NATURAL VENTILATION BY DESIGN

NATURAL VENTILATION PRINCIPLES IN DESIGN

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The requirement for better methods of predicting infiltration and natural ventilation rates has been reinforced by the incentive to reduce energy consumption in buildings.

Natural ventilation is basically dependent on the effects of wind and temperature difference and on the resistance to airflow through the building. These factors are discussed in detail and those areas requiring further study are highlighted.

Some calculations of the effect of applying controlled natural ventilation and mechanical ventilation illustrate the potential energy savings of such measures.

INTRODUCTION

As far back as 1850, the fundamentals of ventilation design were given by Walker who announced[1]:

(i) windows were to admit light; ventilation should be catered for separately.

(ii) both inlets and outlets were necessary.

(iii) incoming air should be warmed to avoid draughts.

(iv) inlets and outlets should be well distributed.

(v) ventilating openings should be permanent, realising that once closed they will remain closed.

It is not easy to find fault with such fundamentals but the major problem in applying these over the years has been to predict quantitatively the size and distribution of ventilation inlets and outlets to ensure an adequate fresh air supply when relying on natural forces.

In the past the design emphasis for naturally ventilated buildings was two-fold. First, to provide sufficient open or openable area to facilitate adequate ventilation. Second, to determine the ventilation heat loss under winter design conditions and so enable it to be taken into account when sizing the main boiler plant and individual heat emitters.

The basis for the selection of the required openable area, whether vents or windows, seems to have been mainly a matter of judgement gained from experience, perhaps backed up by the use of basic information such as that in the British Standard Code of Practice CP3 published in 1950[2].

The general recommendation that the absolute minimum openable window area should be 5% of the room floor area appears to stem from a similar recommendation by Bedford[3] in 1948, and is the same as the value for the area of ventilation openings specified for habitable rooms in the Building Regulations[4]. In practice, however, the range of variation was considerable as may be judged from a survey of naturally ventilated offices[5] in 1964 which revealed a variation in the proportion of openable window area to floor area from 3½ to 27%.

More specific information has been derived for the calculation of ventilation or infiltration heat loss at specific design conditions. One method involves the assumption of an appropriate rate of air change for the particular type of building and its expected use. Recommended air change rates are tabulated in the CIBS guide[6]. A more detailed method also presented in the CIBS Guide, uses known relationships between leakage rate and pressure differential for components such as windows, doors and vents. These relationships are applied for pressure differentials generated by wind or stack effects at the selected design condition.

IMPLICATIONS OF ENERGY CONSUMPTION

The requirement to reduce energy consumption has changed the design emphasis so that it is now necessary to ensure not only that an acceptable level of ventilation is provided but also that the ventilation rate throughout the season is at or as little as possible above the minimum acceptable level. Seasonal energy consumption has become a major criterion.

The significance of ventilation in relation to energy consumption has also increased because of the change in the ratio of fabric to ventilation heat loss brought about by the application of improved standards of thermal insulation. As shown in Figure 1, the proportion of ventilation heat loss to the total for a heating season has typically risen from less than 25% for an older dwelling to about one half for a well-insulated house.

This increased significance and the need to minimise seasonal energy consumption has led to a requirement for more reliable and accurate methods of predicting air infiltration and ventilation rates and the associated energy losses. These methods need on the one hand to be soundly based on the principles governing natural ventilation processes and on the other to be readily applicable by the design team in their quest for optimum energy and cost effectiveness.

PRINCIPLES OF NATURAL VENTILATION

Natural ventilation is basically dependent on two factors (1) the motive forces and (2) the resistance to airflow through the building. However, this simple statement disguises a multitude of complexities which make the prediction of the magnitude of each factor very difficult.

The Motive Forces

The two motive forces primarily responsible for natural ventilation are caused by wind and air temperature differences.

Wind. Wind impingement on a building produces higher-than-ambient pressures on the windward faces and lower pressures on the others. The pressure differences so generated give rise to a movement of air from the higher to the lower pressures through any cracks, gaps or openings in the building.

Wind is turbulent and both its speed and direction undergo continual change. The wind speed and direction are measured at frequent intervals at a large number of sites in the UK by the Meteorological Office. From these measurements hourly mean wind speeds applicable to a standard height of 10m above ground in open countryside are derived.

Wind speeds are, however, affected by the roughness of the terrain over which the wind passes and it is therefore necessary to make a correction to the 'meteorological' wind speed to determine an equivalent value appropriate to the specific location in question. Figure 2 illustrates the effect on wind velocity of various types of terrain. From the exponential profiles of wind speed and height, the factors required to determine the local wind speeds at various heights above ground from the meteorological wind speed have been derived. They are presented in Reference 11.

Prominent topographical features and obtrusive buildings close to the building being considered will further modify the structure of the wind. Taking account of such effects is particularly difficult without resorting to wind tunnel testing.

The pressure distribution on a building exposed to wind is not only dependent on the local wind speed and direction but also on the size and shape of the building itself. However, the pattern of distribution is comparatively independent of wind speed, provided the building has sharp corners.

The pressure on a building generated by wind is thus usually expressed in terms of the dynamic (or stagnation) pressure of the wind by the use of a pressure co-efficient, C, so that

$$p = C\left(\tfrac{1}{2}\rho u^2\right) \qquad (1)$$

where ρ = density of air (kg/m^3)

u = local wind speed (m/s) (conventionally taken as the wind speed at a height equal to that of the buildings)

As is shown in the example in Figure 3, there is a wide variation in the value of the pressure coefficients over the surfaces and with change in wind direction, even for a simple building shape. Such detailed information for simple rectangular building shapes is available from many sources and may be used in a comprehensive study of natural ventilation. For a less critical approach, pressure coefficients averaged over each surface may be used. Such data for two wind directions are presented in Reference 7.

For other than the standard building shapes or where other adjacent buildings may affect the pressure distribution, wind-tunnel tests with a scale model of the building and its surroundings will be required, although for some specific building layouts wind pressure distribution data is now available[8].

The use of mean wind speeds in determining the pressures generated on building surfaces is not a strictly accurate method because of the turbulent character of the wind. The effect of fluctuating pressures on the rate of ventilation has been shown to be significant[9] but, at present, there is insufficient information to quantify the magnitude other than for the particular situations studied.

Another feature which gives rise to some uncertainty is the effect of relatively small irregularities in the surface of the building. For example, the pressure distribution around the edge of a window set in a rebate may be somewhat different from that in equivalent circumstances but with the window flush with the facade. The effects of external mullions has been studied[10] but not in sufficient depth to produce comprehensive data.

Temperature Difference. The difference in temperature, and hence in density, between the air inside a building and that outside causes a movement of air vertically through the building. This temperature motivated transfer of air is called 'stack effect'. In the heating season, for example, when the air temperature within the building is higher than that outside, pressure differences are created such that air flows into the lower levels of the building and out of the upper levels. The reverse occurs when the indoor temperature is lower than outdoors. The 'stack effect' can also generate ventilation in a single room where, for example, cool outside air may flow in through the lower section of an open window and out through the upper part.

The magnitude of the pressure differences caused by 'stack effect' is a function of the indoor and outdoor temperatures and the vertical distance between the openings, as follows

$$\Delta p_\theta = 3462h\left(\frac{1}{\theta_o} - \frac{1}{\theta_i}\right) \quad \text{.......(2)}$$

where Δp_θ = pressure difference caused by stack effect (Pa)

h = vertical distance between openings (m)

θ_o = external absolute temperature (K)

θ_i = internal absolute temperature (K)

A much more complex analysis is required in cases where severe temperature gradients exist within the building and where there is a multiplicity of openings at various heights.

Combined Effects of Wind and Temperature Difference. The effects of wind and temperature differences usually act simultaneously but they cannot simply be added together. The reason for this can perhaps be best illustrated by considering a window in an upper level on the windward side of a building. The wind tends to cause a movement of air inwards through the window, whereas stack effect produces an outward air movement. The two forces are acting contrary to each other. On other parts of the building, for example at the lower levels on the windward side they are complementary.

The overall ventilation rate is generally equivalent to that of the higher of the two effects when acting alone. Thus, at low wind speeds, when stack effect is predominant, the rate of ventilation may be calculated on the basis of temperature difference alone. At high wind speeds, only the effect of the wind needs to be taken into account. Figure 4 illustrates this for a two-storey house.

Although the overall ventilation rate may be determined by considering the predominant force only, the distribution of ventilation air throughout the building may be affected, so for detailed room-by-room analysis, the two effects need to be considered in combination.

Another reason for taking account of the coincidence of conditions of wind and temperature is the calculation of the energy loss attributable to infiltration or natural ventilation. Over the heating season, this energy loss is that required to heat the incoming cold air to the temperature maintained indoors.

i.e $$W = \int_0^T q_v \rho c_p (\theta_i - \theta_o) dt \quad \text{.........(3)}$$

where W = energy required (kJ)

q_v = volume flow rate of infiltration/ventilation (m^3/s)

ρ = air density (kg/m^3)

c_p = specific heat capacity of air (kJ/kg K)

θ_i = indoor absolute air temperature (K)

θ_o = outdoor absolute air temperature (K)

For a proper analysis of the ventilation energy loss over a heating season, it is thus, necessary to analyse the climatic conditions in terms of the coincidence of specific temperature, wind speeds and directions.

The Resistance to Airflow Through the Building

A building may be regarded as a network of air flow paths which interconnect at nodes. The nodes represent spaces inside and outside the building where substantially uniform pressure occurs. The interconnections comprise the components through which air may pass, such as gaps around windows and doors. Figure 5 shows a typical network superimposed on a plan drawing. The air flow paths have a characteristic resistance to air flow dependent on their type.

For large openings such as ventilator grilles and open windows, the following formula may be used:

$$q_v = Cd\ A \left(\frac{2\Delta p}{\rho}\right)^{\frac{1}{2}} \quad \text{.........(4)}$$

where q_v = volume rate of flow (m^3/s)

Cd = coefficient of discharge

A = area of opening (m^2)

Δp = pressure difference across opening (Pa)

ρ = air density (kg/m^3)

The discharge coefficient Cd is normally given the value appropriate to a sharp-edged opening and an equivalent orifice area is prescribed for the particular opening in question. This equivalent area may be taken as the same as the physical area for plain openings (e.g. open windows) but for more complex openings such as air-bricks or ventilation grilles, derived values of equivalent area will be needed. Some are given in Reference 11.

For small openings, such as gaps around closed windows and doors, the relationship between flow and pressure is much more dependent on Reynolds number but over a limited range corresponding to normal conditions the following relationship applies:

$$q_v = C_L (\Delta p)^{\frac{1}{n}} \quad \text{.........(5)}$$

where C_L = leakage factor = $k \times \ell$ where k = leakage coefficient in m^3/s per metre of gap length at a Δp of 1 Pa, and ℓ = total gap length (m)

$\frac{1}{n}$ = exponent where n is normally between 1.4 and 1.6

Typical values of k for windows are also given in Reference 11.

In addition to the types of opening described, air leakage occurs through other gaps and cracks in the building fabric. It may be through cladding components, structural cracks, and even through electrical conduits and where other services penetrate the structure. The magnitude of this 'background' leakage has been found to be significant. Measurements have revealed equivalent areas of similar magnitude to the areas of gaps around closed doors and windows in the building.

These measurements of background leakage area involved pressurising or evacuating the inside of a building using a fan passing a known rate of flow into or out of it. With any purpose-provided ventilation openings blanked-off and the gaps around the windows and external doors sealed, the relationship between internal-to-external pressure difference and air flow rate was established for the background leakage. To fully take account of it, the location of the background leakage paths must also be known and such information is extremely difficult to obtain for an existing building and virtually impossible to predict for a projected building. Much more experimental data are required before information suitable for design purposes can be provided, and even then the wide variations in building workmanship will make its application questionable.

DESIGN DATA

The move towards reduced energy consumption in buildings cannot be undertaken without recognition of the need to maintain safe and comfortable conditions for the occupants and of the economic considerations affecting the relationship between capital and running costs. For ventilation, this requires the ability to design buildings and systems to achieve the minimum ventilation rate criteria, to assess the energy consumption involved and to evaluate the economic advantages (or otherwise) of possible energy saving measures.

There is an urgent need for sufficient information to be made available to enable the designer to achieve these requirements by the application of the principles already outlined. In this section, the shortfall in the available data is highlighted. There is also a need for an understanding of the effectiveness of alternative measures to reduce energy losses as well as an appreciation of the economic criteria for evaluating an increase in capital outlay against the potential long-term savings. Some examples of alternative ventilation control measures are presented but the economic aspects, important though they may be, are not considered within the scope of this paper. The effects of occupant behaviour with respect to openable windows are also not considered.

Prediction of Ventilation Performance

The designer requires information to enable the estimation of ventilation rates from known building design data, or, conversely, the determination of provisions required in the building from knowledge of the ventilation criteria. Associated with both approaches, is the requirement for the calculation of corresponding energy losses.

Figure 6 illustrates how, by the application of the principles of natural ventilation, the gulf the designer has to cross can be spanned. As the diagram shows, the bridge-building is not yet complete. Highlighted as weak links are those relationships for which sufficient reliable data are, as yet, unavailable. These include the relationship between meteorological wind data and wind-generated pressure distributions on a building taking into account fluctuations, local disturbances, characteristics of the building surface; and the magnitude and distribution of 'background' leakage through gaps and cracks in the building fabric. Additionally, specific criteria for minimum ventilation rates are required. There is an obvious need for continuing reseach to strengthen these weaker links.

One of the further important requirements is the translation of these principles of ventilation, involving multiple and complex parameters, into a procedure easily applied by designers.

With the facilities offered by modern computers, it is tempting to opt for the retention of sophisticated procedures for design predictions. However, the required detail and precision of the prediction method is governed not only by the use that is made of the end result, but also by the form of the available supporting information. For example, a calculation precision of 1% is hardly justifiable when constructional tolerances may produce variations of much higher magnitude. Nor is there any point in developing a minute-by-minute analysis of ventilation rates, when available meteorological data is expressed in hourly mean values. The aim perhaps can best be expressed as the achievement of a design process which is comparable in precision, proven reliability and ease of use with those available for the other energy transfer processes in buildings.

Energy Saving Potential

The requirement to maintain ventilation rates at or as little possible above the minimum acceptable value while relying on natural forces presents real difficulties. If the minimum ventilation rate is achieved under mild, still climatic conditions then under all cooler, windier conditions the rate will be in excess of that required with the consequent wastage of energy. To demonstrate the magnitude of the unnecessary energy loss and to examine the potential of alternative measures to reduce energy wastage, comparative calculations of ventilation rates and energy loss have been made for a modern, two-storey dwelling.

Calculations were made to derive, for this particular building, the relationship between ventilation rate and the combination of wind speed and indoor-outdoor temperature difference. In this case, variation in wind direction was not taken into account, because tests had shown that overall ventilation rates were relatively independent of wind direction. These calculations were based on selected pressure distribution data applicable to an urban area, an assumed constant indoor temperature of 19°C and various component and background air leakage characteristics. It was assumed that the windows and doors were always closed. The example shown on Figure 4 illustrates the predominant effect of temperature difference at low wind speeds and of wind at speeds above 3.5 m/s.

Seasonal ventilation rates and the associated energy loss was then calculated by using the derived relationships and specific meteorological data. The meteorological data consisted of a table giving the frequency of occurence of mean hourly wind speeds within 2 K outdoor temperature bands. The wind speeds were modified to relate them to an urban environment and to the height of the dwelling. The data for Birmingham (Elmdon) covered the heating seasons, September to May, over a 10 year period, 1969 to 1979.

Table 1 presents the results of these calculations for a number of conditions and these are discussed below. In this discussion, it has been assumed that the rate of ventilation should not fall below 0.3 air changes per hour. This value has been chosen for demonstration purposes only - whether or not it is an acceptable criteria may be considered in the light of the previous paper.

Natural Ventilation - Variation in Leakage Values. For the same dwelling, two levels of leakage were considered. The first corresponded to the situation as found on site in which window, door and background leakage were taken into account. This could be considered as a house of typical construction with good quality windows and doors. Over the heating season the air change rate was always at or above 0.3 times per hour with a mean rate of 0.81. It was above 0.5 changes per hour for 93% of the time. The associated seasonal energy loss was calculated to be 16.6 GJ. In comparison, the equivalent energy loss for an air change rate of 0.3 and 0.5 air changes per hour consistently over the heating season was 6.1 GJ and 10.2 GJ respectively. There is thus considerable potential for reducing the ventilation energy loss in such a naturally ventilated building provided some control can be applied to reduce the range of ventilation above the minimum rate. This theoretical potential for energy saving is up to 20% of the total seasonal energy loss of the dwelling assuming it to have the thermal insulation values given in the 1976 Building Regulations[4].

The second level of leakage was that with the background leakage eliminated and a reduction in the leakage through windows and doors so that the building met the air leakage requirements of the 1978 Swedish Building Code, i.e. 3 air changes an hour at a pressure difference of 50 Pa. The seasonal energy consumption was reduced to a level that corresponded to a mean air change rate of just less than 0.3 times per hour but for over 60% of the season the ventilation rate was below that level. Simply reducing the leakiness of the structure is clearly not a satisfactory method of minimising ventilation energy losses.

Controlled Natural Ventilation. There are several ways by which the rate of natural ventilation in a building could be controlled if the resulting energy savings were found to be worthwhile.

For example, providing shelter to eliminate the effects of wind on the original dwelling under consideration would, while still maintaining an air change rate consistently above 0.3 times per hour, reduce the ventilation energy loss from 16.6 GJ to 10.8 GJ, a potential saving of just over 30%. Experiments in the United States[12] have demonstrated savings of the order of 10% with shelter provided by evergreen trees.

Another approach might be the control of ventilation openings by devices sensitive to outdoor temperature so that as the temperature outside reduced so the open area of the vents also reduced. Again, the calculation shows that savings of over 30% could be realised while maintaining adequate ventilation at all times.

The control of ventilation opening areas in response to the pressure differential across them could theoretically produce a consistent ventilation rate at the required minimum level and so reduce the associated energy loss to 6.1 GJ. Although such devices were evidently available as long ago as 1948[3], it is unlikely that effective performance could be achieved economically.

The effective adoption of some form of automatic control of ventilation openings implies that other routes of potential leakage must be minimised and this requires detailed attention to structural design.

Mechanical Ventilation. The application of mechanical ventilation systems in dwellings is worthy of consideration. It is being used as an energy saving measure in some countries with climatic conditions more severe than ours, but further studies on its potential in this country are required.

The advantage of mechanical ventilation is that it ensures fresh air supply at a required rate. However, the influences of wind and stack forces can still result in ventilation rates above the required level. Table 1 includes the results of calculations for mechanical ventilation applied to the low-leakage dwelling. With a balanced ventilation system, i.e. both supply and extract fans, providing 0.3 air changes per hour, the ventilation energy loss was twice the value that would result if the natural forces were eliminated. At a mechanical ventilation rate of 0.5 air changes per hour the corresponding ratio was 1.5:1. With extract ventilation the ratios were lower at 1.5:1 and 1.12:1 respectively.

This demonstrates that structures must be well sealed for the effective application of mechanical ventilation systems. In the original naturally ventilated dwelling, a reduction of energy of 7.5 GJ per year would involve not only the purchase, installation and running cost of the mechanical ventilation system but also a five-fold reduction in the leakiness of the structure.

The balanced type of mechanical ventilation system offers the potential of heat recovery by pre-heating the incoming air with the outgoing air. This may be achieved by a plate heat exchanger or more sophisticated heat transfer equipment. If it is assumed that 75% of the heat in the extract air was recovered, the seasonal ventilation energy loss would reduce by 4.3 GJ but again the cost implications need careful assessment.

CONCLUSIONS

Natural ventilation is a complex process affected by many parameters, the values of which are difficult to accurately predict. There is a need for further experimental work to provide more reliable data for the improvement of design procedures. This experimental work should include detailed studies on various building types with measurements of local climatic conditions, wind-generated pressure differences and infiltration rates. The results of such work should be related to the leakage characteristics of the buildings and meteorological data and be used in the development of refined design models.

The results of some sample calculations demonstrate the orders of magnitude of energy savings that could theoretically be achieved by the use of controlled or mechanical ventilation in dwellings. The value of these savings needs to be assessed in relation to the expenditure required to construct buildings with lower air leakage than is usual at present and that required for additional capital equipment.

It is appreciated that the effects of the occupants' use of openable windows has been ignored. This will have a significant influence on the energy consumption but it should nevertheless be the aim of the designer to promote buildings which inherently provide ventilation at a minimum acceptable level while allowing occupants the facility to increase the rate of ventilation for special circumstances.

TABLE 1 - Calculated seasonal ventilation performance and energy loss

	Ventilation energy loss	Average ventilation rate	Time > 0.3 changes/hour	Time > 0.5 changes/hour	Total leakage at 50 Pa
	GJ	air changes/ hour	%	%	air changes/ hour
Constant ventilation (theoretical)					
1. 0.3 air changes/hour	6.1	0.3	100	0	-
2. 0.5 air changes/hour	10.2	0.5	100	100	-
Natural ventilation					
3. House of typical construction	16.6	0.81	100	93	14.6
4. House to 1978 Swedish Building Code (low leakage)	5.4	0.27	37	8	3
Controlled natural ventilation					
5. Typical house fully sheltered	10.8	0.53	100	41	14.6
6. House with temperature-sensitive ventilation control	10.8	0.53	100	49	14.6 at $\Delta\theta$ of 4K 4.6 at $\Delta\theta$ of 20K
7. House with pressure-differential-sensitive ventilation control (theoretical optimum)	6.1	0.3	100	0	-
Mechanical ventilation					
8. Low leakage house with balanced ventilation at 0.3 air changes/hour	11.5	0.56	100	67	3
9. Low leakage house with balanced ventilation at 0.5 air changes/hour	15.6	0.77	100	100	3
10. Low leakage house with extract ventilation at 0.3 air changes/hour	8.9	0.44	100	32	3
11. Low leakage house with extract ventilation at 0.5 air changes/hour	11.5	0.56	100	100	3

SYMBOLS USED

A = area of opening (m^2)

C = wind pressure coefficient

Cd = coefficient of discharge

C_L = leakage factor (m^3/s at a Δp of 1 Pa)

c_p = specific heat capacity of air (kJ/kgK)

h = vertical distance between openings (m)

k = leakage coefficient (m^2/s at a Δp of 1 Pa)

ℓ = length of gap (m)

n = characteristic exponent

p = pressure on a building generated by wind (Pa)

Δp = pressure difference across opening (Pa)

Δp_θ = pressure difference caused by stack effect (Pa)

q_v = volume flow rate of infiltration/ventilation (m^3/s)

T = time (s)

u = local wind speed (m/s)

W = energy requirement (kJ)

ρ = density of air (kg/m^3)

θ_i = internal absolute temperature (K)

θ_o = external absolute temperature (K)

$\Delta\theta$ = indoor to outdoor temperature difference (K)

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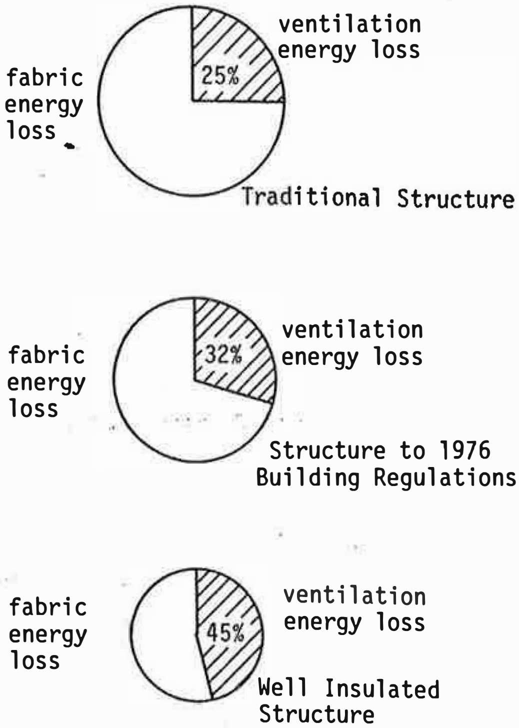


Figure 1 Typical proporations of seasonal energy losses from dwellings

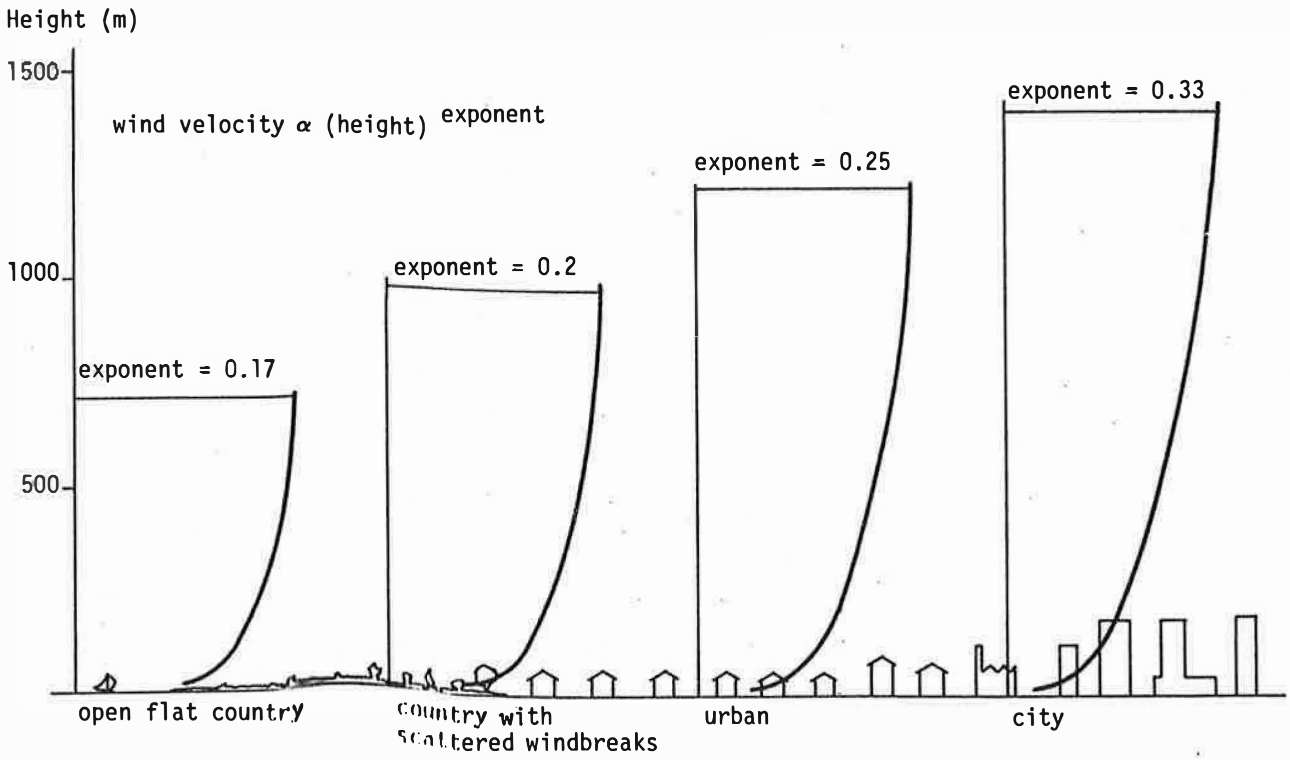


Figure 2 Variation of wind velocity with height over various types of terrain

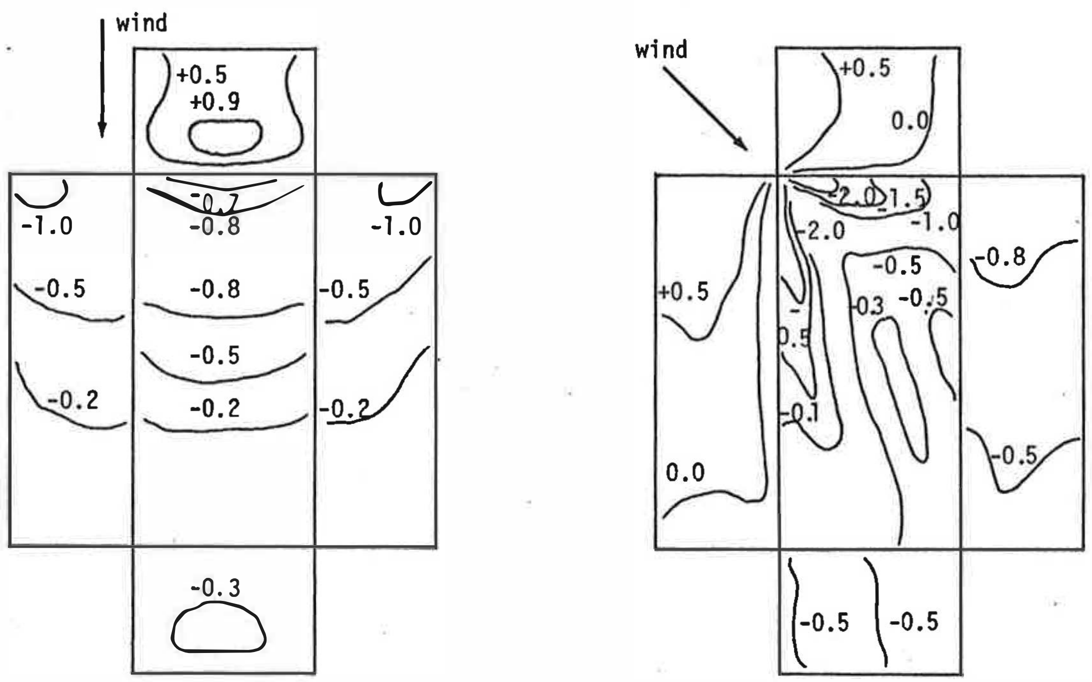


Figure 3 Wind pressure coefficient contours on the surface of a building

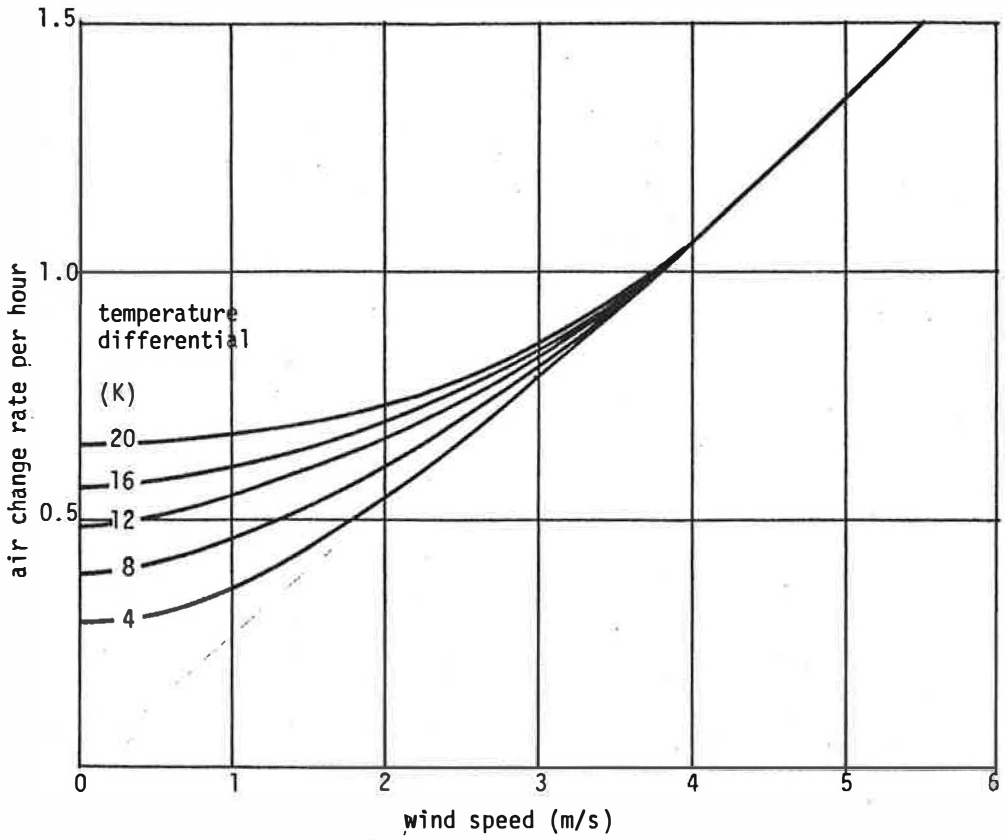
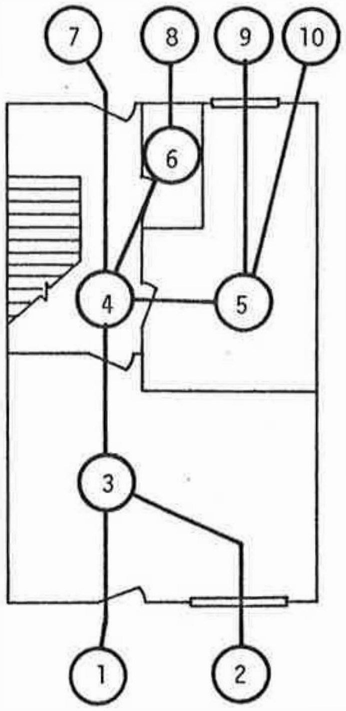


Figure 4 Typical relationship between ventilation rate, wind speed, and temperature differential



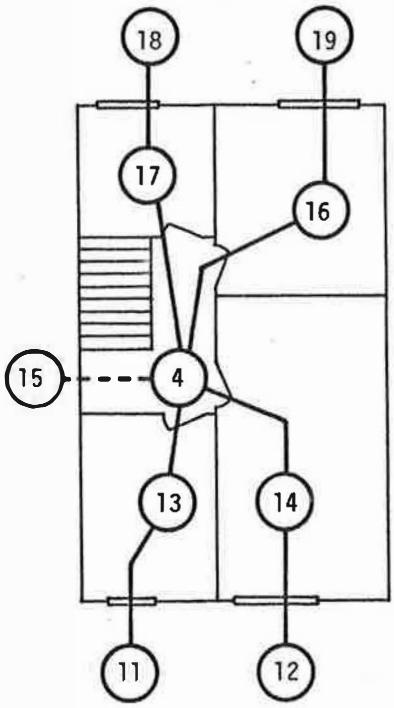


Figure 5 Air flow network of a typical dwelling

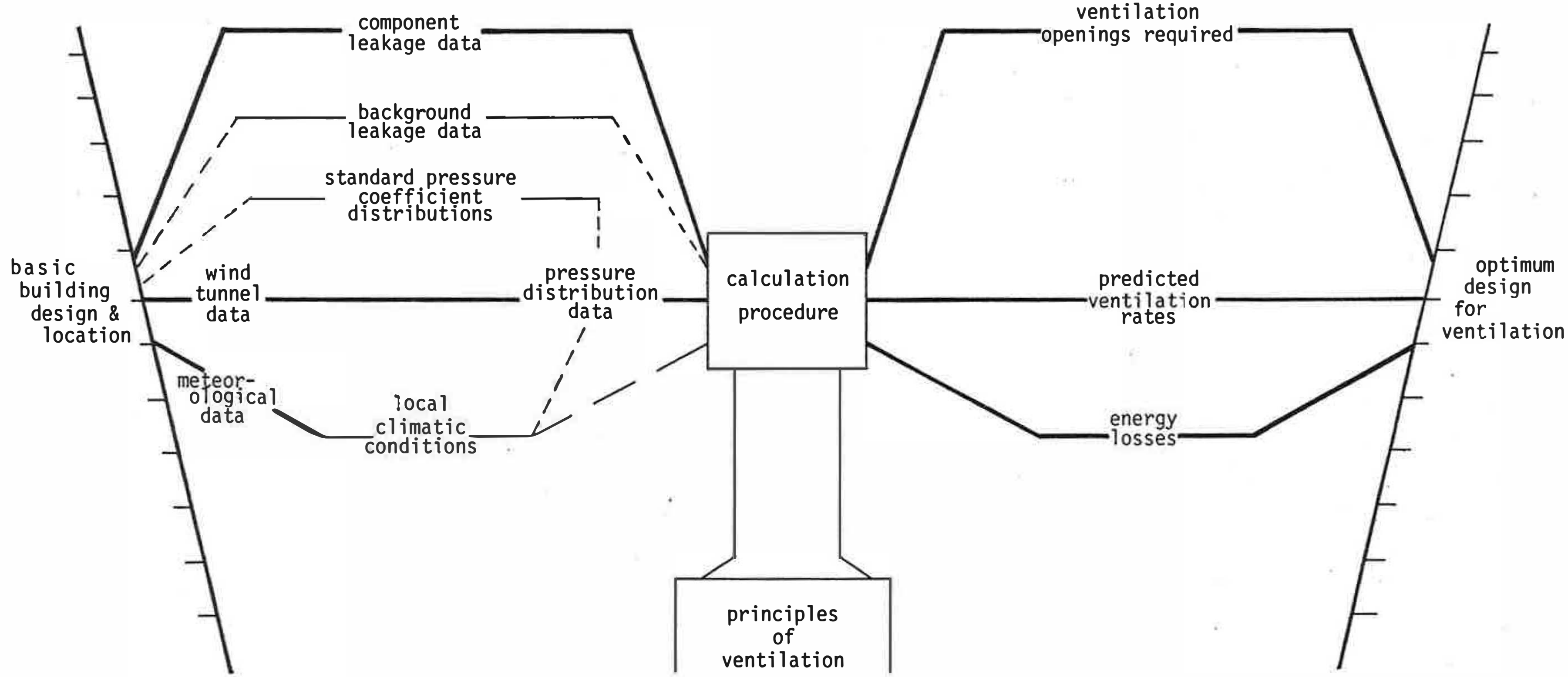


Figure 6 Ventilation design process

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