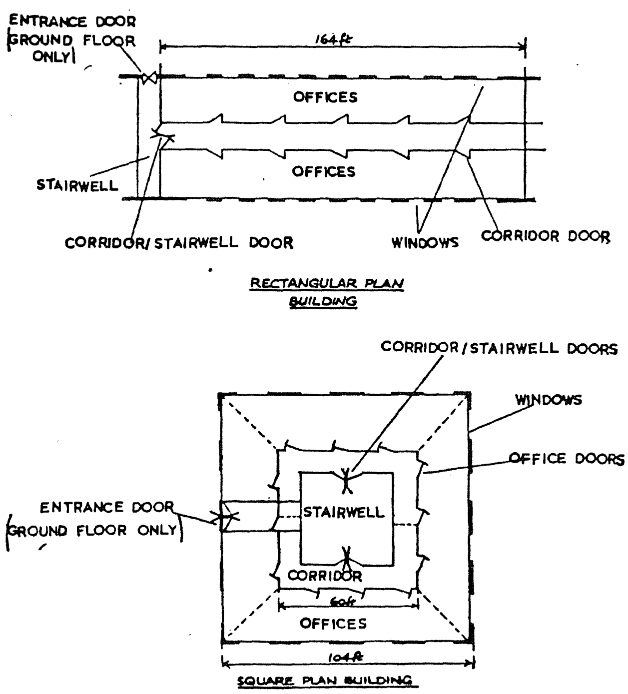


Fig. 1. Internal layout of buildings

In the rectangular plan building, which was representative of a long building with sealed end walls, the offices were located along both of the long sides with a central corridor leading to a stairwell which extended from the ground to the top floor. The offices in the square plan building were located on all four sides around a central core containing the corridors and stairwell. The offices on each side of the building were assumed to be divided from the remainder by partitions shown by the dotted lines on Fig. 1, the ratio of windows to office doors being identical on all sides. The dimensions of the square plan building were selected so that the volume of office space on each floor was the same as that in the rectangular building. For each building shape, the floor plans were identical on each floor except the ground floor which included an entrance door located alternativel the windward or leeward side.

3. Pressure distribution on a building due wind

The study of the nature of wind and, in particular, structural effects, has received considerable attentio recent years as taller buildings increase in number. several experimenters have shown[4,5] there is consic able difference in the pressure distribution on the face a tall building, between that caused by a wind hav uniform velocity and that caused by wind having increasing velocity with height. The latter is the m realistic but the velocity gradient is dependent on type of terrain over which the wind is passing. Close the ground, the higher friction caused by a built-up a results in a lower wind speed compared to flat, op terrain, for which the meteorological wind speed deemed to apply.

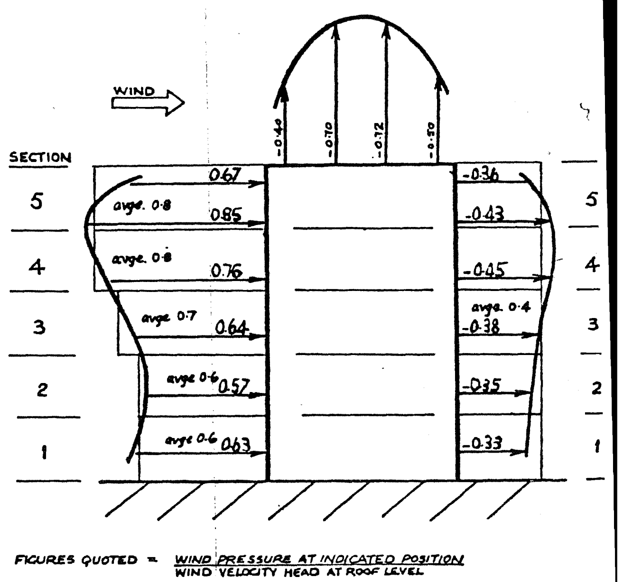


Fig. 2. Wind pressure distribution on a building

The pressure distribution around a rectangular pl building was investigated by wind tunnel experimen conducted by the Institute of Public Health Engineerir TNO Delft. The atmospheric boundary layer effect w simulated by using a technique suggested by Jensen an Franck[6], in which wooden blocks were arranged in zig-zag pattern on the upstream bottom surface of th wind tunnel to represent the effect of an urban area. Th results, given in terms of the velocity pressure of th wind at the height of the top of the building, are show on Fig. 2. For convenience, the building was subdivide into five horizontal sections and the wind pressure developed over these sections were averaged as detaile below.

Table 1

	Average Air Pressure	
Section	Windward Side	Leeward Side
1	$+0{\cdot}6\ \frac{1}{2}\rho V^2$	$-0{\cdot}4\ \frac{1}{2}\rho V^2$
2	$+0{\cdot}6\ \frac{1}{2}\rho V^2$	$-0{\cdot}4\ \frac{1}{2}\rho V^2$
3	$+0{\cdot}7\ \frac{1}{2}\rho V^2$	$-0{\cdot}4\ \frac{1}{2}\rho V^2$
4	$+0{\cdot}8\ \frac{1}{2}\rho V^2$	$-0{\cdot}4\ \frac{1}{2}\rho V^2$
5	$+0{\cdot}8\ \frac{1}{2}\rho V^2$	$-0{\cdot}4\ \frac{1}{2}\rho V^2$

In the case of a long rectangular plan building the win will have maximum effect if it approaches at an angle c

90° to one of the long faces. This condition may therefore be taken as the design case. However, the situation is not as clear in the case of a square, or near square, plan building in which a wind at other than perpendicular to one of the faces may produce maximum ventilation. For this reason some attention was given to the study of a square plan building with the wind approaching at 90° and at 45° to one of its faces. A survey of work reported by previous experimenters was undertaken to ascertain the wind pressure distributions under such conditions. On square plan buildings only data relating to perpendicular wind angles was found but there have been some wind tunnel studies with rectangular buildings of different length to width (aspect) ratios in wind at various approach angles. One set of data, reported by Baturin,[7] was related to a building of a 1·5:1 aspect ratio and two National Physical Laboratory Reports[8,9] gave results of experiments using model buildings of 2·4:1 and 3·3:1 aspect ratios. From these results it was possible to plot the pressure distribution curves shown on Fig. 3 for both the wide and narrow windward faces of the buildings in a wind at 45° to the faces. The values plotted relate to the mid-height of each face and, as expected, the difference between the pressure values for the wide and narrow faces increased with increase in the aspect ratio. It was assumed that a central line, indicated on Fig. 3, would approximate to the pressure gradient on the windward faces of a square plan building. From this, and the results given for the leeward sides of the buildings, the pressure distribution diagrams for the five horizontal sections were plotted and are shown on Fig. 4. Fig. 4 also shows the pressure distribution assumed for a wind approaching at 90° to one of the building faces.

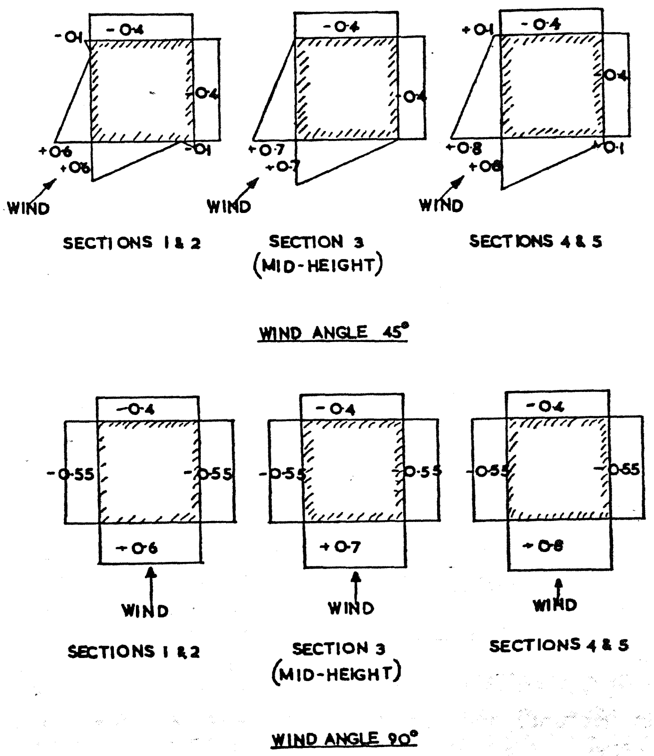


Fig. 4. Wind pressure profile on square plan building

4. Wind pressures at assumed meteorological wind speeds

To make use of the pressure distribution data for both the rectangular and square plan buildings it is necessary

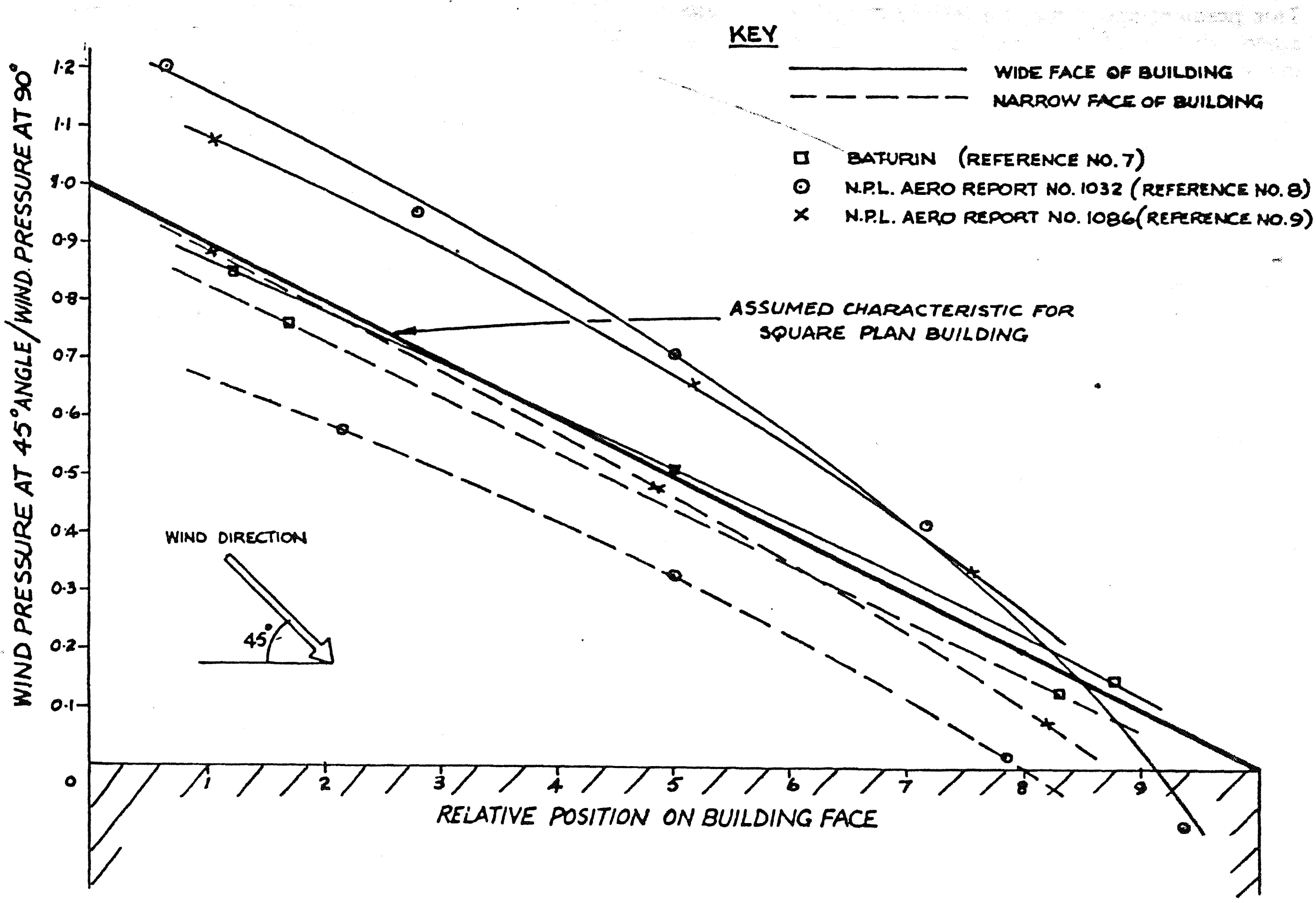


Fig. 3. Wind pressure distribution at mid-height of buildings with a wind angle of 45°

to derive the wind speed at the building roof level from a knowledge of the meteorological wind speed. The formula, generally used to describe the velocity gradient of the wind, is:

$$\frac{V_x}{V_a} = \left(\frac{h_x}{h_a}\right)^{\frac{1}{\alpha}} \quad \ldots (1)$$

where v_x is the wind speed at a height h_x, and v_a and h_a refer to a known speed at a known height. The exponential term $\frac{1}{\alpha}$ varies in accordance with the nature of the terrain, as does the height of the boundary layer, h_g. Above the boundary layer the wind speed, known as the gradient speed, is unaffected by changes in the terrain over which it is passing.

The following values for h_g and α, derived by Davenport[10] were assumed.

Flat open country (meteorological site):

h_g = 920 ft (280 m) $\alpha = 7$.

Urban area (building location):

h_g = 1640 ft (500 m) $\alpha = 3$.

In Holland, the meteorological wind speed v_m is measured at a height h_m of 6 metres* (19·7 ft) and, using this together with the values of h_g and α for the meteorological site, in equation (1) the gradient speed was found:

viz.

$$\frac{v_g}{v_m} = \left(\frac{920}{19 \cdot 7}\right)^{\frac{1}{7}} \quad \ldots (2)$$

$$v_g = 1 \cdot 73 v_m.$$

This gradient speed may be related to the urban area, again using equation (1), so that, at any height h_x above the town the wind speed will be:

$$v_x = v_g \frac{h_x^{\frac{1}{3}}}{1640} \quad \ldots (3)$$

$$= 1 \cdot 73\, v_m \frac{h_x^{\frac{1}{3}}}{1640}$$

Thus, for the three building heights in question, the speeds at roof level were:

h_x = 50 ft $\qquad v_x = 0 \cdot 536\, v_m$

h_x = 100 ft $\qquad v_x = 0 \cdot 675\, v_m$

h_x = 200 ft $\qquad v_x = 0 \cdot 855\, v_m$

The wind pressures on the building faces at each horizontal section were then calculated for the meteorological wind speeds of 10 and 20 mile/h, making use of the relative pressures found in the model experiments.

The calculated pressure values are shown on Table 2.

Table 2

Wind pressures on rectangular plan building				
Meteorological Wind speed mile/h	Building Height feet	Horizontal Section No.	Pressure (in wg)	
			Windward side	Leeward side
10	50	1 & 2	+0·0083	−0·0055
		3	+0·0097	−0·0055
		4 & 5	+0·0110	−0·0055
	100	1 & 2	+0·0138	−0·0087
		3	+0·0152	−0·0087
		4 & 5	+0·0173	−0·0087
	200	1 & 2	+0·0208	−0·0139
		3	+0·0244	−0·0139
		4 & 5	+0·0279	−0·0139
20	50	1 & 2	+0·0330	−0·0220
		3	+0·0386	−0·0220
		4 & 5	+0·0440	−0·0220
	100	1 & 2	+0·052	−0·035
		3	+0·061	−0·035
		4 & 5	+0·069	−0·035
	200	1 & 2	+0·083	−0·056
		3	+0·098	−0·056
		4 & 5	+0·112	−0·056

5. Pressure differences caused by stack effect

Stack effect arises from temperature differences between air inside and outside the building. These differences result in changes in air density so that, over vertical distances, pressure gradients between inside and outside are generated. If, for instance, the air temperature within a building is higher than that outside, a pressure lower than that outside is produced in the lower part of the building with an inward flow of air as a consequence. The reverse occurs at the upper levels of the building, and at some intermediate height a neutral level exists where the internal and external pressures are equal. The height of the neutral level is dependent on the distribution and comparative resistance to airflow of the apertures in the building.

The relationship between air density ρ and temperature T (in °K) is described by:

$$\rho = 0 \cdot 079 \left(\frac{273}{T}\right) \text{lb/ft}^3 \quad \ldots (4)$$

The difference in air density between outside air and inside air is thus given by:

$$\Delta\rho = 0 \cdot 079 - 273 \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \text{lb/ft}^3 \quad \ldots (5)$$

where T_o is the outside air temperature and T_i the internal air temperature.

From this expression, the change of pressure differential with respect to vertical distance was calculated to be 0·00106 in wg/ft (0·0882 mm wg/m) for the assumed outside and inside air temperatures of 32°F and 68°F respectively.

6. Characteristic equation of airflow

The airflow through cracks around windows and doors can be expressed by the equation:

$$V = C.l\,(\Delta p)^{1/n} \quad \ldots (6)$$

where V is the volume flow of air in ft³/min;

C is the air leakage coefficient in ft³/min per foot of crack at a pressure difference of 1 in wg. It is a measure of the air tightness of the crack;

l is the total length in linear feet of the crack around the window or door (= total perimeter of opening parts);

Δp is the pressure difference across the component in wg, and

$1/n$ is an exponent in which n has a value between 1 and 2.

The values of C and n have been assessed for a range of window types from measurements taken on

*In Britain, the meteorological wind speed is measured at a height of 33ft (10m). (See Section 12.1).

finished building constructions and on individual assemblies in a number of countries. For various types of window the values of C showed a wide divergence, the most extreme values being 0·14 and 20 ft³/min ft in wg (0·1 and 15 m³/h m mm wg).

However, for the type of building under consideration the window quality is generally somewhat better than average and C values were therefore assumed to vary between the limits of 0·14 and 6·8 ft³/min ft in wg (0·1 and 5 m³/h m mm wg). For this investigation a C value of 1·15 ft³/min ft in wg (0·85 m³/h m mm wg) was selected to represent a well fitting window, while a value four times as high (4·6 ft³/min ft in wg) was chosen for an average window.

For the interior doors between room and corridor and between corridor and stairwell, C was taken as 23 ft³/min ft in wg (17 m³/h m mm wg) and for the main entrance doors it was assumed that double doors would be used, thus reducing the value of C to 16·3 ft³/min ft in wg (12 m³/h m mm wg).

The values for the exponent $1/n$ derived from a large number of test results were not subject to much appreciable variation. From an investigation carried out in the Netherlands some time ago on 16 different window types, the value of n was found to vary from 1·37 to 1·72. These values corresponded well with British and American data and a value of $n = 1{\cdot}6$ was taken as representative of average conditions.

The length of the crack for the windows and internal office doors was expressed in terms of the surface area of the building face. The values given in a number of reports[11, 12, 13] indicate that the percentage of window area in a building façade can vary from 15 per cent to 65 per cent or, more unusually, to 90 per cent. The ratio of crack length to window area given by Harrison[14] as 0·7 to 1·4 ft per ft² was confirmed by analysis of a wide range of window types. Thus the range of window crack lengths per building surface area (l) was taken as 0·09 to 0·9 ft/ft². Specific crack lengths chosen for use in this study were 0·076, 0·305, 0·610 and 0·915 ft/ft² (0·25, 1·0, 2·0 and 3·0 m/m² respectively). The value of l for the office doors was assumed to be 0·152 ft/ft² (0·5 m/m²), and for the entrance door and corridor/stairwell doors a crack length of 33 ft (10 m) was used.

7. Summary of ventilation parameters used in study

Meteorological wind sped:
0, 10 and 20 mile/h

Wind approach angle:
90° (and 45° with square plan building).

Air temperatures:
outside 32°F, inside 68°F.

Building plan: rectangular and square.

Building height:
50, 100 and 200 ft
(five, ten and twenty storeys).

Position of entrance door:
windward or leeward.

Corridor/stairwell doors:
with or without.

Window leakage characteristics:
C = 1·15 and 4·6 ft³/min ft in wg
l = 0·076, 0·305, 0·610 and 0·915 ft/ft² building face.

Office door leakage characteristics:
C = 23 ft³/min ft in wg
l = 0·152 ft/ft² building face.

Corridor/stairwell door leakage characteristics:
C = 23 ft³/min ft in wg
l = 33 ft.

Entrance door leakage characteristics:
C = 16·3 ft³/min ft in wg
l = 33 ft.

Exponent of Δp:
n = 1·6.

8. Determination of ventilation rates

While it is relatively simple to calculate the flow through a simple aperature given the appropriate values of pressure and leakage factor ($C \times l$), the problem becomes extremely complex when a complete building, with external and internal pressure gradients and multiple flow paths, is considered. The solution is rendered particularly difficult by the exponential characteristic of the equations of the flow and normal calculation procedures are tedious and time consuming. A more suitable technique for the determination of ventilation rates throughout a building was required. Two methods were used in this study; one, an electrical analogue technique and the other a digital computer technique.

9. The electrical analogue method

There is an analogy between the flow of air through a building and the passage of an electrical current through a number of resistances in series and parallel. By using electrical resistances showing a relation between current and potential of the form:

$$i = C_1(E)^{1/n} \quad \ldots (7)$$

and providing adjustment of the values of C_1 and n, the problem was reduced to an electrical circuit of resistances in which the currents corresponded to air flows and the potential differences represented pressure differentials.

A test programme involving some 216 combinations of variables for rectangular plan buildings was conducted by the Institute for Public Health Engineering TNO on their electrical analogue instrument. The instrument[15], evolved specifically for ventilation studies, simulated each window and door crack by one or more electrical lamps connected in parallel and in combination with series or shunt resistances or both.

For representation in the electrical analogue, the buildings were subdivided into five equal horizontal sections corresponding to one, two and four storeys for the three building heights considered. The resistances in the analogue were set to correspond with the window and door characteristics for each condition. The pressures generated by the wind and/or stack effects at the five levels were applied as potential differences at corresponding points in the analogue circuitry. A measuring panel was provided on which the currents (= airflows) and potentials (= pressures) at selected points in the circuitry were indicated.

10. The digital computer method

A digital computer programme for calculating the air flows and pressures throughout a naturally ventilated building was developed from a programme originally designed for the determination of flows and pressures in

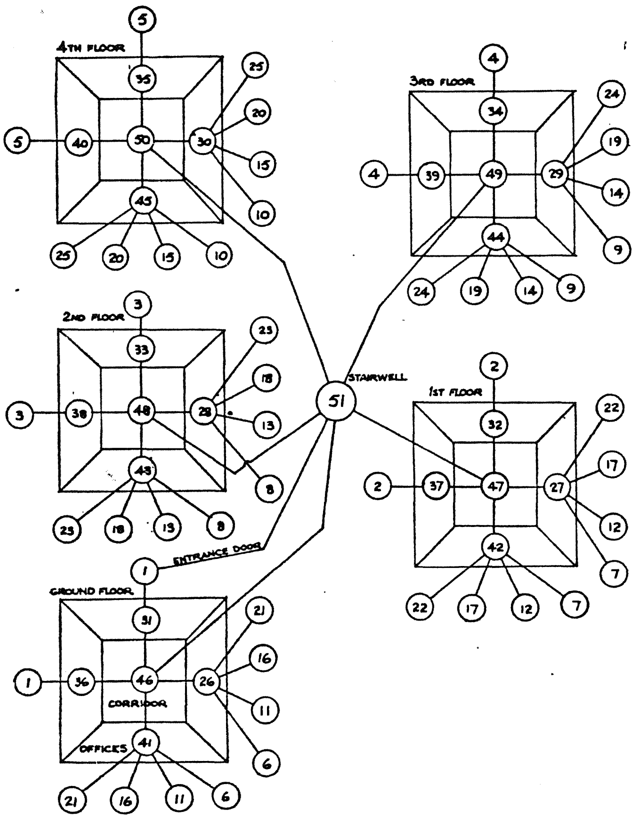


Fig. 5. Example of identification of Air Flow Paths for use in digital computer programme

pipe networks. To use the programme, the ventilation paths in the building under consideration were defined by a series of interconnected nodes, as illustrated by the example in Fig 5. Each node in the network was separately identified and Equation (6) was used to specify the flow between them. The relevant coefficients, i.e. leakage factor ($C \times l$) and exponent ($1/n$) for each flow path, were tabulated together with the known pressures (due to wind and/or stack effects) at some of the nodes. With these data, the programme approached a solution by making successive corrections to the pressure value at each of the nodes at which the pressure was not specified, until a flow balance at each of these nodes was achieved. The print-out of the results of the computer calculation incorporated the value and direction of the flow rate between all the connected nodes and the pressure level at each node.

11. Analysis of results

11.1 Comparison of the analogue and digital methods

At an early stage during the investigation comparisons were made between the results derived by the analogue and the digital methods for a small number of selected conditions. Good correlation between the sets of results was evident, as shown by the sample on Fig 6.

Apart from some difficulty in setting the electrical analogue to accurately represent selected leakage characteristics, there was little to choose in terms of speed and efficiency between the two methods of determining air flows in naturally ventilated buildings. The scope of both methods may be extended to include mechanical ventilation and buildings of particular design, but as the use of the digital method is dependent only on the availability of a digital computer of suitable capacity, it is considered to be the more versatile technique. Details of the computer programme can be made available to those wishing to use this technique in the study of the ventilation of particular buildings or of other specialised ventilation problems.

11.2 Ventilation rates

For purposes of general analysis, the infiltration rates at each floor level were summated to give the ventilation rate of the entire building (equal to the total exfiltration). It was found convenient to plot these total ventilation rates versus the window leakage factor for the wind speeds and range of building heights considered. The graphs on Figs. 7, 8 and 9 relate to the rectangular plan buildings incorporating corridor/stairwell doors while those on Fig. 10 show the results for a similar ten-storey building without such doors. Values of air change rate, which were derived assuming the width of the offices were 21ft (6·5 m) and related to one side of the building only, are superimposed on the vertical scales of these graphs.

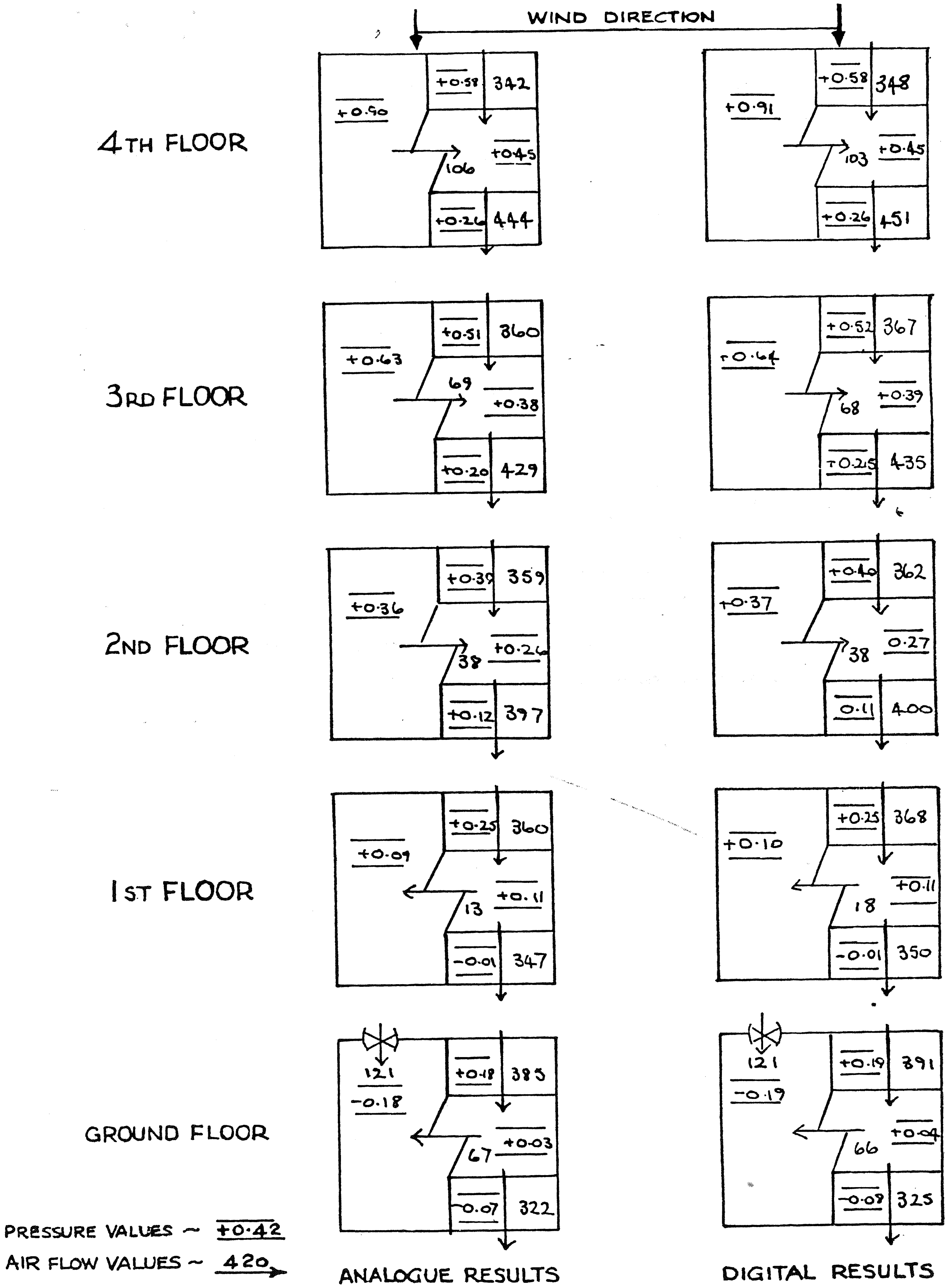
The results derived with the square plan buildings are shown, in terms of total ventilation rates plotted against window leakage factor, on Figs. 11, 12 and 13. The curves are similar in form to those shown on Figs. 7, 8 and 9. Under equivalent conditions more ventilation was generated by a wind approaching the square plan building at 45° to one face than at 90°, the maximum ratio being approximately 1·2:1. However, making a comparison on the basis of unit window area and equivalent wind speeds and window leakage factors shows that the maximum ventilation in the square plan building is lower than that in the rectangular building by some 25 per cent. Thus the rectangular plan building may be taken as the basis for ventilation assessment with a suitable reduction factor applied for square plan buildings with openable windows on all four sides.

The rates of ventilation were somewhat less than the values suggested in the *IHVE Guide*[3] for design calculations. For instance, the average air change rate for the offices in a 20-storey building with large average fitting windows in a 20 mile/h wind was found to be 1·3 times per hour and for small, well-fitting windows the equivalent rate of air change was 0·2 times per hour. In equivalent conditions the ventilation rates for five- and ten-storey buildings were substantially lower. The design values in the *IHVE Guide* range from 1·5 to 1·75 for office buildings of more than five storeys. Thus the *Guide* gives an over-estimate of the likely ventilation rate, particularly significant when small, well-fitting windows are used in the building.

11.3 The influence of wind and stack effects

In the initial analysis of the results it was desirable to determine those parameters which had little or no influence on the ventilation rate and to isolate those whose influence warranted further consideration. In fact, the ventilation process was influenced to a significant extent by the majority of the parameters considered, the only minor factor being that of the positioning of the entrance door, on the windward or leeward sides.

However, the variation of such factors as buildings height and wind velocity produced predictable changes to the total ventilation rate. For instance, for a building subject to wind pressures it is possible to determine a relationship between ventilation rate and building height by combining the equations relating velocity to building height, pressure difference to wind velocity, and airflow to pressure difference and building height.



Wind Speed 20 m.p.h. Temperature Difference (Indoors to Outdoors) 20°C

Fig. 6. Comparison of analogue and digital results

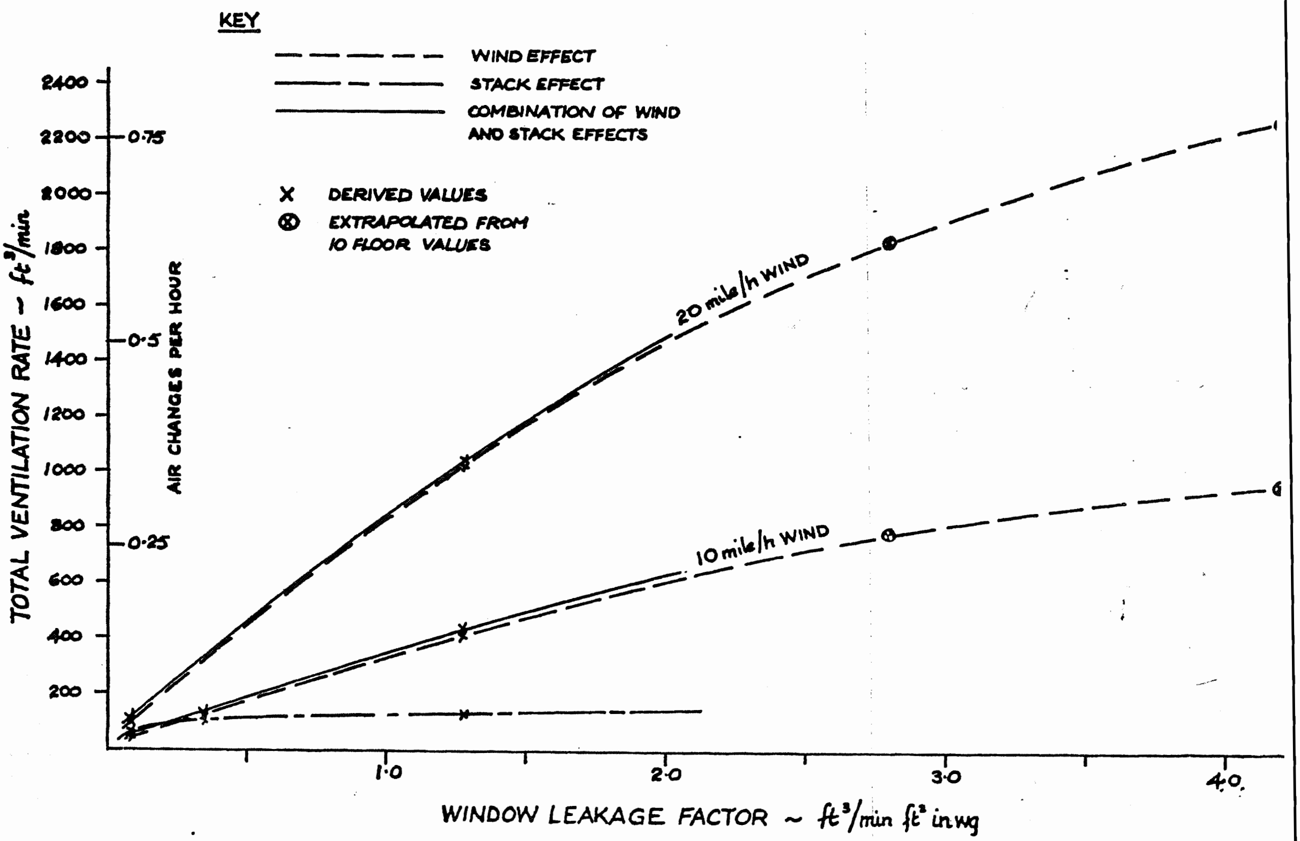


Fig. 7. Natural ventilation of 5 floor rectangular plan building (with corridor to stairwell doors)

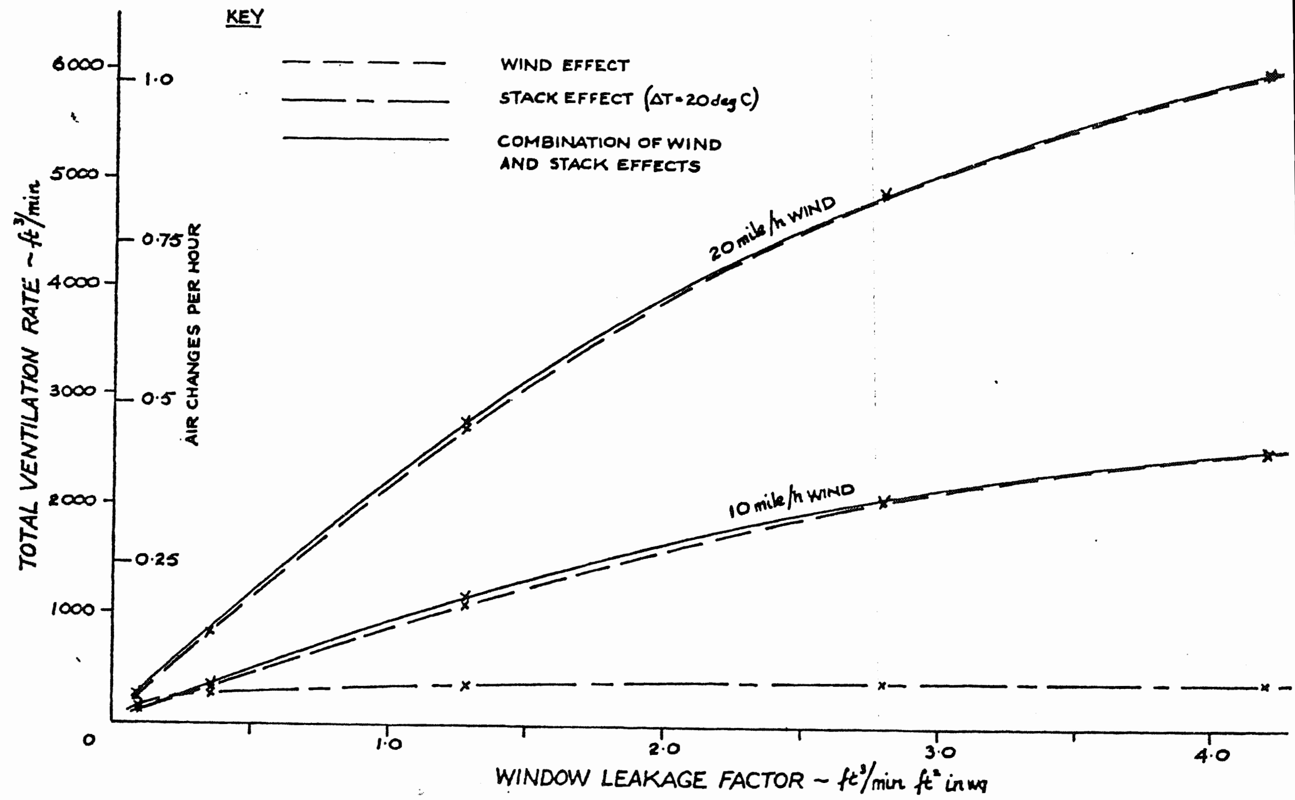


Fig. 8. Natural ventilation of 10 floor rectangular plan building (with corridor to stairwell doors)

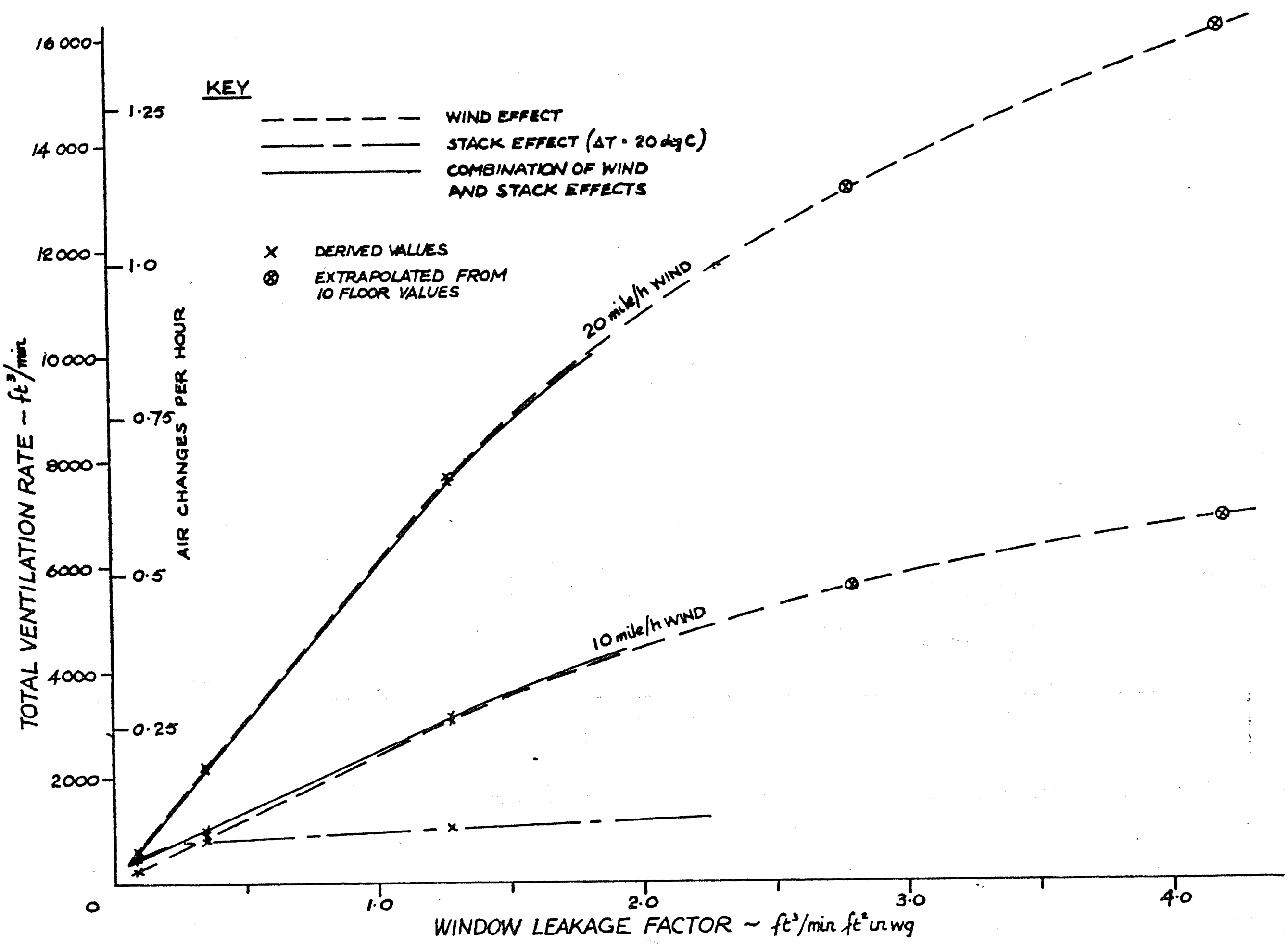


Fig. 9. Natural ventilation of 20 floor rectangular plan building (with corridor to stairwell doors)

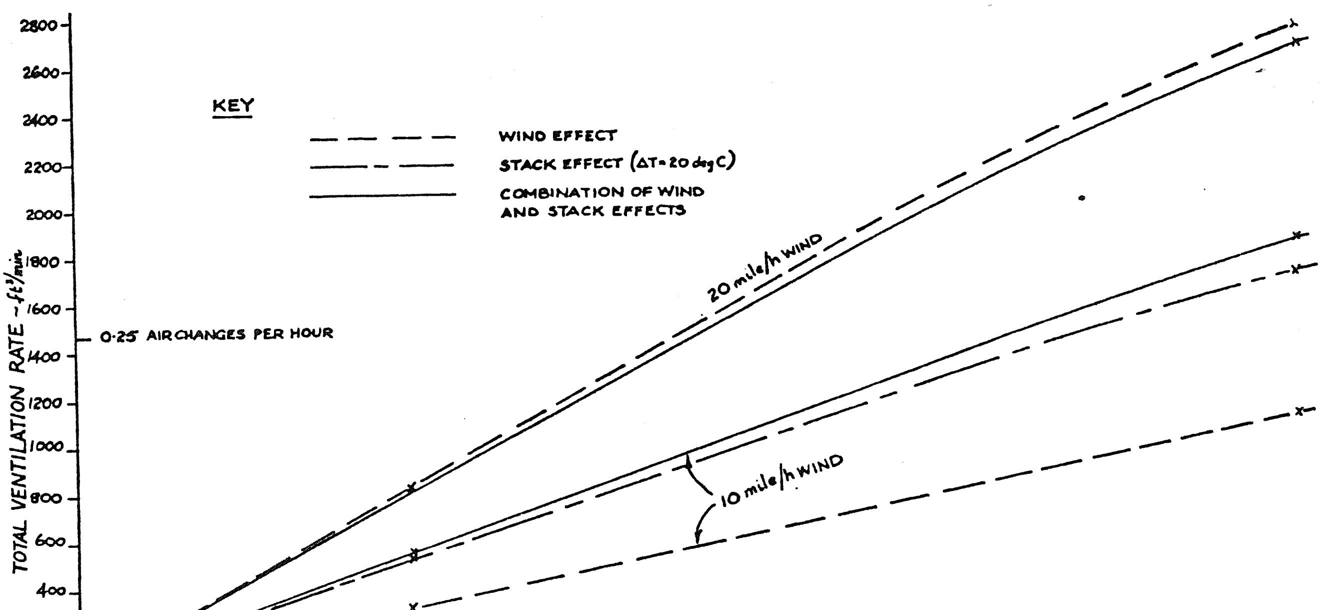


Fig. 10. Natural ventilation of 10 floor rectangular building (with no corridor to stairwell doors)

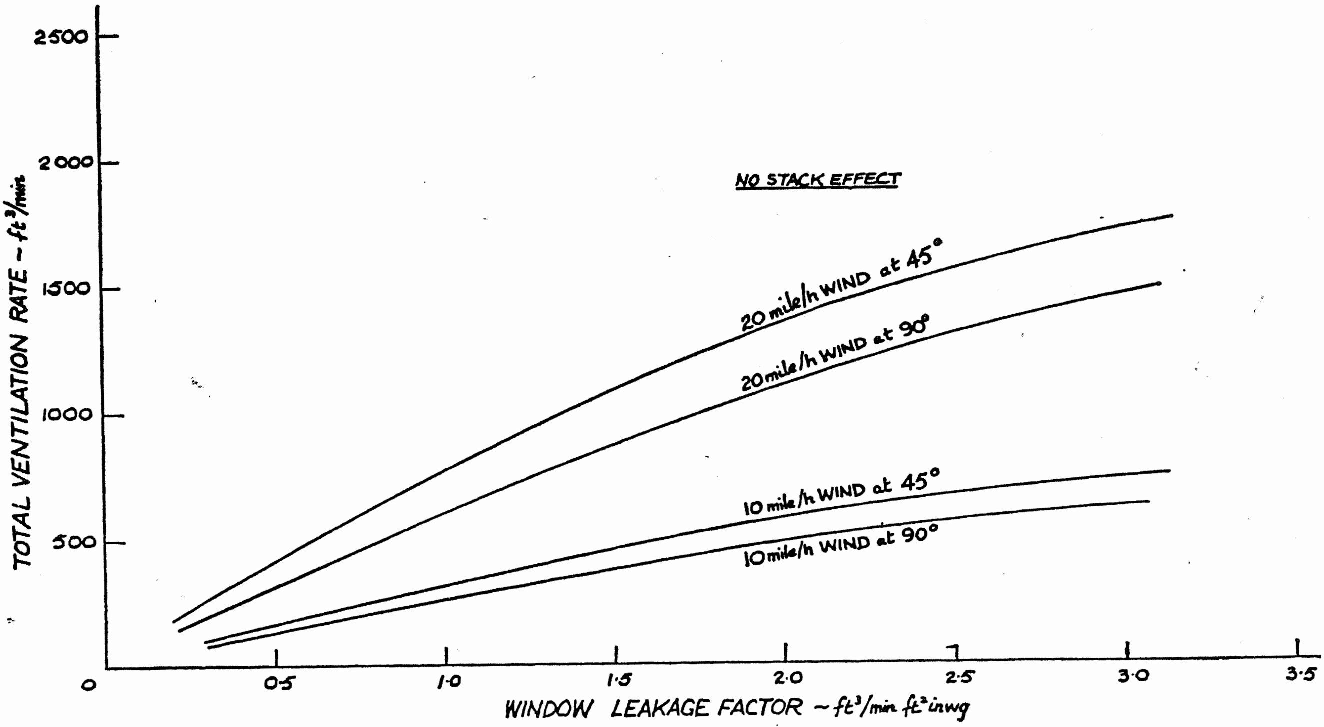


Fig. 11. Natural ventilation of 5 floor square plan building (with corridor to stairwell doors)

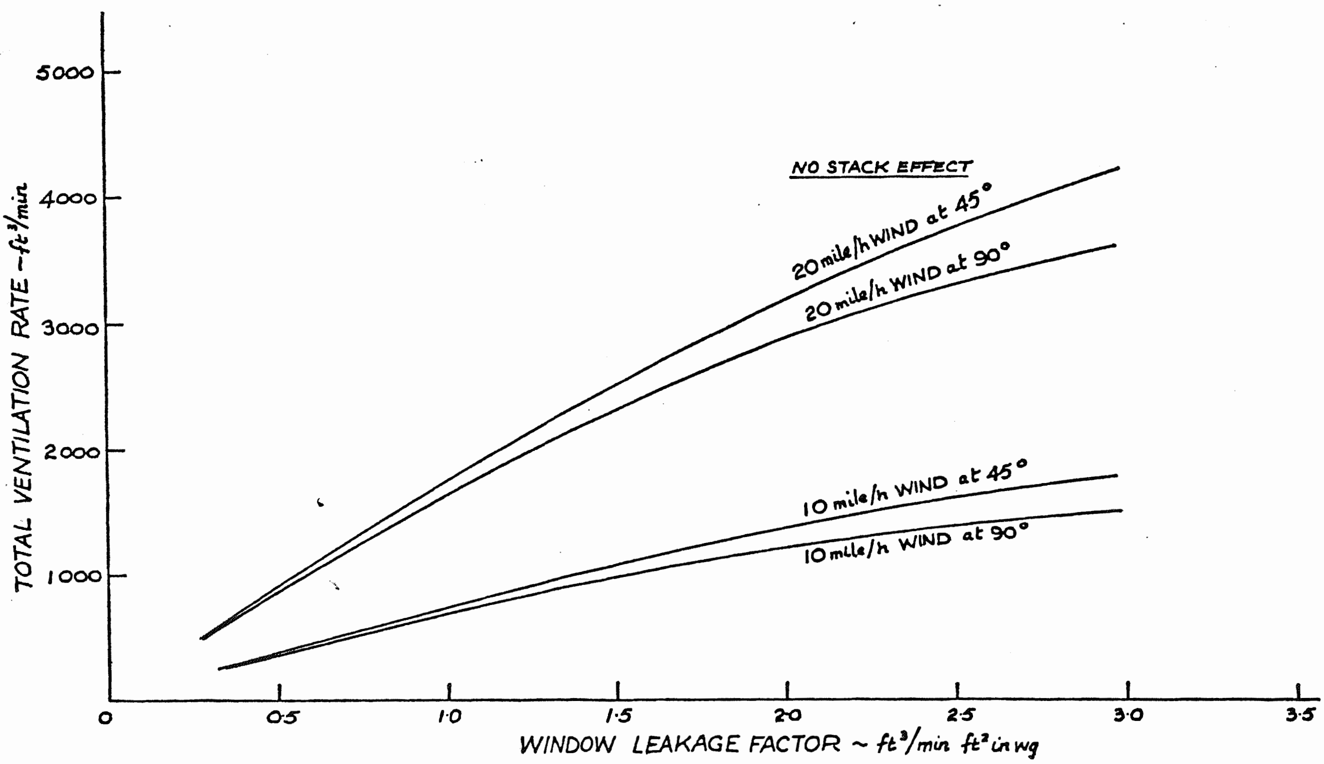
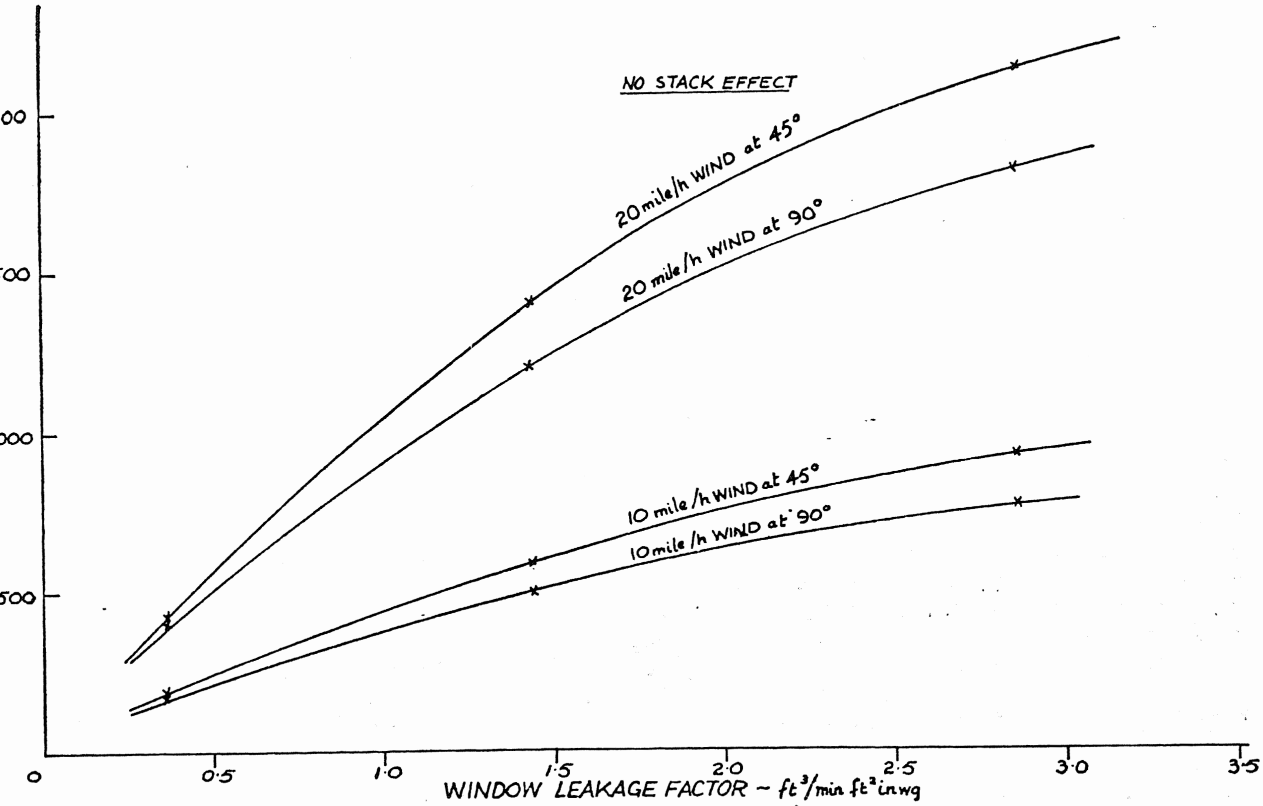
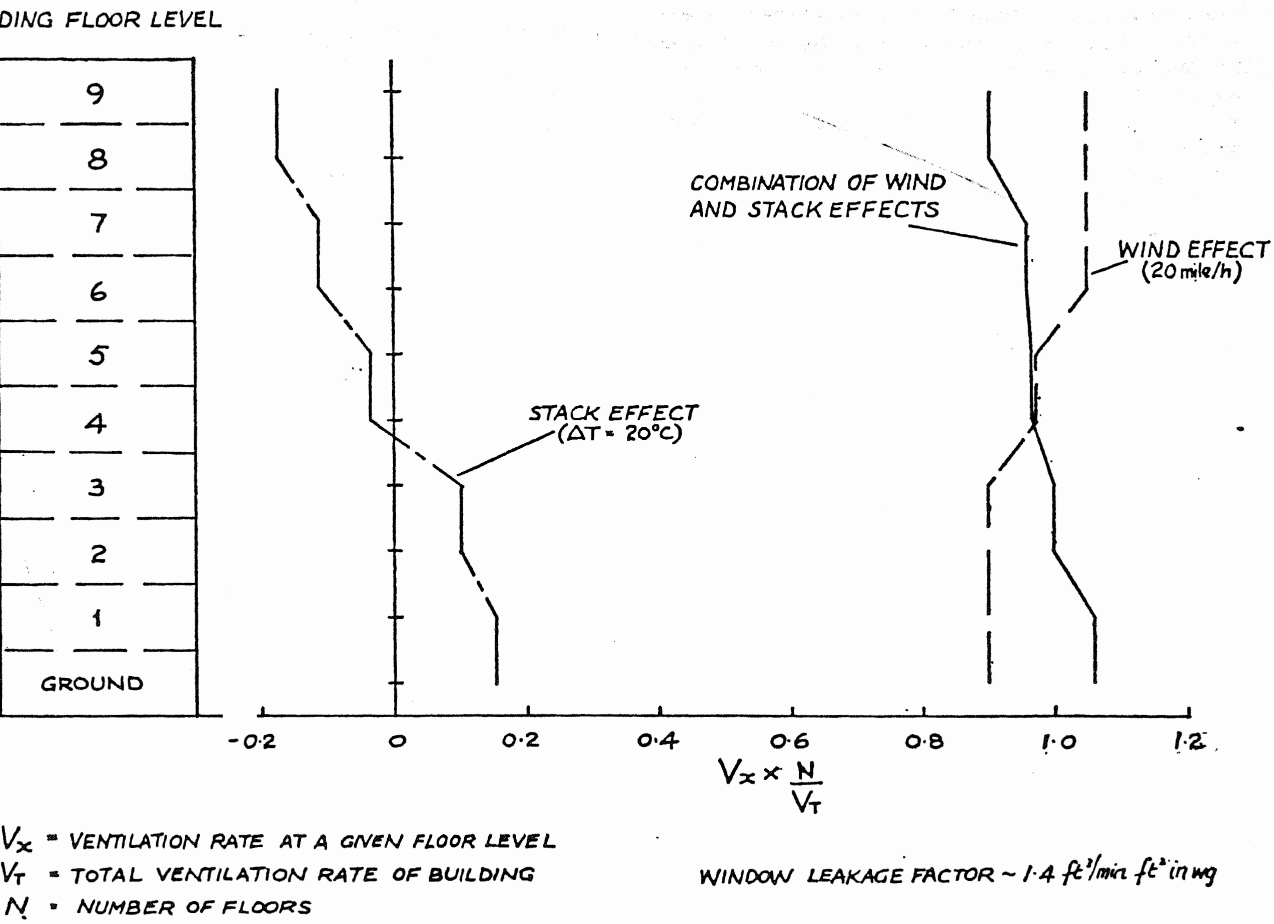


Fig. 12. Natural ventilation of 10 floor square plan building (with corridor to stairwell doors)



13. Natural ventilation of 20 floor square plan building (with corridor to stairwell doors)



. 14. Natural ventilation in windward rooms of 10 floor rectangular plan building (with corridor to stairwell doors)

This gives: $V \propto ch^{1.42}$*. Therefore, doubling the building height could be expected to increase the ventilation rate by a factor of $2^{1.42}$, i.e. 2.67. The equivalent ratio in the test results ranges from 2·62 to 2·78 (i.e. − 2 to + 4 per cent error). Similarly, the ventilation rate may be related to wind speed, viz. $V \propto v^{1.25}$**. That is, doubling the wind speed could be expected to increase the ventilation rate by a factor of $2^{1.25}$ (2.38). The ratio between the ventilation rates generated by the two wind speeds, 20 mile/h and 10 mile/h, was found to range between 2·36 and 2·50, the lower values being associated with the digital method and the higher values with the analogue method. Further relationships may be derived for buildings under the influence of stack effect.

Once the total ventilation rate has been calculated for a given set of circumstances, adjustments to this ventilation rate, due to changes in the parameters of building height, wind velocity and temperature difference, can be readily made, at least when the motivating forces of wind or temperature differences are acting independently.

With wind and stack effects acting together, the resulting total airflow into the building was found to be approximately equal to the flow caused by the greater influence when acting on its own. This is best illustrated by Fig. 10 relating to a 10-storey building with no corridor/stairwell doors. In this case the stack effect was greater than that of the 10 mile/h wind but less than that of the 20 mile/h wind. In the combination of stack and the 10 mile/h wind the effect was approximately the same as that due to stack effect alone, while combining the stack and 20 mile/h wind effects produced a total ventilation rate equivalent to that caused by the wind on its own. This feature has been similarly noted by Dick[16].

The inclusion of corridor/stairwell doors had the effect of restricting the flow of air between the corridors and the stairwell at each floor level, thus considerably reducing the ventilation caused by stack effect. (Compare Figs. 8 and 10.) Thus in such buildings the ventilation, due to the action of the wind, mainly in the horizontal direction, was substantially greater than that caused by stack effect, with the result that combination of the two motive forces produced a ventilation rate approximately the same as that due to wind pressure alone. This is shown by the proximity of the appropriate pairs of lines on Figs. 7, 8 and 9.

As modern offices are normally fitted with corridor/stairwell doors to comply with fire regulations, the total ventilation rates can be assessed by considering the action of wind on its own, assuming that the difference between inside and outside temperature is of the order of 36 deg F. In applications where the temperature difference is two or three times greater than this some consideration may have to be given to the increased stack effect.

It is worth noting that, although the stack effect did not modify the total ventilation rate in such buildings, it had some influence on the proportional air infiltration at each floor level. Fig. 14 shows an example of the difference between the infiltration pattern with wind alone and that with the combined influence of wind and temperature difference on a building with average window leakage.

The deviation of the ventilation rate at any floor level from the average value for the building is given in the table below for the buildings of five, 10 and 20 storeys with corridor/stairwell doors.

Table 3

Condition	Building Storeys	Ventilation—% higher than the average	Level of maximum ventilation
Wind acting alone	5	3%	topmost floors
	10	6%	topmost floors
	20	8%	topmost floors
20 mile/h wind+ stack effect (36 degF)	5	3%	lowest floors
	10	10%	lowest floors
	20	20%	lowest floors

11.4 The influence of component leakage

For a given pressure difference it has been shown that the airflow through a component such as a closed window or door is in a linear relationship with its leakage factor ($C \times l$). There is also a relationship between the leakage factors of components linked in an air path such that the overall leakage factor may be derived as follows, assuming an identical value of n in all terms:

$$\left(\frac{1}{Cl}\right)^n_o = \left(\frac{1}{Cl}\right)^n_1 + \left(\frac{1}{Cl}\right)^n_2 + \left(\frac{1}{Cl}\right)^n_3 + \quad \ldots (8)$$

in parallel

$$(Cl)_o = (Cl)_1 + (Cl)_2 + (Cl)_3 + \quad \ldots (9)$$

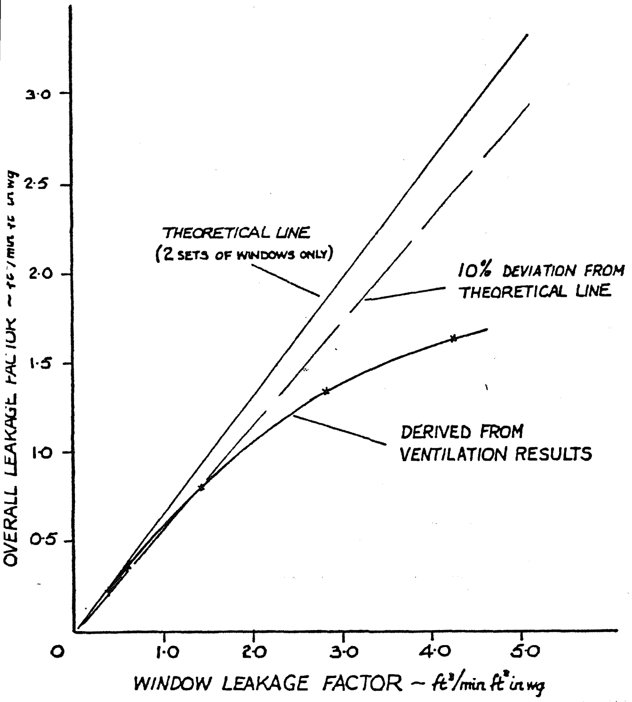
While it may thus be possible to derive an overall leakage factor for a complete building, the calculation involved is complex, particularly for components in series. However, it was possible from the results of total ventilation rates to derive overall leakage factors by using the average pressure drop across the buildings in Equation (6). A curve of the overall leakage factors so derived for the rectangular buildings with a range of window leakage factors is shown on Fig. 15, where it is compared with a line indicating the calculated overall leakage factor based solely on the window leakage, i.e. two sets of windows in series at each floor level. The former curve lies within 10 per cent of the latter up to a window leakage factor of 1·10ft³/min ft² in wg (2·7 m³/m² mm wg). This is equivalent to a ratio of window leakage factor/internal leakage factor of 0·3. This ratio was found to be similarly appropriate to the square plan buildings. For convenience, therefore, data may be presented in terms of the window leakage factor with the introduction of a correction factor for conditions in which the window leakage factor/internal leakage factor ratio exceeds 0·3.

11.5 Infiltration allowance in heating system

In all the established conditions, air entered on part of the building and left though another part so that not all of the rooms were subject to the infiltration of fresh air at the same time. Generally, the air passed from one side of the building to the other (wind effect) or from the lower floors to the upper floors (stack effect) so that fresh air was infiltrating into approximately one-half of the rooms at any one time. However, in the case of the

*$V \propto h^3$ (Equation (3)), $\Delta p \propto v^2$ (Table 1) and $V \propto h(\Delta p)^{\frac{1}{1.6}}$ (Equation (6)) so that $V \propto h\,[(h^{\frac{1}{2}})^2]^{\frac{1}{1.6}} = h^{1.42}$

**$\Delta p \propto v^2$ (Table 1) and $V \propto (\Delta p)^{\frac{1}{1.6}}$ (Equation 6) so that $V \propto (v^2)^{\frac{1}{1.6}} = v^{1.25}$



ig. 15. Overall leakage factors for rectangular buildings

;quare plan building, with wind perpendicular to one of he faces, only the windward rooms were subject to fresh ιir infiltration, and exfiltration was taking place on the ›ther three sides of the building.

\ distinction must therefore be made between the ›verall heating load imposed by natural ventilation in vinter and the heating allowance for infiltration in ndividual rooms. In any given situation the windward ·ooms will carry the majority of the infiltration load and :he room heating appliances must be capable of catering 'or changes of wind direction, so that the rooms on all sides of the building need equal provision for infiltration. t follows that in the rectangular building the boiler capacity required to meet the actual overall infiltration at any one time will be approximately half the heating load derived by summating the infiltration allowances for each room. In the square plan building, with rooms on all four sides, the boiler capacity allowance need only be about a quarter of the total heating provision for infiltration in the rooms.

12. The estimation of total rates of natural ventilation for design purposes

A design method for the estimation of the natural ventilation of an existing or projected building has been devised from the results of this study. The method involves the knowledge of a minimum number of parameters and allows the determination of rates of ventilation with the minimum of calculation.

The results indicated that the process of natural ventilation of a building is governed mainly by the action of wind and the leakage of windows. These are the two criteria on which the estimation procedure is based; its principle and operation are outlined as follows.

12.1 The action of wind

It has been shown that local wind speed may be related to the meteorological wind speed taking account of the type of terrain in which the building is sited (see Section 4). In this country meteorological wind speed is related to a height of 33ft (10 m) from ground level and the variation of wind speed with height is defined by Equation (1). With these data, and that already assumed for an urban area, wind speeds at various heights over flat, open country and over a town environment were calculated for meteorological wind speeds of 10 and 20 mile/h. The pressures generated on the faces of a building are related to the wind speed at roof level (see Section 3) and the mean pressure difference across the building in the direction of the wind is 1·1 times the velocity head at roof level (+ 0·7 on the windward face and − 0·4 on the leeward side). Using these relationships the upper part of the proposed 'Natural Ventilation Chart' (Fig. 16) has been plotted, so that for a building of known height in either an urban or exposed site subjected to a design meteorological wind speed of 10 or 20 mile/h, the mean pressure difference (termed 'pressure factor') may be determined.

12.2 Window leakage

On the assumption that, in the flow path through a building, the windows present by far the greatest resistance to airflow, the natural ventilation process may be considered in terms of sets of windows in series with a pressure difference (due to wind) acting across them. The rate of air flow through the building can thus be assessed from the knowledge of the pressure difference and the overall leakage factor of the windows, using Equation (6). The lower part of the 'Natural Ventilation Chart' consists of ventilation rate plotted against pressure factor for three grades of window leakage. These three grades, identified by the upper limit of their leakage coefficients, correspond approximately to different types of metal-framed windows, as follows.

Table 4

Leakage Coefficient	Window Type
ft³/min ft in wg	
1·0	Horizontally or Vertically Pivoted—weather-stripped
5·0	Horizontally or Vertically Pivoted—non-weather-stripped
2·5	Horizontally or Vertically Sliding—weather-stripped
5·0	Horizontally or Vertically Sliding—non-weather-stripped

It is, however, anticipated that the British Standard Code of Practice for windows and roof lights, now in course of preparation, will specify acceptable window leakage rates for different classes and exposure of buildings. These criteria could easily be substituted in place of the three grades suggested above.

The 'Natural Ventilation Chart' provides a simple method for the estimation of the ventilation rate (per foot of window opening joint) given the building height, location, window quality and wind speed.

12.3 Internal resistance to air flow

The 'Natural Ventilation Chart' is based on the assumption that the windows present the greatest resistance to flow. For the majority of cases (particularly with the

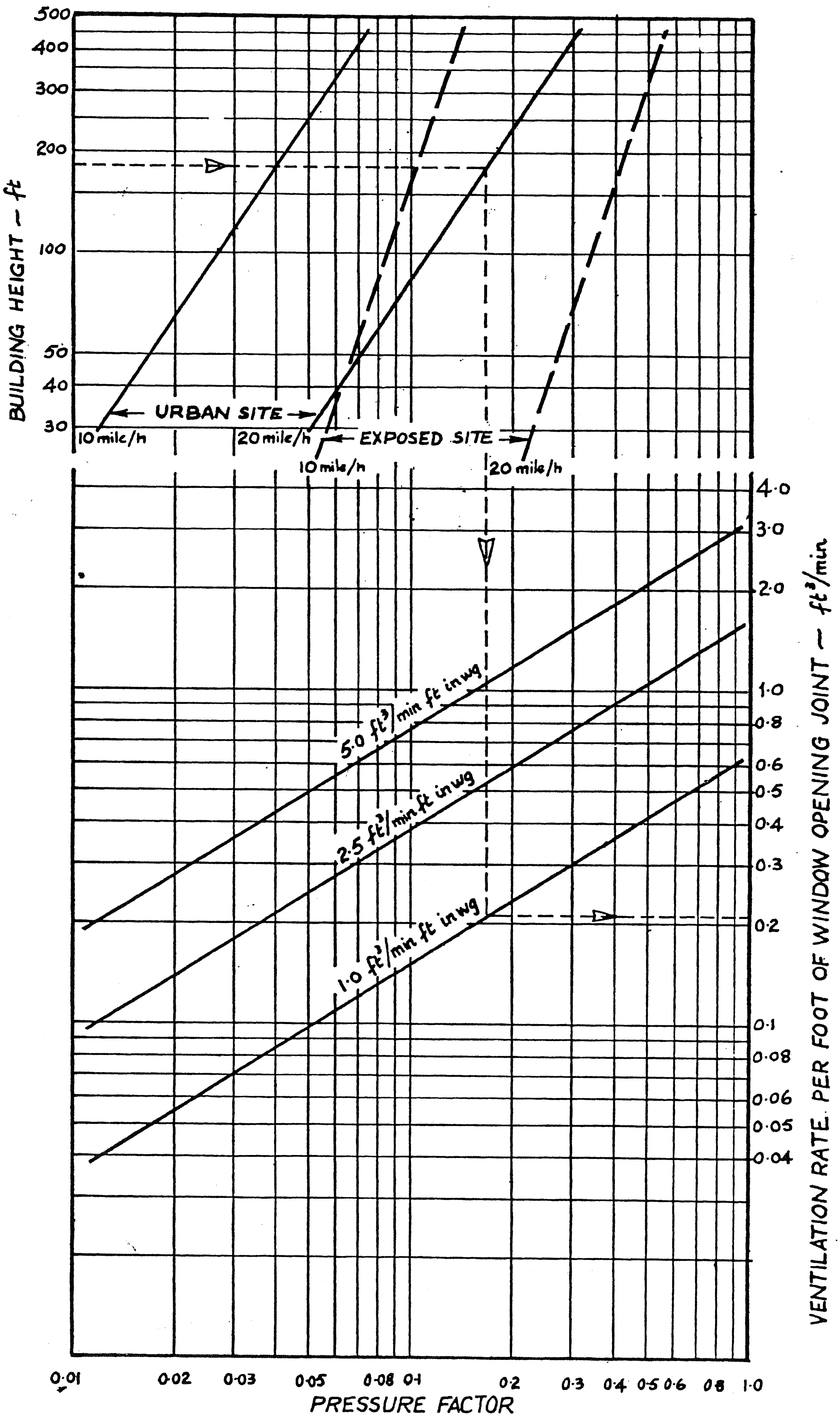


Fig. 16. Natural ventilation chart

modern trend for 'open plan' design) in reality this will be so, but, if the internal structure of the building is such that substantial resistance to air flow is introduced, then the estimated ventilation rate will be too high and correction should be applied. The degree of correction required is dependent on the ratio of the leakage factor of the windows to that of the internal structure, as is shown on Fig. 17. This curve has been derived on the assumption that the exponent in the air flow equation is identical for all leakage paths and equal to 1·6. If the ratio is 0·3 or less, then the error in the ventilation rate will be below 10 per cent and therefore no correction need be applied. If the leakage factor of internal structure equals that of the windows, i.e. factor ratio = 1, then the derived ventilation will need to be corrected by multiplying by 0·65. As the ratio increases to values beyond 4, i.e. very high internal resistance and many poor quality openable windows, the correction factor, by which the ventilation rate should be multiplied, approximates to the reciprocal of the ratio itself.

A designer is unlikely to have sufficient data to calculate the leakage factor of the internal structure of the building. However, the degree of resistance of the internal structure in comparison to that of the windows can be approximately assessed and correction factors determined. The following table gives some examples.

Table 5

Window Type	Internal Structure	Correction factor
All types	Open plan (no full partitions)	1·0
Short length of well fitting window opening joint	Single corridor with many side doors	1·0
Short length of well fitting window opening joint	Liberal internal partitioning with few interconnecting doors	1·0
Long length of well fitting window opening joint or short length of poor fitting joint	Single corridor	1·0
Long length of well fitting window opening joint or short length of poor fitting joint	Liberal partitioning	0·8
Long length of poor fitting joint	Single corridor	0·8
Long length of poor fitting joint	Liberal partitioning	0·65
Very long length of poor fitting joint	Single corridor	0·65
Very long length of poor fitting joint	Liberal partitioning	0·4

'2.4 *Total ventilation rate*

[he ventilation rate derived from the 'Natural Ventilation ːhart' is in terms of unit length of the window opening oint. The total rate of ventilation in the building is letermined by multiplying the derived ventilation rate ɪy the total length of window opening joint, *and* by an ɪrea factor.

'he area factor is equal to a representative cross-ectional area divided by the total area of the building

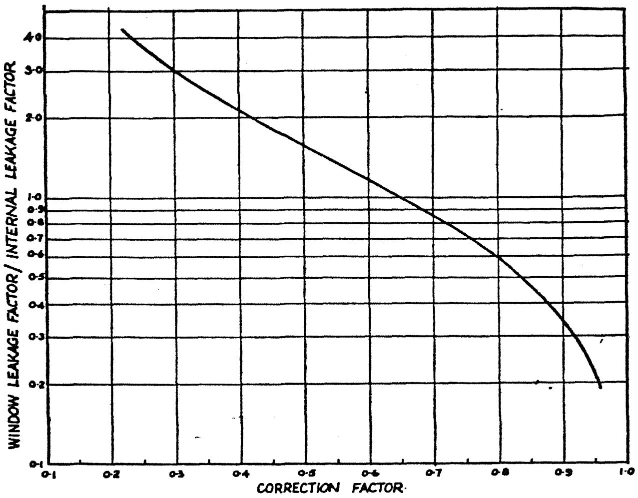


Fig. 17. Ventilation correction curve

faces in which the openable windows are located. The representative cross-sectional area depends on the number of walls in which there are openable windows and this is illustrated in Fig. 18. For a building with two sealed end walls (usually a long rectangular building) the representative cross-sectional area is the area of one of the glazed faces. In the case of a building with glazing on all four sides the representative cross-sectional area is that of the vertical diagonal plane. This makes allowance for the fact that the ventilation per unit face area of such a building is approximately 25 per cent less than that in a long rectangular type.

The following example illustrates the steps in the estimation of the rate of natural ventilation.

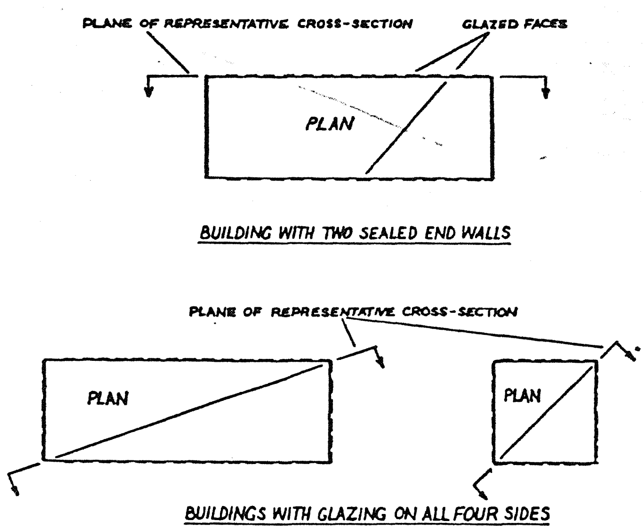


Fig. 18. Representative cross-sections for area factor calculation

Problem

To find the rate of natural ventilation in a rectangular plan building of 150 × 60 × 180ft high located near a town centre for a winter design wind speed of 20 mile/h. The building has metal horizontally pivoted windows on all four sides with an average length of opening joint (weather-stripped) per unit area of building face of 0·5ft/ft^2. The internal layout of the building is generally of 'open plan' design.

From the 'Natural Ventilation Chart', the pressure factor is determined for the height of 180ft (see dotted line on

Chart). The vertical line is then traced until it crosses the line for the appropriate window leakage, in this case, 1·0ft³/min ft in wg (see Table 4). A horizontal line projected from the point of intersection to the ventilation rate scale, gives a ventilation rate per foot of window opening joint of 0·21ft³/min. No correction is applied for an open plan office (see Table 5). The total window joint length is 0·5 × A, where A is the sum of the area of all four sides of the building. The area factor is equal to the diagonal cross-sectional area (Fig. 18) divided by A,

and is given by $\frac{\sqrt{150^2 + 60^2} \times 180}{A}$

The total ventilation rate

$$= 0{\cdot}21 \times 0{\cdot}5 \times A \frac{\sqrt{150^2 + 60^2} \times 180}{A}$$

$$= 0{\cdot}21 \times 0{\cdot}5 \times 162 \times 180$$

$$= \underline{3060 \text{ft}^3/\text{min}}$$

This rate of ventilation is equivalent to an air change rate of approximately 0·5 times/hour (in windward office area assuming infiltration on one side of the building only) compared to 1·3 air changes/hour given by the *IHVE Guide*.

The total ventilation rate so determined will be valid for buildings in which the window characteristics are similar on all of the glazed faces of the building and where the openable windows are reasonably equally distributed over the building faces. It has also been assumed that the building is uniform in shape and is substantially square or rectangular in plan with similar types of internal layout on each floor.

In instances where the building features do not conform to these assumptions it may well be possible to estimate the ventilation rates for particular zones or groups of similar floors and make a summation to determine the total ventilation rate. In such circumstances the effectiveness of the estimation method will depend on the judgement of the designer involved, but for particularly complex or unique buildings, specific analysis of the ventilation process will need to be undertaken for which purpose the computer programme developed for this study may be advantageously used.

13. Conclusion

The rates of ventilation derived in this study for both rectangular and square plan buildings were somewhat less than the design values suggested in the *IHVE Guide*. The over estimate of the *Guide* is particularly significant when well fitting windows are used.

A comparison, based on unit window area, revealed that the maximum ventilation rates in the square plan building, were some 25 per cent lower than those in the rectangular building. Thus the rectangular building may be employed as the basis for the assessment of ventilation with the incorporation of suitable modification to take into account the lower rate of ventilation in a square plan building.

The test results indicate that the ventilation of a building is significantly affected by the majority of the parameters considered. The combined action of the wind and stack effects was approximately equivalent to that of the greater of these motive forces acting alone. In the case of a building with doors isolating each floor level from the stairwell (these are normally fitted to comply with fire regulations) the effect of wind was predominant, so that an assessment of ventilation rates may be made by considering the action of wind on its own. While the stack effect did not modify the total ventilation rate of the building, it had some influence on the proportion of ventilation at each floor level.

The relationship between ventilation rate and window leakage factor was found to be approximately linear until the influence of the resistance of the internal structure became evident. It should thus be convenient to present ventilation data in terms of window leakage criteria and make provision for the introduction of a correction factor to account for the internal resistance if necessary. On the basis of the test results, a design method for the estimation of natural ventilation was produced. This method involves the knowledge of a minimum number of parameters and allows a reasonably accurate determination of ventilation rates with the minimum of calculation.

Acknowledgements

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