4. THE NATURAL VENTILATION OF TALL OFFICE BUILDINGS

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SYNOPSIS

The factors on which the process of natural ventilation is dependent are both numerous and complex. At present the methods of estimation of the natural ventilation of buildings are either too laborious for general use or based on such broad approximations that their accuracy is questionable. A simple but accurate design procedure is desirable.

A study of the natural ventilation in elementary, tall office buildings has been made using the analogy between the flow of air through a building and the passage of an electrical current through a circuit of resistances. The prime motive forces, that of wind pressure and stack effect, are detailed and experimental values for these and other parameters related to the building are outlined. The results indicate that, for design purposes, natural ventilation can be assessed for modern slab buildings by prime consideration of the pressure generated by wind impingement and the air infiltration through windows so caused.

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NOMENCLATURE

C	air leakage coefficient	m^3/h m mm w.g.
C_1	coefficient of electrical resistance	
D	representative dimension in nature	m
E	potential difference	
T	air temperature	^oK
T_i	inside air temperature	^oK
T_o	outside air temperature	^oK
V	volume flow of air	m^3/h
Z	roughness parameter in nature	cm
d	representative dimension in model	m
h	height above ground	m
i	electrical current	
l	length of crack around window or door	m
n	exponent	
p	pressure	mm w.g. or kg/m^2
v	velocity of wind	m/sec
v_a	velocity of wind at known height h_a	"
v_g	gradient velocity of wind at height h_g	"
v_m	meteorological wind velocity	"
v_x	velocity of wind at height h_x	"
z	roughness parameter in model	cm
α	exponent	
ρ	air density	kg/m^3

1. INTRODUCTION

The air passing into and out of a building due to natural causes is not only likely to account for a significant proportion of the heating or cooling requirements but is also an important factor in determining the relative humidity and contaminant concentration of the air within the building. It is therefore important, at the design stage, to be able to assess the amount of natural ventilation that will take place under specified conditions in order that its effect may be counteracted or supplemented as required.

The prediction of rates of natural ventilation for buildings is a complex task at best and at present only the broadest of approximations are used. One method of estimating air infiltration 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 method, 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 but only the air change method is presented in the IHVE Guide[2]. The crack method has been adopted in the German Standard DIN 4701 (1958). The crack method, on which the work in this paper is based, 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 differences. In the detailed analysis of a complete building, such a method is too complex and laborious to warrant its general use by a designer. A simplified procedure is desirable.

A study, with this in mind, is being undertaken by the Heating and Ventilating Research Association in conjunction with the Institute of Public Health Engineering TNO in Holland. Analysis of the experimental results indicates that the prediction of the natural ventilation of elementary office buildings can be made in terms of a few major variables and it is anticipated that the use of such data, suitably interpreted to cater for specific conditions, may be extended to include more complex buildings.

2. THE FACTORS WHICH INFLUENCE NATURAL VENTILATION

The factors on which the process of natural ventilation is dependent, may be broadly divided into three categories, namely (a) the motive forces, (b) the external form and dimensions of the building and (c) the resistance to air flow through the building.

2.1. The Motive Forces

The two motive forces primarily responsible for natural ventilation are caused by wind impingement and air temperature differences. The study of the nature of wind and, in particular, its structural effects on buildings, has received considerable attention in recent years,[3,4,5] as taller buildings increase in number. Studies by wind tunnel techniques[6,7,8,9] and by direct measurement[9 & 10] have shown that regions of substantially different pressures are generated on a building located in an air stream. In general, a positive pressure exists on the windward face of the building while negative pressure (suction) is experienced on the leeward face and the faces parallel to the wind direction.

The wind pressure on a building is neither uniform nor constant since both the speed and direction of wind undergo continual change. In addition local topographical features have a significant effect on the wind by creating disturbances to the airflow and reducing the average wind speed at lower levels.

The second motivating force is the stack effect arising from temperature differences between air inside and outside the building. These differences result in differences in air density so that, over vertical distances, pressure gradients between inside and outside exist. 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 dependant on the distribution and comparative resistance to air flow of the aperatures in the building. If the aperatures are uniformly distributed then the neutral level will be at the mid-height of the building but should there be lower resistance to air flow at the lower levels then the height of the neutral zone will be reduced and vice-versa. In the case of internal air temperature being lower than that outside, the air flow will be reversed so that air will enter the upper part and be discharged at lower levels of the building.

2.2. Building shape and dimensions

The degree to which the natural forces produce ventilation is governed to a certain extent by the external form and dimensions of the building. For instance, one would expect the effect of wind to be different on a tall slender building than on a wide building of the same height.

For the initial stages of this investigation, a simple flat-roofed slab type of building, with the wind perpendicular to the long faces was studied. In order to eliminate the question of end effects the building was considered as a 50 m length of long block but in fact, apart from the rooms near each end, this is very nearly representative of a rectangular plan building in which the end walls are blank. A range of three building heights, 15, 30 and 60 m (equivalent to 5, 10 and 20 storeys) was selected.

2.3. The resistance to air flow through the building

The rate at which ventilation takes place in a building is not only dependant on the external forces but also on the resistance to the movement of air through the building. If the building structure is completely air tight then external pressures will produce no ventilation. On the other hand, considerable movement of air through the building will take place if there is low resistance to flow through the external and internal structure. Apart from openings specially designed for ventilation purposes, the aperatures through which air infiltrates and exfiltrates are doors and openable windows. This study has been conducted on the assumption that all windows and doors remain closed so that the passage of air is limited to the leakage paths or cracks around their periphery.

3. PRESSURE DISTRIBUTION AROUND A BUILDING DUE TO WIND

3.1. Variation of wind velocity with height

As several experimentors have shown,[11 & 12] there is considerable difference in the pressure distribution on the faces of a tall building, between that caused by a wind having uniform velocity and that caused by wind having an increasing velocity with height. The latter is the more realistic case but the velocity gradient is dependant on the type of terrain over which the wind is passing. Close to the ground, the higher friction caused by a built-up area results in a lower wind speed compared to flat, open terrain for which the meteorological wind speed is deemed to apply. The formula generally used to describe the velocity gradient of wind existing in the atmospheric boundary layer is:-

$$\frac{v_x}{v_a} = \left(\frac{h_x}{h_a}\right)^{1/\alpha} \qquad (1)$$

where v_x is the wind velocity at a height h_x, and v_a and h_a refer to a known velocity at a known height. The exponential term $1/\alpha$ varies in accordance with topographical nature of the terrain. A.G. Davenport[13] reviewed the values found for α at several places in the world. Within the extreme values of $\alpha = 10.5$ (coastal regions of the Caspian Sea) and $\alpha = 1.6$ (New York), he differentiates between three typical areas:

flat, open country	α	= 7
small towns, outer quarters of large cities	α	= 3.5
centres of large towns	α	= 2.0

Much less is known of the factor h_g, that is, the thickness of the boundary layer for which the above mentioned formula is valid and it cannot be determined as accurately as α. The wind velocity at height h_g is known as the gradient velocity v_g.

For this investigation, in which the case of a tall office building in an urban area was considered representative, the following values for h_g and α were assumed:

for flat open country (meteorological site)	h_g = 280 m, α = 7
for urban area	h_g = 500 m, α = 3

the selection of $\alpha = 3$ was based on the consideration that an urban environment would have a lower value of α than a small town and that an assumed value of $\alpha = 2$ equivalent to the centre of a large town, would result in an underestimate of the influence of wind on a single tall building in a more rural area.

3.2. Variation of velocity with height for model tests

In the investigation of the pressure distribution on a building using a model in a wind tunnel, it is obviously necessary to simulate the atmospheric boundary layer effect as accurately as possible. In consideration of this, Jensen and Franck [8] suggest that model test conditions in which the velocity profile in the wind tunnel is similar to that in nature may be achieved by coating the upstream bottom surface of the wind tunnel with an appropriate material. They introduce the term "roughness parameter" and state that the roughness parameter for the coating of the tunnel bottom must be proportional to the roughness parameter of the terrain under consideration:

$$\frac{Z}{z} = \frac{D}{d} \qquad (2)$$

where Z and z are the roughness parameter in nature and wind tunnel respectively, D and d are a dimension of the object in nature and tunnel respectively. For the city of Copenhagen, Jensen found that Z = 750 cm.

Some other values of the roughness parameter are as follows:

very smooth, harrowed soil	Z = 0.08 cm
grassland, 2 cm high grass	Z = 0.2 cm
stubble field	Z = 0.8 cm

Mention should be made of a specific advantage gained by adopting this artificial roughness, in that close agreement is obtained for the relation between turbulence as noted on the model and that occurring in reality. For representing a town, for instance, wooden blocks arranged in a zig-zag pattern on the bottom of the wind tunnel are used.

In this investigation, the measurements of pressure were made on a model 44 cm high with the wind in a direction perpendicular to the long sides. The height of the wooden blocks varied from 10 to 12 cm giving a value of z equal to 2 cm. Three building heights were considered, 15, 30 and 60 metres so that for these values the scale of the model was 1:34, 1:68 and 1:136 respectively. Thus for a value of z = 2 cm, the values of Z were 68, 136 and 272 cm. These values are representative of urban conditions, being much higher than those given for open countryside while being lower than the value of 750 cm found for the city centre in Copenhagen.

3.3. Results derived from model tests

Figure 1 shows the pressures measured on the vertical centre section of the model given in terms of the velocity pressure of the wind at a height equal to the top of the building. For convenience, the buildings have been sub-divided vertically into 5 equal sections and the air pressures developed over these sections have been averaged as given below:

Section	Windward side Average air pressure	Leeward side Average air pressure
1	+ 0.6 $\frac{1}{2}\rho v^2$	− 0.4 $\frac{1}{2}\rho v^2$
2	+ 0.6 $\frac{1}{2}\rho v^2$	" "
3	+ 0.7 $\frac{1}{2}\rho v^2$	" "
4	+ 0.8 $\frac{1}{2}\rho v^2$	" "
5	+ 0.8 $\frac{1}{2}\rho v^2$	" "

3.4. Calculation of pressure values due to wind at an assumed meteorological velocity

It is assumed that the meteorological wind velocity v_m occurs at a height of 6 metres. The gradient velocity v_g, may be found by inserting the assumed values of h_g and α in equation (1)

$$\frac{v_g}{v_m} = \left(\frac{280}{6}\right)^{1/7} \qquad (3)$$

i.e. $v_g = 1.73\ v_m$

According to Davenport, this gradient velocity can be found at 500 m. above a town, when α = 3. Therefore, at any height h_x above the town the wind velocity will be:

$$v_x = v_g \left(\frac{h_x}{500}\right)^{1/3} \qquad (4)$$

$$= 1.73 v_m \left(\frac{h_x}{500}\right)^{1/3}$$

so that for the three buildings in question the velocities at roof level will be:-

h_x = 15 m $\quad v_x = 1.73\ v_m \times 0.310 = 0.536\ v_m$
h_x = 30 m $\quad v_x = 1.73\ v_m \times 0.390 = 0.675\ v_m$
h_x = 60 m $\quad v_x = 1.73\ v_m \times 0.493 = 0.855\ v_m$

Thus, for a given meteorological wind velocity, the roof level velocity and consequently the pressure on the building face can now be readily calculated by making use of the pressure values found for the model.

The average value for the meteorological wind velocity throughout the entire year was taken to be 4.4 m/sec, approximately 10 miles/h. For our experiments values of 0, 4.4 m/sec and 8.8 m/sec were used. The following table gives the pressure values derived for the latter conditions.

TABLE 1

Wind Pressures

Meteorological wind velocity m/sec	Building height m	Section no.	Pressure mm w.g.	
			windward	leeward
4.4	15	1 & 2	+ 0.212	– 0.140
		3	+ 0.246	"
		4 & 5	+ 0.280	"
	30	1 & 2	+ 0.350	– 0.220
		3	+ 0.386	"
		4 & 5	+ 0.440	"
	60	1 & 2	+ 0.530	– 0.354
		3	+ 0.620	"
		4 & 5	+ 0.708	"
8.8	15	1 & 2	+ 0.84	– 0.56
		3	+ 0.98	"
		4 & 5	+ 1.12	"
	30	1 & 2	+ 1.32	– 0.88
		3	+ 1.54	"
		4 & 5	+ 1.76	"
	60	1 & 2	+ 2.12	– 1.42
		3	+ 2.48	"
		4 & 5	+ 2.84	"

4. PRESSURE DIFFERENCES CAUSED BY STACK EFFECT

The density of air varies with temperature and humidity. However, under normal ambient conditions the effect of humidity is negligible and the density of air is given by:

$$\rho = 1.3 \cdot \left(\frac{273}{T}\right) \qquad (5)$$

where T = air temperature in °K.

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

$$\Delta \rho = 1.3 \cdot 273 \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \qquad (6)$$

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

From this, the change of pressure differential with respect to vertical distance is calculated to be 0.0882 mm w.g./m using outside and inside air temperatures of 0°C and 20°C respectively, being the normal winter time design values.

5. INTERNAL LAYOUT OF THE BUILDING

The layout of offices and corridors, which were identical on each floor is shown in Figure 2 and is taken to represent a simple office block.

Offices were incorporated along both of the long sides of the building with a central corridor leading to a stairwell which extended from the ground to the top floor. The arrangement at ground floor level included an entrance door leading into the stairwell. Internal doors providing access to the offices were located along both sides of the corridors and alternative arrangements, with and without doors separating the corridor and stairwell, were considered. Both of the long sides of the building had identical window configurations.

6. CHARACTERISTIC EQUATION OF AIRFLOW

The equation governing the flow of air through cracks around windows and doors is:

$$V = C.\ell \; (\Delta p)^{1/n} \qquad (7)$$

where V is the volume flow in m^3/h.

- C — is the total air leakage coefficient in m^3 per hour per metre of crack at a pressure difference of 1 mm w.g., being a measure for the greater or lesser air-tightness of the construction of the crack.
- ℓ — the total length in lineal metres of the crack around the window or door (= total circumference of openable parts).
- Δp — the pressure difference over the window in mm w.g.
- $1/n$ — an exponent in which n has a value between 1 and 2. For a crack that closes badly n approximates to 2, whereas n approaches 1 in the case of a crack that closes well. There is a relation between n and C.

The values of C and n have been assessed for a range of window types from measurements taken on finished building constructions and on individual assemblies in a number of countries. It was found that the values for each type of window show a wide divergence. The most extreme values of the factor C, which is mainly a function of the tolerance to which the window has been constructed, were 0.1 and 15 m^3/m mm w.g. However, for the type of building under consideration the window quality is generally somewhat better than average and C values can be assumed to vary between the limits of 0.1 and 5 m^3/m mm w.g. For the present investigation, the average C value for a well fitting window has been assumed to be 0.85, while a value four times as high (3.4 m^3/m mm w.g.) was chosen to represent an average window.

For the interior doors between room and corridor and between corridor and stairwell, C has been taken as 17 m^3/m mm w.g., and for the main entrance doors it was assumed that double doors would be used reducing the value of C to 12.

The length of 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 [14,15,16] indicate that the percentage of window area in a building facade can vary from 15 to 65%. The ratio of crack length to window area given by Harrison [17] as 2.3 to 4.6 m/m^2 has been 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 0.30 to 3.0 m/m^2. For convenience crack length values of 0.25, 1.0, 2.0 and 3.0 were used in this study.

The value of l for the corridor doors was assumed to be 0.5 m/m^2 and for the entrance door and the corridor/stairwell doors the assumed crack length was 10 m.

The values for the exponential $^1/n$ derived from a large number of 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 and there was some indication that the higher n value corresponded with the higher C value. These exponential values correspond well with British and American data. For average conditions, the value of n in this case has been taken as 1.6.

7. THE ELECTRICAL ANALOGUE

7.1. Air flow through a building

While it is relatively simple to calculate the flow through a simple aperture given the appropriate values of pressure and leakage factor (C x l), the problem becomes extremely complex when a complete building, with external and internal pressure gradients and multiple flow paths, is considered. When calculating the natural ventilation, for instance in an office block, the number of unknowns is equal to the number of rooms; each room has a pressure level that is unknown. The solution is rendered particularly difficult by the exponential characteristic of the equations of flow and if the value of n is not the same throughout the building, then calculation becomes practically impossible.

7.2. The principle governing the electrical analogue model

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. An electrical resistance showing a relation between current and potential of the form

$$i = C_1 \ (E)^{1/n} \qquad (8)$$

(Compare with equation (7))

would mean that, provided the value of n (between 1 and 2) and that of C_1 could be adjusted at will, the problem could be reduced to an electrical circuit of resistances and groups of resistances in which the currents correspond to air flows and the potential differences represent pressure differences.

7.3. Simulation of test conditions on the analogue

The electrical analogue instrument evolved by the Institute for Public Health Engineering T.N.O. simulates each window or door crack by one or more electric lamps connected in parallel and in combination with series or shunt resistances or both. The analogue is provided with some forty built-in resistances of this kind, the proportionality constant being capable of regulation in the ratio of 1 to 50.

The instrument, which is provided with a measuring panel on which the currents (= air flows) and the intermediate potencials (= pressures) in the circuits can be determined, is illustrated in Figure 3.

For the application of the electrical analogue, the buildings were subdivided vertically into 5 equal sections, each section corresponding to 1, 2 and 4 storeys for the three building heights considered. The resistances in the analogue were set to correspond with the window and door characteristics for each test condition. The average pressures generated by the wind and/or stack effects at the 5 levels, were applied as potencial differences at corresponding points in the analogue circuitry. The currents and potencials in the "building" were determined at the measuring panel.

8. ANALYSIS OF RESULTS

8.1. Ventilation Rates

Typical results, in terms of the average ventilation rate per floor, are given in Figures 4 and 5. For convenient comparison with values given in the IHVE Guide [2], the ventilation rates in the present results may be converted to a number of air changes per hour by dividing by the office volume which was assumed to be $1000 m^3$. From Figure 4, it may be concluded that the mean air change rate for the buildings up to 20 storeys, under normal wind conditions would be somewhat below 0.6 times per hour and in a stronger wind (8.8 m/sec) would be below 1.3 times per hour. The design values given in the IHVE Guide range between 1.5 and 1.75 for office buildings of more than 5 storeys.

8.2. The influence or 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 investigation. In fact, the ventilation was influenced to a considerable extent by the majority of the parameters considered, the only minor factor was that of the positioning of the entrance door, on the windward or leeward sides.

The air flow due to the action of wind pressure alone, was substantially in the transverse direction and so was virtually unaffected by the presence or absence of corridor/stairwell doors. The influence of such factors as building height, wind velocity and component leakage closely conformed to theoretical expectations. The airflow produced by stack effect was significantly reduced by the presence of corridor/stairwell doors.

In the building, with corridor/stairwell doors, the effect of wind was always greater than the stack effect, the difference increasing with increase of window leakage (Fig. 4), but without corridor/stairwell doors, the stack effect produced a ventilation rate equivalent to a wind velocity between 4.4 and 8.8 m/sec. (See Fig. 5.)

With wind and stack effects acting together, the resulting airflow into the building was found to be approximately equal to the flow caused by the greater influence when acting alone. This is shown on Fig. 5. In a 4.4 m/sec wind the stack effect is greater and the combined effect was approximately the same as that due to stack effect alone. The effect of an 8.8 m/sec wind was greater than the stack effect and in this case the ventilation due to the combined influences was similar to that caused by wind pressure alone. This feature has been similarly noted by Dick [18]. Thus, in the building with corridor/stairwell doors the combined effect was approximately the sam as that due to wind pressure alone, as illustrated by the proximity of the pairs of lines on Figure

As modern offices are normally required to be equipped with corridor/stairwell doors to comply with fire regulations, natural ventilation can be assessed for design purposes by only considering the action of the wind.

It is worth noting, however, that although the stack effect does not modify the total ventilatio rate in the building, it has some influence on the proportional air infiltration at each floor level. Figure 6 shows a typical example of the difference between the infiltration pattern with wind alor and with the combined influence of wind and temperature difference. Under the combined influenc the infiltration is greatest in the lower floors.

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References

1. ASHRAE Handbook of Fundamentals 1967
American Society of Heating, Refrigeration and Air Conditioning Engineers.

2. I.H.V.E. Guide 1965

3. National Physical Laboratory "Wind Effects on Buildings and Structures"
Vols. I and II H.M.S.O. 1965

4. American Society of Civil Engineers "Wind forces on Structures"
Journal A.S.C.E. 1961 126 p.1124

5. De Bray B.G. "Wind Pressures on Multi-storey Buildings"
Engineering 6th July, 1962 pp. 10–11

6. Whitbread R.E. "Model simulation of wind effects on Structures"
– included in reference 3

7. Ning Chien et al "Wind tunnel studies of Pressure Distribution on Elementary Building Forms"
Iowa Inst. of Hydraulic Research 1951

8. Jensen M. and Franck N. "Model-scale tests in turbulent wind"
Parts I and II
Danish Technical Press, Copenhagen 1965

References

9. Wise A.F.E. et al "Studies of air flow round buildings"
Architect's Journal 1965 141 pp. 1185–9

10. Newberry C.W. "The measurement of wind pressures on tall buildings"
– included in reference 3

11. Baines W.D. "Effects of velocity distribution on wind loads on a tall building"
University of Toronto, Department of Mechanical Engineering
TP 6203, 1962

12. Davenport A.G. "The relationship of wind structure to wind loading"
– included in reference 3

13. Davenport A.G. "Wind loads on Structures"
Division of Building Research, Ottawa, Canada.
Tech. Paper No. 88

14. Building Research Station "Window design and solar heat gain"
B.R.S. Digest 68 (Second series) H.M.S.O.

15. Langdon F.J. "Modern office buildings: a user survey"
National Building Studies Research Paper No. 41
H.M.S.O. 1966

16. Kibblewhite D and Stewart L.J. "A survey of the thermal environment in naturally ventilated offices in summer"
J.I.H.V.E. July 1967 35 pp. 121–126
(H.V.R.A. Laboratory Report No. 31)

17. Harrison E. "Air infiltration into heated buildings"
Heating and Ventilating Research Association Technical Report.
"The Heating of Buildings by off-peak Electricity Supplies"
Appendix 2. May 1961

18. Dick J.B. "The fundamentals of natural ventilation of houses"
J.I.H.V.E. 1950 18 pp. 123–134

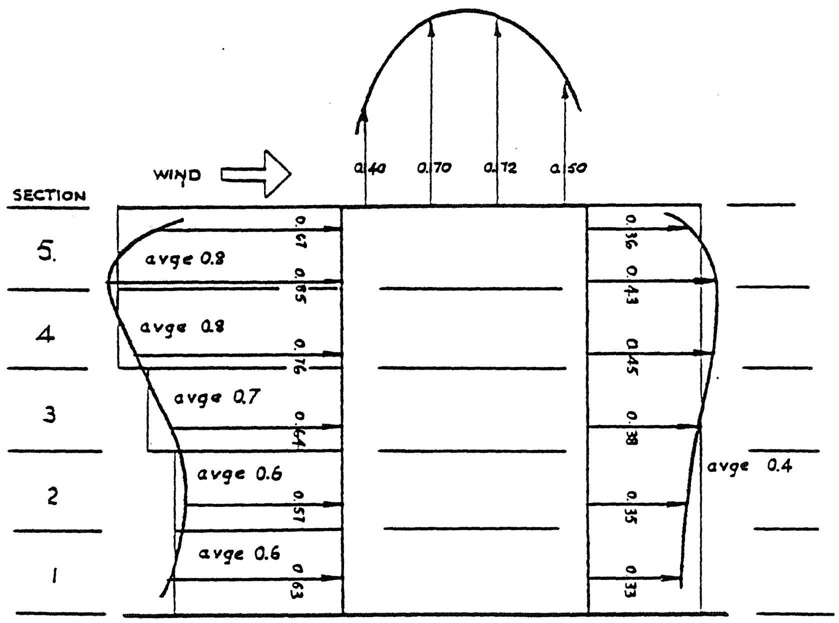

Fig. 1 Wind pressure as a fraction of velocity pressure at roof level

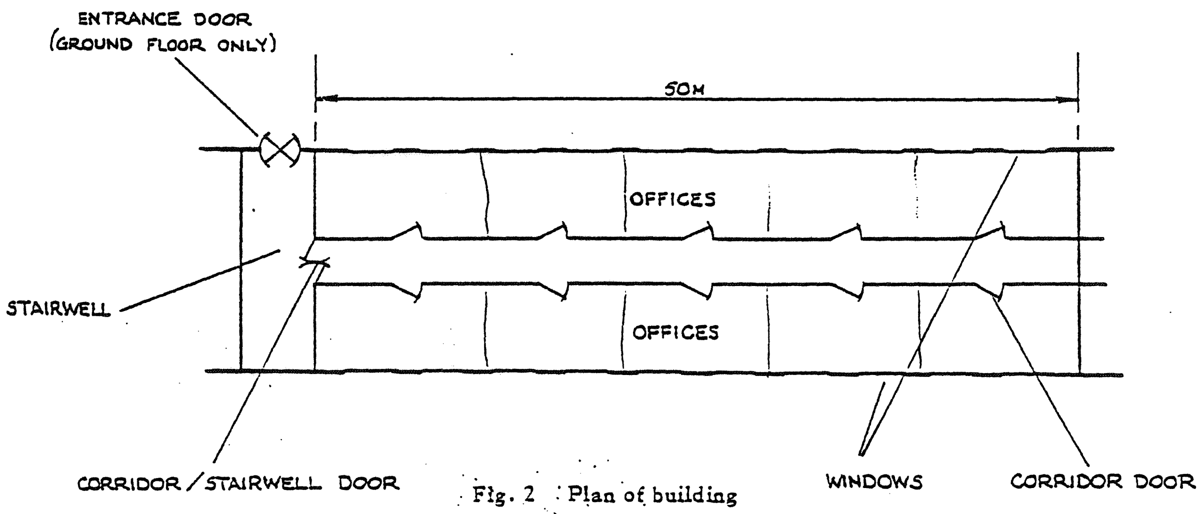

Fig. 2 Plan of building

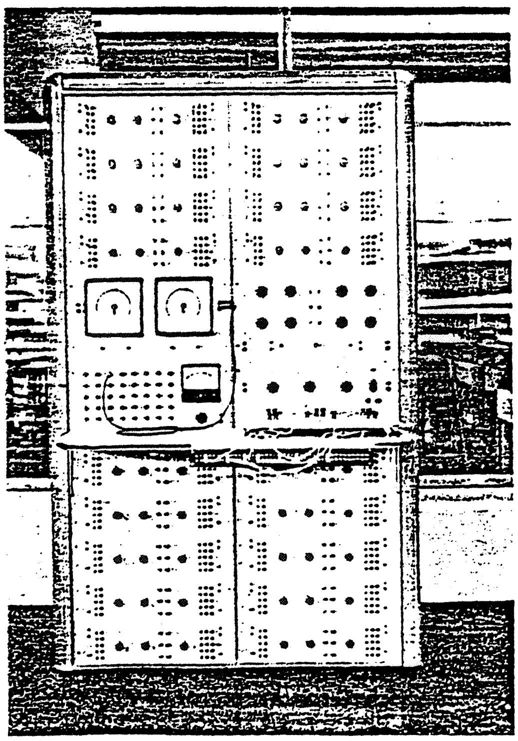

Fig. 3 Exterior view of the analogue

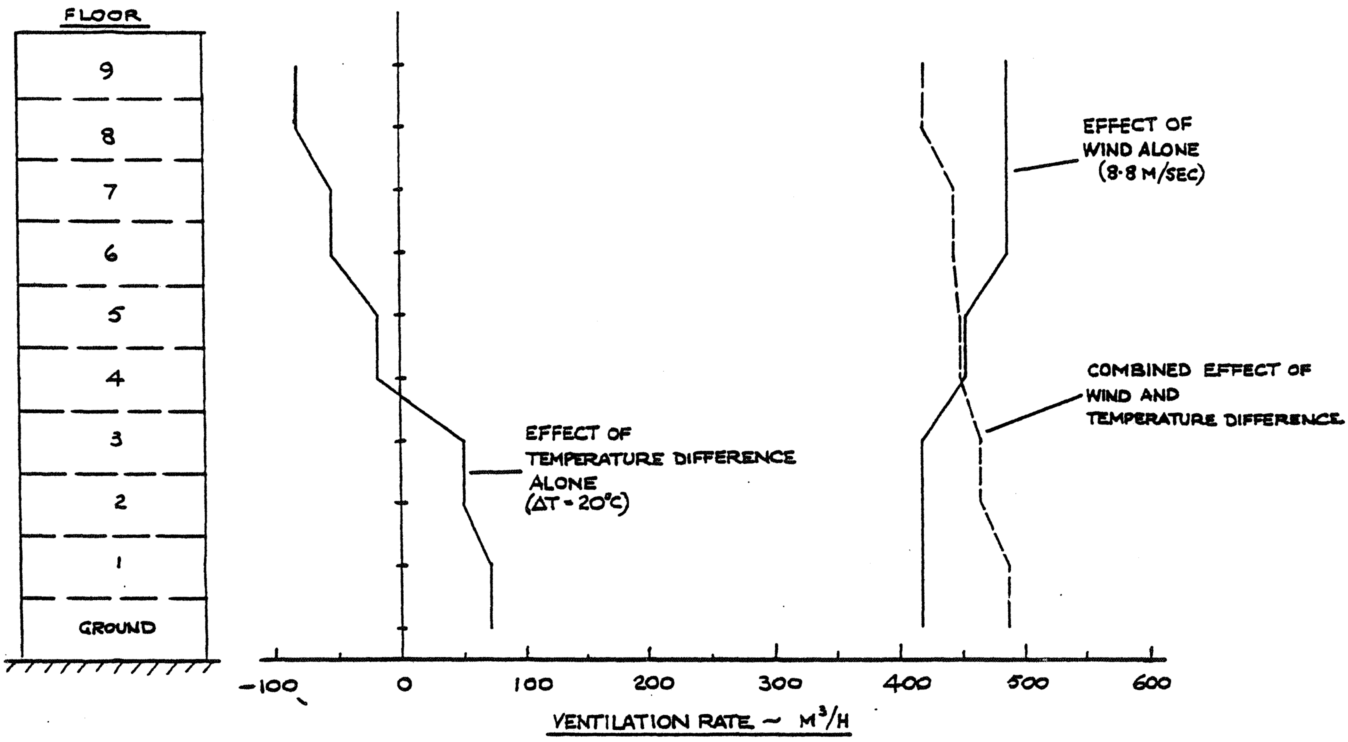

Fig. 6 Ventilation rate in windward rooms of 10 storey building with corridor/stairwell doors