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THE CALCULATION OF WIND EFFECT ON VENTILATION

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ABSTRACT

Natural ventilation is governed by the overall leakage characteristics of a building (accidental and purposely provided) and by the driving forces of wind and temperature. As greater control is influenced over airtightness design, the reliable prediction of naturally driven air change becomes increasingly dependent on the quality of climatic data. The influence of wind is particularly difficult to quantify, since its behavior is dramatically influenced by surrounding terrain and shielding conditions. This paper seeks to review and address the relevance of wind pressure as a driving mechanism. A simple multi-flow path simulation model is introduced and is used to illustrate the effects of wind on air change rate. The model is specifically used to illustrate the sensitivity of results to variations in surface wind pressure coefficients and to differing shielding and terrain roughness conditions. Model results are also used to discuss the significance of both temperature differences and mechanical ventilation on the impact of wind.

INTRODUCTION

Wind and temperature provide the motivating forces for natural ventilation and may also influence the performance of mechanical ventilation systems. It is therefore important to understand the interaction of these driving forces and to relate them to the ventilation performance of buildings. The need to incorporate these driving mechanisms is recognized in many infiltration and ventilation models (e.g., Walton 1984; Sherman et al. 1986). In understanding weather-driven ventilation, it is necessary to consider such factors as climate, terrain roughness, local shielding, the shape of the building, and the nature of building porosity. Additionally, since climate varies on both a seasonal and daily basis, it is necessary to recognize that the rate of ventilation is highly variable. Consequently, although it may be possible to design for a given average air change rate, there will inevitably be transient periods in which ventilation falls short of requirements. Hence, the duration and implications of such eventualities also need to be determined.

The mathematical representation of airflow through openings in the building fabric is extremely complex, since little is usually known about the character, distribution, and size of openings and cracks; hence, considerable simplifications are necessary in order to develop an acceptable formulation of the flow process. Nevertheless it is possible to use such formulations to understand the relationships between the various driving forces and to develop reliable predictive tools. Such a technique is developed in this paper for the purpose of demonstrating the significance of wind infiltration and to show how the effect of wind is modified by temperature differences (stack

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effect) and mechanical ventilation. Wind infiltration is calculated on the basis of either local or remote wind speed data combined with building wind pressure coefficients. A direct solution to the flow balance equation for a simplified network enables the significance of both wind speed and shelter to be evaluated in the absence of temperature effects. A more detailed network then enables the modification of wind infiltration due to other effects to be evaluated.

THEORETICAL OUTLINE

A detailed outline of calculation techniques is reviewed in the AIVC Calculation Techniques Guide (Liddament 1986) and therefore only a brief description is presented here.

The flow of air through openings in the fabric of a building is commonly approximated by a power law equation of the form:

$$Q = k(\Delta p)^{n} \quad m^3/s \tag{1}$$

where

Δp = pressure difference across opening (Pa).

n = flow exponent

k = flow coefficient

The coefficient, k, is, in part, related to the size of opening, while the exponent, n, characterizes the flow regime and has a value between 0.5 and 1.0. In practice, the flow exponent is influenced by such factors as path length and shape but has been found to have a value of between 0.6 and 0.7 for many of the cracks and background leakage paths in buildings.

Under conditions of natural ventilation, the pressure difference across each opening is induced by the actions of wind and inside/outside temperature difference. Under conditions of mechanical ventilation, pressure differentials are additionally created by the ventilation system itself. Mechanically induced pressures can often dominate, with the result that the effects of wind and temperature become negligible. An important aspect of design for mechanically ventilated buildings is to optimize the airtightness of the building envelope in order to minimize the effects of climate yet ensure the free flow of makeup or exhaust air.

WIND-DRIVEN VENTILATION

Wind is characterized by seemingly random variations in speed and direction, which are governed by a vast number of parameters ranging from global patterns to local terrain roughness and shielding. For any given "free stream" wind speed, the speed close to the ground is governed by the distance from the surface and by surface roughness. In infiltration studies, the nature of wind is normally approximated by a time-averaged mean velocity. For certain conditions, the turbulent fluctuations about the mean value can provide an additional driving force (Etheridge et al. 1980). However, this force is normally small in relation to the mean wind pressure and it should not be relied upon as a satisfactory driving mechanism. Its significance is most apparent in relation to single sided ventilation (open windows) and to low wind speed or to low temperature differentials. For these reasons it is not considered in this analysis.

On impinging the surface of a rectangular building, wind deflection induces a positive pressure with respec to atmospheric pressure on the upwind face and negative pressures along the sides and downwind face (Figure 1a,b). The distribution on the downwind face of the roof is also negative, but the upwind pressure coefficient is a function of roof pitch angle, with a positive value for angles greater than approximately 30 degree and a negative value for less than 30 degrees (Figure 1c,d). Wind directly incident to the corner of a building tends to induce a positive pressure on both of the leading faces, but as the wind veers to a particular side, the remaining face undergoes a transition from positive to negative (Figure 1e,f).

In general it is observed that relative to the static pressure of the free wind, the mean pressure acting at any point on the surface of a building may be represented by the equation:

$$p_w = \frac{\rho}{2} Cp\, V^2 \qquad (2)$$

where

ρ = air density (kg/m^3)

p_w = surface pressure due to wind (Pa)

Cp = pressure coefficient

V = mean wind velocity at a specified datum level (usually building height) (m/s)

The pressure coefficient, Cp, is a function of the pattern of flow around the building and of local shielding. For low-rise buildings (up to three floors), it is commonly expressed as an average value for each face of the building and for each 45° sector in wind direction. Walton (1982) uses an algorithm that interpolates wind pressure coefficient for each 1 degree sector in wind direction. For high-rise buildings, the height and spatial distribution of wind pressure is significant, and local pressure coefficients are used to define the wind pressure value at each location (Bowen 1976; Akin 1979). Unfortunately, much information on pressure coefficients comes from the results of wind loading tests made in wind tunnels on scale models of isolated buildings. These results do not adequately represent conditions for buildings surrounded by local shelter. Wiren (1987) has published more representative data for low-rise buildings, and Bowen (1976) has published data for high-rise buildings for various degrees of surrounding shielding. A more detailed analysis of existing data is presented by Swami et al. (1987), while a summary of data for three levels of shielding is tabulated in the AIVC Calculation Techniques Guide (Liddament 1986).

Since the strength of the wind is influenced by surface terrain roughness and height, it is essential to apply the correct wind speed; any error is substantially magnified by the nature of the square term of Equation 2. For this reason a datum height, usually taken as the height of the building, must be specified in conjunction with the pressure coefficient data. Normally wind data are only available from a remote weather station, and hence wind speed must be corrected for both the difference in height between measurement level and building height and for the intervening terrain roughness. A typical correction equation (Sherman et al. 1980) with appropriate constants is presented below.

$$V = \frac{\alpha \quad (z/10)^\gamma}{\alpha' \quad (z'/10)^{\gamma'}} V' \qquad (3)$$

where

V = required site wind speed at level z above ground (m/s).

V' = measured windspeed at level z' above ground (see below) (m/s).

α',γ' = constants dependent on off-site terrain conditions.

α,γ = constants dependent on on-site terrain conditions (see below).

Terrain description	γ	α
Ocean or other body of water with at least 5 km of unrestricted expanse	0.10	1.30
Flat terrain with some isolated obstacles, e.g., buildings or trees well separated from each other	0.15	1.00
Rural areas with low buildings, trees, etc.	0.20	0.85
Urban, industrial, or forest areas	0.25	0.67
Center of large city, e.g., Manhattan	0.35	0.47

Therefore, to estimate the wind pressure at a particular location on the face of a building, the following steps mus be taken:

- determine the wind pressure coefficient according to orientation and shielding;
- evaluate building height or reference height wind speed. If remote data only are available then it mus be corrected for both height and terrain roughness using Equation 3.

OTHER DRIVING MECHANISMS

Temperature-driven ventilation (stack effect) and mechanical ventilation are both capable of modifying c outweighing the influence of wind-driven ventilation.

The temperature or "stack" effect occurs as a result of temperature differences and, hence, air densit between the interior and exterior of the building. The pressure difference resulting from stack action between tw vertically placed openings, a distance, h, apart, is given by:

$$p_s = -\rho_o g 273 h \left(\frac{1}{t_{ext}} - \frac{1}{t_{int}} \right) \quad \text{(Pa)} \qquad (-$$

where

ρ_o = air density at 273 K and ambient pressure (kg/m^3)
h = vertical distance between openings (m)
t_{ext} = external air temperature (K)
t_{int} = internal air temperature (K)

It is not possible to calculate the effect of stack ventilation in isolation from the wind component, since it is combined influence of all driving forces that influences the total magnitude of infiltration. Instead, the st: pressure at each of the defined flow paths is added to the wind pressure to obtain a total pressure. Thus, fc leakage path, i, the total pressure is given by:

$$p_i = p_{si} + p_{wi} \qquad ($$

Mechanical extract or supply ventilation influences the pressure difference between the inside and outside of a building in relation to the need to maintain a flow balance between the incoming and outgoing air. The mechanical ventilation rate can often be treated as a constant provided that there are sufficient openings to allow the free flow of air without the development of large pressure differences (typically 10-20 Pa). Otherwise, the mechanical ventilation rate itself must be expressed as a function of the pressure difference (Liddament 1986). Balanced supply/extract systems within a single-zone approximation of a building can only be simulated by adding the given ventilation rate directly to the ambient infiltration rate. This assumes that the ventilation system does not alter the pressure balance within the zone. In multi-room structures, where supply points are located in different zones to extract points, the ventilation system can be included as part of the flow path network.

NUMERICAL MODEL

The driving forces and flow mechanisms are most easily combined in the form of a multi-flow path, single-zone model. Such a technique combines an extremely simple numerical approach with a complex range of predictive ability, which is able to provide solutions for a considerable range of design problems. A number of such models have been previously reviewed and evaluated (Liddament et al. 1983). The essence of the method is to represent the building as a single enclosed volume at uniform pressure. Any number of flow paths may be defined by the user to represent openings. Assuming a total of i such flow paths then, for a balance between incoming (infiltrating) air and outgoing (exfiltrating) air, the flow equation (Equation 1) can be written as:

$$\sum_{i=o}^{j} \underbrace{k_i \, |p_i - p_{int}|^{n_i}}_{\text{Term I}} \; \underbrace{\frac{(p_i - p_{int})}{(|p_i - p_{int}|)}}_{\text{Term II}} = 0 \qquad (6)$$

where k_i = flow coefficient of the i'th flow path

n_i = flow exponent of the i'th flow path

p_i = external pressure acting on the i'th flow path (Pa)

p_{int} = internal pressure (Pa)

Term I expresses the absolute value of the internal/external pressure difference across each opening rather than the actual value. This is applied to avoid exponentiating a negative number when $p_i<p_{int}$. Term II restores the sign of the flow direction, which is lost in Term I.

The flow coefficients k_i and n_i are user defined and are based on measurement and/or typical leakage characteristics of openings. A common leakage-measurement technique is to incrementally pressurize or depressurize a building with a blower door (ASTM 1982) from which the flow exponent and flow coefficient for the total building fabric may be inferred by substitution of the data into Equation 1. This total flow coefficient is then divided between the user-defined flow paths in proportion to their relative magnitudes. The external pressure, p_i, is based on the components due to wind (Equation 2) and temperature (Equation 4), while mechanical ventilation may be introduced in the form of a separate path in which the flow rate is specified. Thus the only unknown is that of the internal pressure, p_{int}. In a few instances this pressure can be evaluated directly, but most often an iterative process must be used in which an initial arbitrary guess at the pressure is successively improved until a flow balance within acceptable tolerances (typically ± .0001 m^3/s) is achieved.

This approach is normally acceptable for open plan structures or ones in which internal partitioning is leaky in comparison to the porosity of the building envelope. Apart from ease of calculation, a further advantage of this technique is that the magnitude and direction of flow through each opening are also evaluated; therefore, it provides an indication of air movement patterns in addition to quantifying the overall air change rate.

Where flow resistance between zones or rooms within a building cannot be ignored, then it is necessary to use a multizone model of the building which incorporates the flow characteristics of openings between each zone. In principle, the same method of solution is used. Walton (1984) describes a multizone solution technique in detail; other such methods have been previously reviewed (Liddament et al. 1983).

SIMPLIFIED SIMULATION OF WIND-DRIVEN VENTILATION

A simplified analysis of wind-driven air change is possible by considering a two-path flow network as indicated in Figure 2. Paths of identical flow characteristics are located on the upwind and downwind faces of the building and are chosen to represent the overall leakage performance of the structure. Clearly this rules out temperature effects and nonlinear leakage distributions, but, nevertheless, it represents a useful example in which the influence of such factors as the strength of the wind and shielding parameters may be evaluated in the absence of stack-driven ventilation. Once the magnitude of wind influence is established, it is then possible to analyze more realistic flow networks. This two-path approximation also provides for a direct solution to Equation 6.

Assume a building of height 8 m with an enclosed volume of 250 m³ in which the results of a blower door depressurization yields 6 air changes per hour (6 each) at 50 Pa and a flow exponent, n, of 0.6. By substitution into the flow equation (Equation 1), the overall flow coefficient for the building is:

$$k = \frac{6 \times 250}{3600} \; / {}_{50}0.6 \cong 0.04 \text{ m}^3\text{/s at 1 Pa.} \qquad (7)$$

Since the flow characteristics of each path are identical, dividing the total flow coefficient between these two paths yields:

$$k_1 = k_2 = k/2 = 0.02 \text{ m}^3\text{/s at 1 Pa.} \qquad (8)$$

Substituting into Equation 6 gives:

$$k_1(p_1 - p_{int})^n + k_2(p_2 - p_{int})^n = 0 \qquad (9)$$

$$p_{int} = (p_1 + p_2)/2$$

Therefore, the infiltration rate may be determined directly for any known values of p_1 and p_2 by back substitution into Equation 6.

Continuing with this example, it is now possible to illustrate the effects of wind speed, terrain roughness, and shelter on wind-driven ventilation. Consider first the necessary adjustment to be made to wind speed, measured at a weather station at a height of 10 m in open countryside, to allow for intervening terrain roughness and building height. Table 1 contains the wind correction factors (based on the data in Equation 3) for intervening "flat," "rural," and "urban" terrain. These values are the factors by which the weather station wind speed must be multiplied in order to represent the building height wind speed at the location of the building. Thus, the building height wind speed for each of the three terrain conditions is 97%, 81%, and 63% of the measured value, respectively. Since the square of the wind speed is used in the wind pressure term, these correction factors have a considerable influence on the calculated wind pressure.

In addition to the wind speed correction, the pressure coefficient must also be selected according to the surrounding shielding condition. In this example, the "flat," "rural," and "urban" terrain conditions are additionally used to describe the degree of surrounding shielding. Approximate but by no means definitive values of pressure coefficient for each of these terrain/shielding conditions are also presented in Table 1. In general, the effect of shielding is to substantially influence the upwind pressure coefficient value. Therefore, the selection of shielding class may be expected to have an important impact on the predicted infiltration rate.

By applying the data presented in Table 1 to the two-flow path network represented by Equation 9, it is possible to calculate the relationship between wind speed and infiltration rate for each terrain and shielding condition. The resultant air change rates for each of these shielding and wind correction conditions are presented in Figure 3 for building height wind speeds in the range between 0 and 10 m/s. To emphasize the significance of intervening terrain roughness on wind speed and, hence, to reinforce the need to use the on-site building height value, the corresponding wind speed scales relating to 10 m weather station values for each of the three intervening terrain roughness conditions are also included in the diagram.

At a building height wind speed of 10 m/s, the predicted infiltration for "flat terrain" exposure is approximately 2.2 ach compared with 1.7 ach for rural exposure and 1.4 ach for urban exposure. In percentage terms, the flat terrain and rural values are 57% and 21% greater than the urban value respectively. Taking a 10 m/s open site wind speed, the corresponding air change rates are 2.0 ach for flat terrain, 1.3 ach for rural terrain, and 0.8 ach for urban terrain; hence the difference between flat and urban terrain conditions amounts to 150%. These results, therefore, highlight the enormous significance of terrain and shelter in controlling the impact of wind.

INFLUENCE OF WIND-PRESSURE COEFFICIENT

The above example illustrates the effect of wind speed and terrain on wind-driven ventilation. Another uncertainty is that of the wind pressure coefficient itself, which is rarely known to any absolute degree of accuracy unless extensive wind tunnel tests are made. It is therefore desirable to investigate the effect on infiltration prediction of any error in wind pressure coefficient. Sufficient information is provided by the two-flow path simulation to obtain some guidance. One way to achieve this is to consider the difference between the upwind and downwind pressure coefficient values for each shielding class and to compare these differences with the corresponding calculated infiltration rates for a given wind speed condition. It is convenient to express the differences in pressure coefficient of each class and the corresponding infiltration prediction as a proportion of that of the "urban" value. Such a relationship between the pressure coefficient difference and infiltration prediction is illustrated in Figure 4. A change in shielding class from "urban" to "rural" represents a change in pressure coefficient difference of 33%, while the corresponding change in infiltration prediction is 18%. Similarly, a change from "urban" to "flat" terrain results in a 100% change in pressure coefficient difference and a 52% change in infiltration prediction. The infiltration prediction is, therefore, relatively insensitive to changes in pressure coefficient. Although these results only strictly apply to this specific example, they are applicable to other buildings exhibiting similar flow characteristics. The reason for this is that while the magnitude of the wind pressure is directly proportional to the pressure coefficient, the derived pressure is raised to the power of the flow exponent, n, which is less than unity. This allows for some approximation in specifying the flow coefficient, and therefore enables tabulated data containing representative values of wind pressure coefficient covering typical building shapes and shielding conditions to be used.

IMPACT OF TEMPERATURE

In the previous example, a two-flow path network was used to analyze the influence of wind on air infiltration into a building. In this section, the same building is represented by a four-flow path network, which is used to investigate the combined effect of wind and temperature. Despite the increased number of flow paths, the principle of solution of Equation 6 remains the same, with the objective being to evaluate an internal pressure, p_{int}, so that there is a balance between the infiltrating and exfiltrating airflows.

For simplicity, each path is again assumed to have identical flow characteristics. The network is illustrated in Figure 5. Leakage openings are represented by flow paths at levels of 1 m and 5 m on both the upwind and downwind faces of the building. By introducing vertically spaced openings, it is possible to apply the stack pressure equation (Equation 4). Since the number of flow paths has been doubled, the flow coefficient, k, of each has been halved to 0.01 m^3/s at 1 Pa in order to retain the same overall leakage characteristics as the wind-only example. To compare with the previous example, simulations were again performed for "flat," "rural," and "urban" shielding/terrain conditions. Stack effect was incorporated by introducing inside/outside temperature differences of 10°C, 20°C and 30°C. The infiltration characteristics are summarized in Figure 6a and are typical of the characteristics of a leaky structure subjected to the combined effects of wind and temperature (e.g., Sinden 1978). Initially, at low wind speeds, the rate of air infiltration is invariant to the wind condition. This is the "stack dominant" regime. As the wind speed increases, wind begins to take over as the driving mechanism, and the infiltration pattern follows that of the wind-only example. The extent of the temperature-dependent region is a function of such factors as the temperature differential, the vertical spacing of openings, and the effect of shielding. Hence, the infiltration characteristics are unique to each building and in part are subject to design. Techniques to extend the temperature regime are sometimes used to provide the stack effect in order to provide a reliable form of natural domestic ventilation in the winter months (Edwards et al. 1986).

At the junction between the temperature-dominant and wind-dominant regimes, it is common to observe a depression in the infiltration rate (Warren 1975). The magnitude of this depression varies according to the size and distribution of leakage paths but occurs when wind and stack pressures oppose each other to restrict the rate of flow across some of the openings. This is depicted in Figure 6b and is based on the four-flow path network assuming "urban" shielding and a temperature differential of 30°C. At zero wind speed, air enters the building at equal flow rates through the lower openings and exfiltrates through the upper openings. As the wind speed increases to 2 m/s, a wind-induced positive pressure is combined with the stack pressures of the upwind openings, while a wind-induced negative pressure is applied to the stack pressures acting on the downwind openings. Although the infiltration rate remains at 0.48 ach, the balance of flow has altered, with the wind pressure reinforcing the flow through the upwind lower opening and downwind upper opening (paths 1 and 4) while reducing the flow through the remaining openings (paths 2 and 3). At a wind speed of 4.2 m/s, the opposing effects of wind and temperature have completely eliminated flow in paths 2 and 3, and the infiltration rate has fallen to 0.37 ach. At a wind speed of 4.6 m/s, the infiltration rate has returned to 0.48 ach, but the flows in paths 2 and 3 are now reversed when compared to the stack flow condition. This marks the beginning of the wind-dominant regime.

IMPACT OF MECHANICAL VENTILATION

Mechanical ventilation systems may be represented by two basic forms, these being either balanced systems, in which mechanically extracted air is replaced by an equivalent volume of mechanically supplied air, and extract o supply-only systems, in which flow balance is maintained by inducing a pressure difference across openings in the building fabric. To a first order of approximation, balanced ventilation has little effect on the infiltration characteristics of a building, and hence, for energy efficiency, it is desirable to have an airtight structure. This is essentially the objective of the Canadian R2000 approach (Riley 1987) and of a number of building airtightness standards. However, extract or supply-only systems have an influence on the infiltration performance of buildings and need to be analyzed with respect to both the total air change rate and potential indoor air quality problems. Thi is especially so for domestic extract ventilation systems, which, in excessively tight structures, can cause the backdrafting of combustion products into the dwelling. Such a system can also cause other problems such as radon ingress and high velocity draughts.

By returning to the two-flow path network, it is possible to investigate the interaction of wind-induced infiltration on mechanical extract (or supply) ventilation. Two examples are considered, the first relates to th original fairly leaky building of 6 ach at 50 Pa and the second relates to a much tighter structure of 1.5 ach at 50 Pa. Mechanical extract ventilation of 0.5 ach (0.035 m³/s) is assumed, and each of the previous terrain/shieldin conditions is considered. The flow balance equation now becomes:

$$\sum_{i=1}^{2} k_i |p_i - p_{int}|^{n_i} \frac{(p_i - p_{int})}{(|p_i - p_{int}|)} + 0.035 = 0 \qquad (10$$

The air change results are illustrated in Figure 7. In the leaky building, ventilation is dominated by the mechanical ventilation system up to wind speeds of 2 m/s. Thereafter, the wind effect begins to dominate the flow process and above a speed of 4 m/s the curve follows that of the wind-only example. In the tight building, air change is controlled by the ventilation system up to a wind speed of 6 m/s, and at greater wind speeds the influence of wind is only relatively marginal. Thus it appears that ventilation is most constant in the tight building. However, extract ventilation creates a suction or building underpressure. While small underpressures are normally considered desirable in dwellings, as a means to prevent interstitial moisture penetration, large underpressures can cause serious backdrafting problems. A requirement for mechanical extract systems fitted to R2000 homes with naturally aspirated furnaces is that this pressure should not exceed –10 Pa (Duffy et al. 1986). The internal pressure is plotted for each building and terrain condition in Figure 8. In the leaky building, the initial underpressure is approximately –0.8 Pa, and, as the wind speed increases, it is soon dominated by the wind pressure. In the "rural" and "flat" shielding conditions, the pressure eventually becomes positive, reflecting that the pressure coefficient on the upwind face is greater in absolute magnitude than the coefficient on the downwind face. The reverse happens for "urban" conditions. The picture is very much more complicated in the tight dwelling, where the underpressure at zero wind speed is close to –8 Pa. For both "rural" and "urban" terrains, the underpressure increases to –10 Pa and –15 Pa, respectively, at a wind speed of 10 m/s. This, therefore, represents a potentially serious hazard. Fortunately, it is possible to add additional flow paths to the flow network, representing purposely provided openings, and to determine the optimum size of such openings to avoid these underpressure problems.

CONCLUSIONS

By considering simple multi-path flow networks, it is possible to gain a quantitative insight into the effects of wind and other driving forces on fresh air exchange rates in buildings. A two-path flow simulation was used to investigate the influence of terrain roughness and shielding conditions on wind-driven ventilation. For a given building height wind speed, it was shown that shielding could affect the wind infiltration by as much as 50% and, for a given remote climatic station windspeed, the combined effect of intervening terrain and shielding conditions could affect the result by as much as 150%. It is, therefore, essential that adequate correction is made to the wind pressure terms.

A four-flow path simulation was used to investigate the combined effect of wind and temperature. This illustrated the characteristic dominance of temperature or stack effect as a driving mechanism at low wind speeds. At higher wind speeds, the results followed that of the two-flow path solution. The extent of the temperature-dominant zone is a function of temperature difference, the vertical distance between openings, and the influence of shelter in modifying wind pressure.

The two-path flow model also enabled the effect of mechanical ventilation to be quantified. For a relatively leaky structure, corresponding to an air change rate of 6 ach at 50 Pa, wind influence dominated at wind speeds above 2 m/s. In a tight structure of 1.5 ach at 50 Pa, wind had no effect below 6 m/s and had only a weak influence at greater speeds. However, care is needed to ensure that building underpressures are not excessive. This basic analytical approach is capable of providing substantial guidance on ventilation patterns and pressure conditions.

Pressure coefficients are used to estimate the wind pressure acting on openings. Only a proportion of any error in pressure coefficient value is transferred to the infiltration prediction (typically 50%) and therefore only approximate values are necessary; these should distinguish between each shielding class and represent typical building shapes.

A multi-flow path, single-zone ventilation model provides an easy method for analyzing a comprehensive range of air infiltration and ventilation problems. In its simplest two-path form, direct analytical solutions are possible for which much quantitative information about ventilation performance can be obtained. For more detailed flow analysis, which combines the effects of wind, temperature, and mechanical ventilation, a simple iterative approach is needed to solve the flow equation.

REFERENCES

Akin, R.E.; Peterka, J.A. and Cermak, J.E. 1979 "Averaged pressure coefficients for rectangular buildings." Proceedings 5th Inst. Conf. Wind Engineering. Fort Collins: Pergamon Press.

ASTM. 1982. ASTM Standard E779-81. "Measuring air leakage by the fan-pressurization method." Philadelphia: American Society for Testing and Materials.

Bowen, A.J. 1976 "A wind tunnel investigation using simple building models to obtain mean surface wind pressure coefficients for air infiltration estimates." Report LTR LA 20N, National Aeronautical Establishment, NRCC, Canada.

Duffy, P. and Riley, M. 1986. "Controlling pressure differences across the building envelope – A compliance with the R2000 programme technical requirements." Proceedings BTECC Symposium Air Infiltration, Ventilation and Moisture Transfer. 2-4th December.

Edwards, R.E. and Irwin, C. 1986. "The use of passive ventilation systems for condensation control in dwellings and their effect upon emergency consumption." Proceedings AIVC 7th Annual Conference, Occupant Interaction with Ventilation Systems. Stratford-upon-Avon, UK.

Etheridge, D.W. and Alexander, D.K. 1980. "The British Gas multi-cell model for calculating." ASHRAE Transaction, 86, Pt. 2.

Liddament, M.W. and Allen, C. 1983. "The validation and comparison of mathematical models of air infiltration." AIVC Technical Note 11. Air Infiltration and Ventilation Centre, England.

Liddament, M.W. 1986. Air infiltration and calculation techniques – An application guide. Air Infiltration and Ventilation Centre, England.

Riley, M. 1987. "An overview of the R2000 home program design and installation guidelines for ventilation systems." Proceedings AIVC 8th Annual Conference. Überlingen, FRG.

Sherman, M.H. and Grimsrud, D.T. 1980. "Measurement of infiltration using fan pressurisation and weather data." Proceedings of 1st AIC Conference "Air Infiltration Instrumentation and Measurement Techniques." UK.

Sherman, M.H. and Modera, M.P. "Comparison of measured and predicted infiltration using a LBC infiltration model." Proceedings Measured Air Leakage of Buildings. ASTM STP 904 ASTMS. Philadelphia, ASTM, 1986, pp. 325-347.

Sinden, F.W. 1978. "Wind temperature and natural ventilation – Theoretical considerations." Energy and Buildings 1, 1977/1978, pp. 275-280.

Swami, M.V. and Chandra, S. 1987. "Procedures for calculating natural ventilation airflow rates in buildings." Final Report, ASHRAE Research Project 448-RP. Florida Solar Energy Center, March.

Walton, G.N. 1982. "A computer program for estimating infiltration and inter room air flows." NBS Report NBSIR 83-2635, November 1982.

Walton, G.N. 1984. "A computer algorithm for predicting infiltration and inter room air flow." ASHRAE Transactions, Vol. 90, Pt 1, pp. 601-610.

Warren, P.R. 1975. "Preliminary studies of domestic ventilation." Proceedings of Aston University/Electricity Council Research Establishment Conference on Controlled Ventilation. Aston UK. September.

Wiren, B.G. 1987. Effects of surrounding buildings on wind pressure distribution and ventilation losses for single-family houses. Part 2, 2-storey terrace houses. National Swedish Institute for Building Research, Gavle, March.

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TABLE 1

Pressure Coefficient and Wind Reduction Factors for Two-Path Flow Model

Face	Flat terrain	Rural	Urban
Upwind	0.7	0.4	0.2
Downwind	–0.2	–0.2	–0.25
Wind correction factor	0.97	0.81	0.63

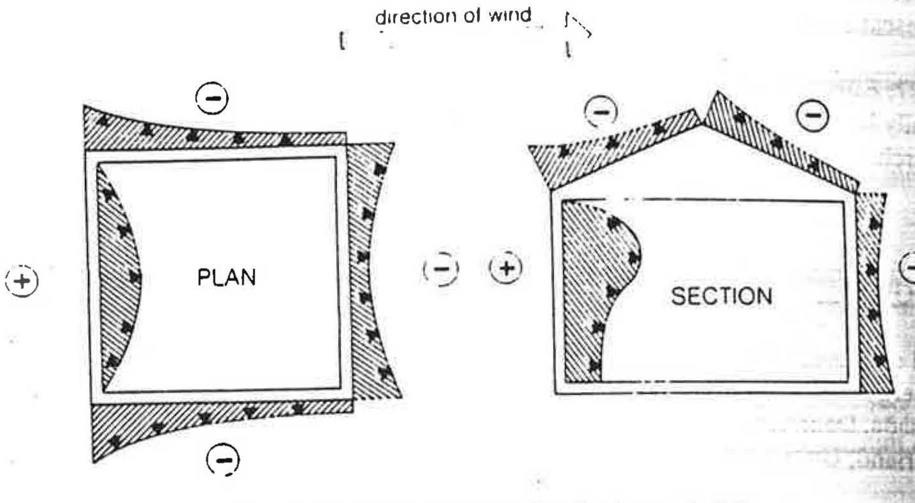


Figure 1a Wind pressure distribution on building

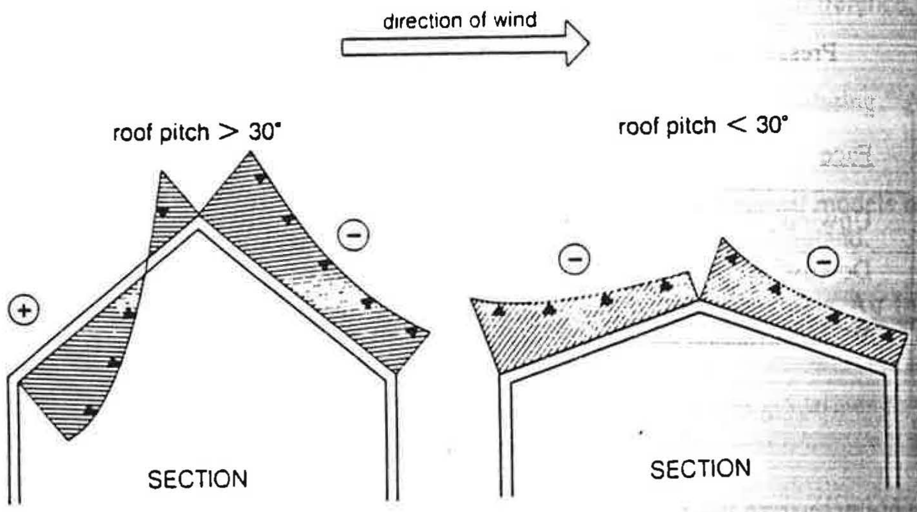


Figure 1b Wind pressure distribution according to roof pitch angle

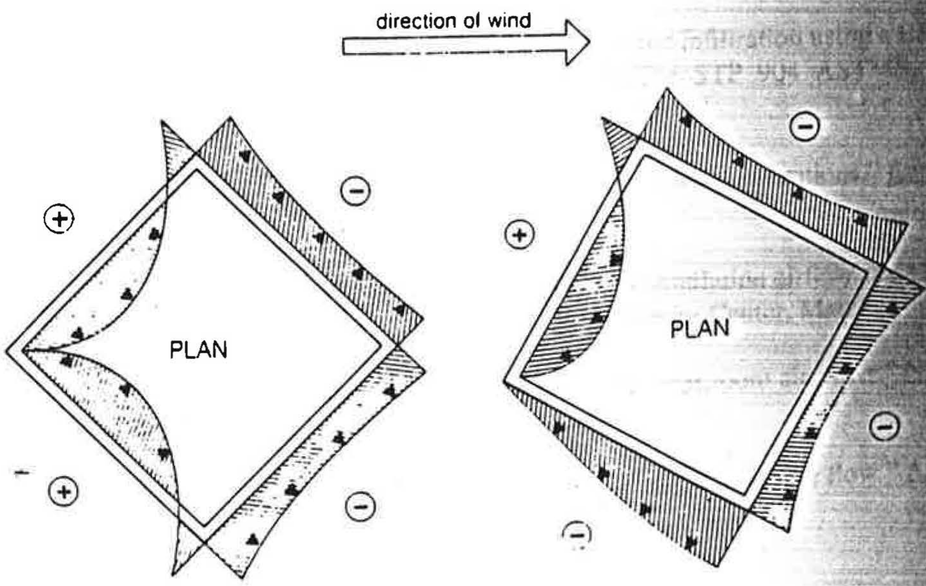


Figure 1c Pressure distribution due to wind incident on the corner of a building

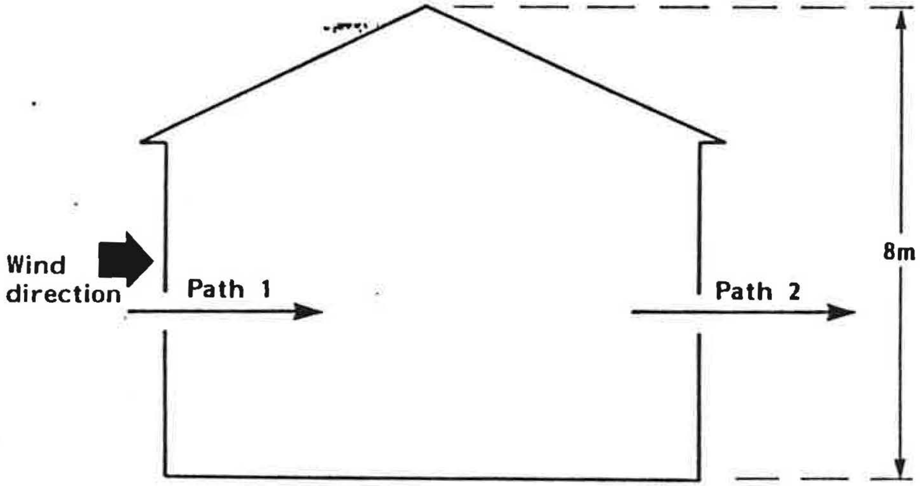


Figure 2   2 - path flow network

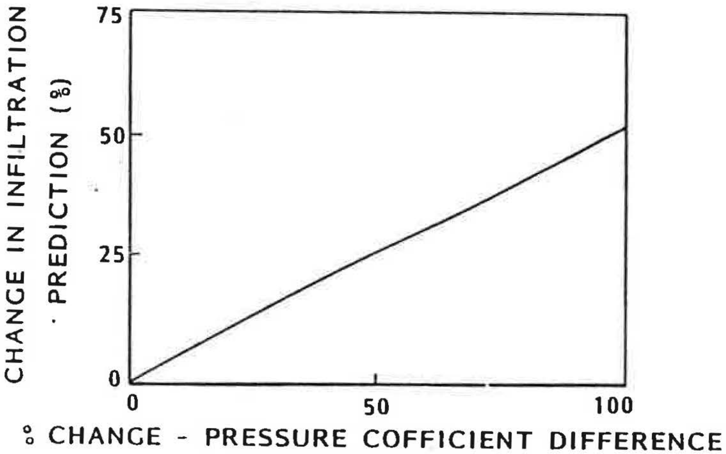


Figure 4   Influence of pressure coefficient on infiltration rate (2 - path flow network)

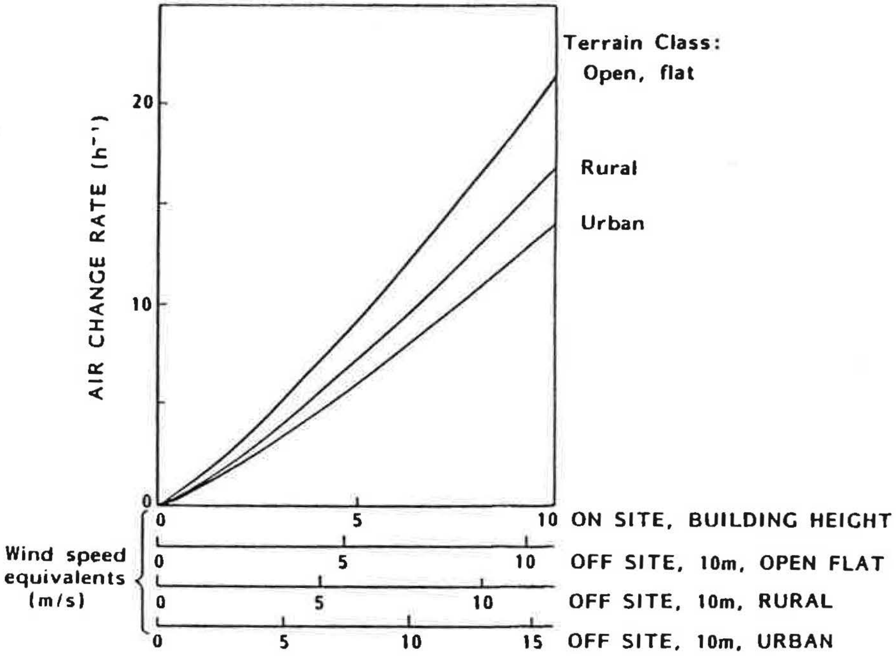


Figure 3   Influence of shelter on infiltration rate (2 - path flow network)

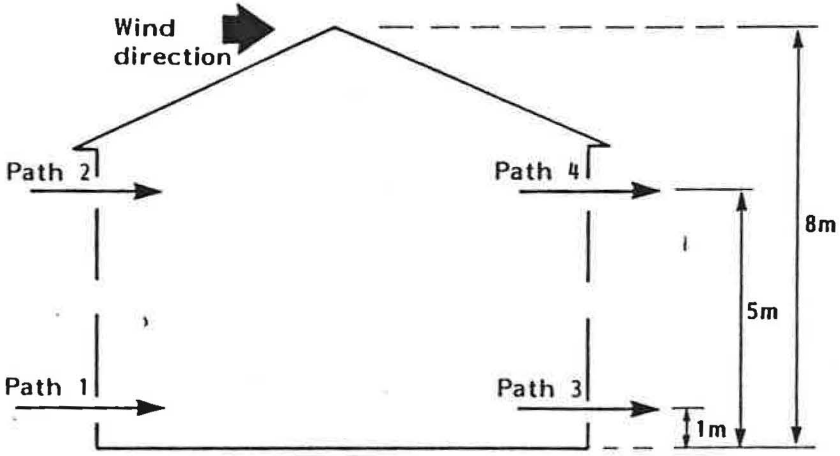
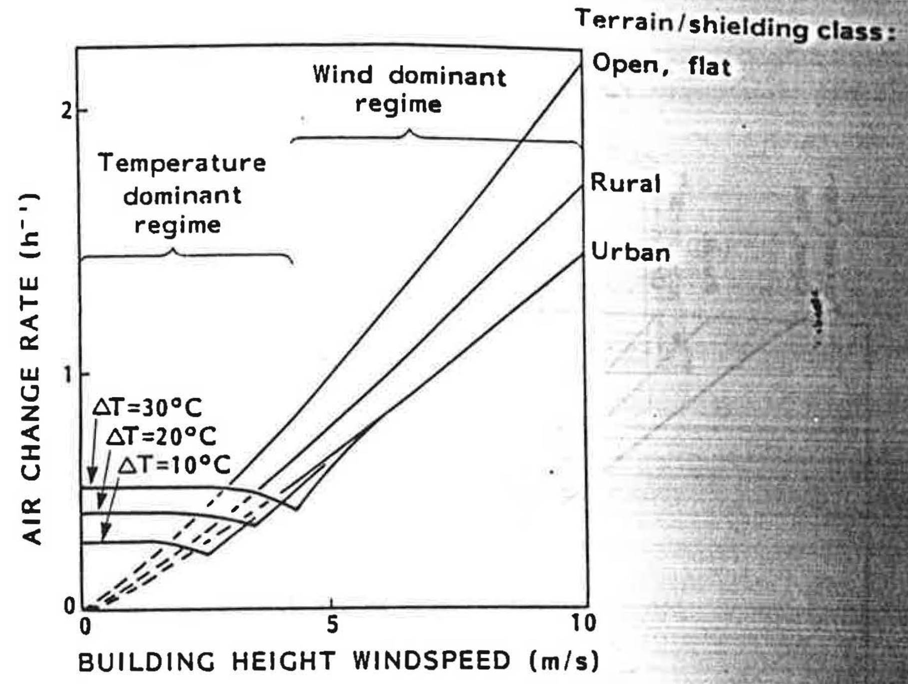
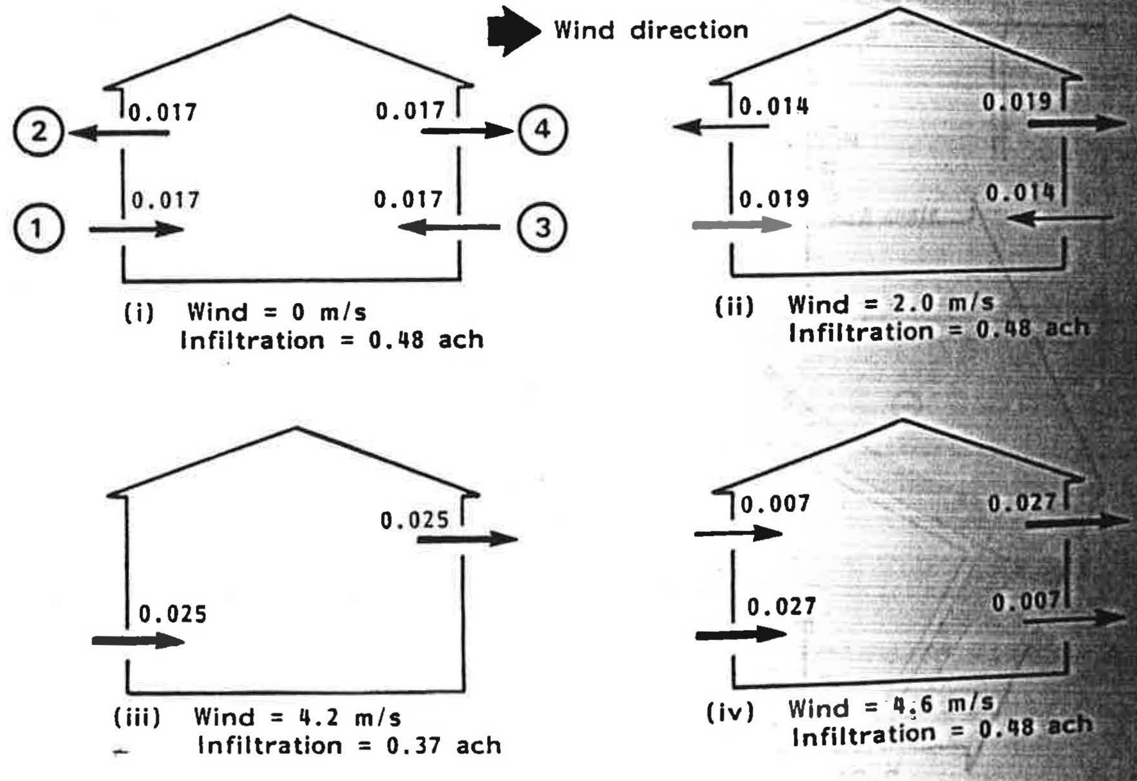


Figure 5   4 - path flow network

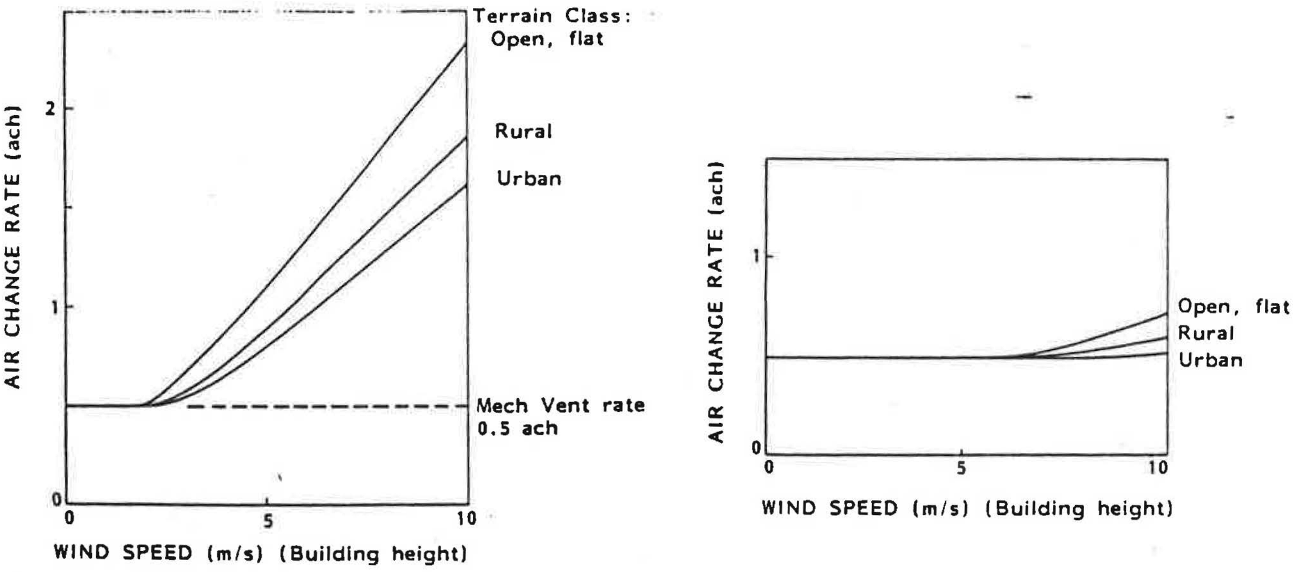


(a) Infiltration characteristics



(b) Airflow patterns (m^3/s)

Figure 6 Combined wind and influence of stack effect



(a) 'Leaking' building (6 ach at 50 Pa)

(b) 'Tight' building (1.5 ach)

Figure 7 Influence of mechanical ventilation

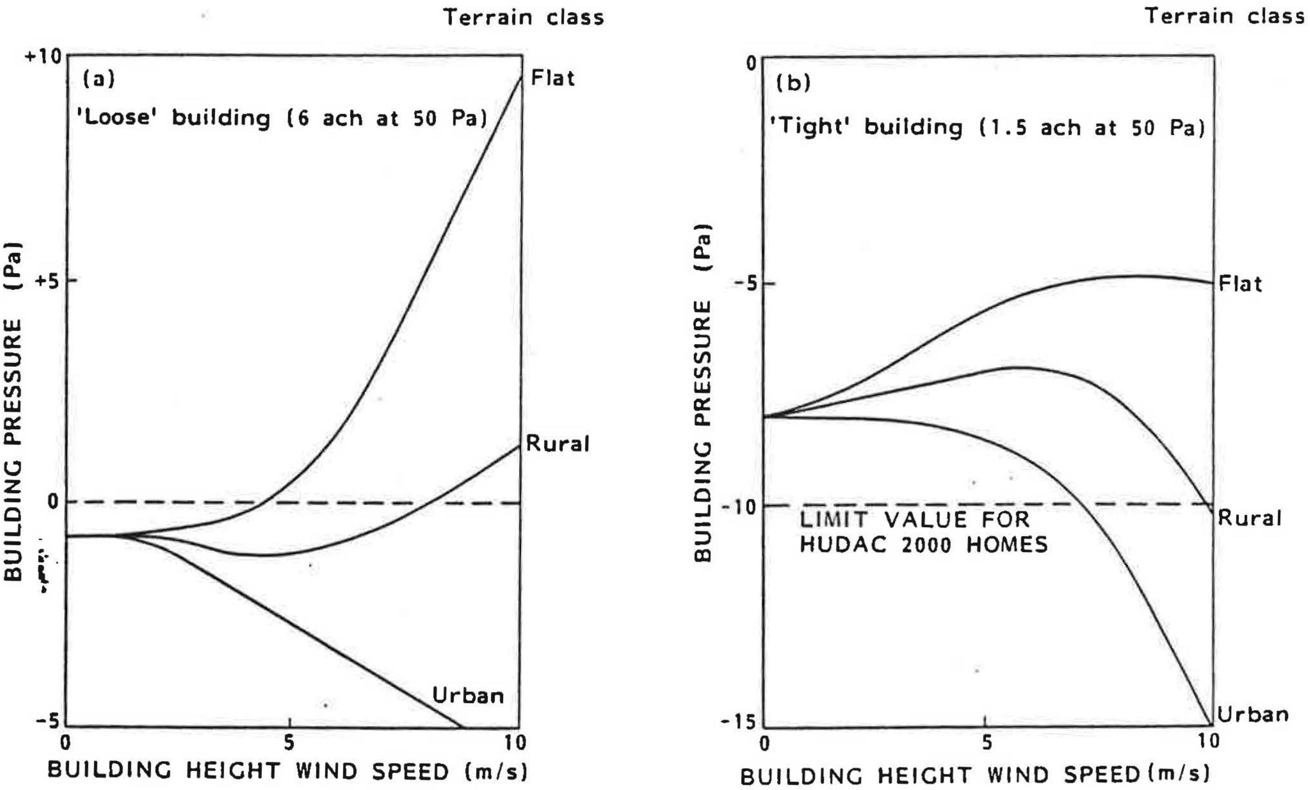


Figure 8 Internal building pressure for 0.5 ach mechanical extract ventilation