#2633

AIVC
2167
2633

BTECC SYMPOSIUM
"AIR INFILTRATION, VENTILATION AND MOISTURE TRANSFER"
Worthington Hotel, Fort Worth, Texas, USA
2-4 December 1986

SESSION IV: AIR TIGHTNESS AND AIR QUALITY

AIR INFILTRATION AND INDOOR AIR QUALITY

M.W. Liddament, BA, PhD
Head
Air Infiltration and Ventilation Centre
Bracknell, Berkshire, UK

AIVC

ABSTRACT

Infiltration and the natural ingress of air provide the main mechanisms of ventilation in many buildings. However, in addition to meeting ventilation requirements, the behaviour of both infiltration and exfiltration can have an important influence on indoor air quality. Problems such as backdraughting can easily occur with misplaced openings, while insufficient airflow may result in inadequate dilution and dispersion of internally generated pollution. Other problems may be caused by the development of underpressures which can promote radon ingress from underlying strata or formaldehyde ingress from building materials.

The objective of this paper is to highlight some of these problems and to indicate simple analytical methods for quantifying the impact of air infiltration and ventilation on indoor air quality. Specifically, information will be presented on building airtightness limitations for acceptable indoor air quality, the benefits of alternative ventilation strategies and the role of calculations in optimising ventilation performance. Consideration will also be given to airborne moisture transport in relation to the basic physical mechanisms involved and the the ventilation required to minimise water vapour concentration.

INTRODUCTION

Ventilation provides the key to habitable conditions within buildings. Its primary role is to ensure a pollution-free environment in which occupants can live without detriment to health and comfort. As awareness of the possible harmful effects of poor ventilation has grown, there has been an increasing need to establish guidelines and standards covering ventilation requirements. Over recent years much has been accomplished in the research sector, with the result that it is now possible to provide the designer and building end user with practical guidelines on the implementation of efficient, cost effective ventilation methods.

Ventilation approach ultimately depends on such factors as the type of building, climatic conditions and the requirements of occupants. Therefore, no single approach can be expected to provide a universally acceptable solution. The alternatives vary in extreme from natural air infiltration to fully controlled mechanical ventilation, perhaps incorporating heat recovery and air conditioning. Between these extremes lies a full spectrum of strategies which, if properly tailored to the design need, will provide the designer with a solution to his particular problem.

By its very nature, the design process demands the use of calculation techniques. It is therefore the objective of this paper to outline some of the numerical processes that the designer or consultant may apply to the basic ventilation and indoor air quality aspects of design. The concepts of ventilation effectiveness and room air movement are also introduced although no attempt has been made to detail the equations covering this subject.

MOISTURE AND INDOOR AIR QUALITY

In the past, odour has often been regarded as a good indicator of indoor air quality, especially in densely occupied buildings. In dwellings, moisture provides one of the most obvious air quality indicators and can be a very serious problem. Changing lifestyles has resulted in the increasing use of water in the home and estimates indicate that as much as 14 Kg/day [1] of moisture can be released in vapour form as a result of washing, clothes drying, unvented space heating and other activities. In some climates the problem is exacerbated by the incoming air itself having a high water content. Since the capacity of air to hold water vapour is a function of temperature, condensation first occurs on cold surfaces such as single glazing or uninsulated walls. High overall relative humidities also give rise to mould growth and general discomfort.

Often moisture problems are considered to be a consequence of poor ventilation or excessive building airtightness, although in reality it is unlikely that any amount of ventilation will provide a cure if the thermal insulation of the building fabric is at fault. A poorly insulated surface will tend to respond to the cooling effects of low outdoor temperatures, while excessive ventilation will only further cool the building interior thus creating additional difficulty. The only satisfactory answer is to improve the thermal performance of the building shell and to introduce a ventilation approach which promotes the extraction of moisture at source. Effort should be applied to minimise the discharge of water vapour, especially in relation to clothes drying and to the use of unvented heating appliances.

Other indoor pollutants which are currently causing concern are radon and formaldehyde, neither of which need be directly detectable by the occupant. Each pollutant normally requres a different ventilation rate to ensure sufficient dilution and, as a rule, the overall ventilation rate must be equal or exceed that which is necessary to disperse the pollutant requiring most ventilation. It is therefore important to identify the dominant pollutant and to ventilate accordingly. The theoretical concepts outlined in this paper may be used to analyse the ventilation requirements and air flow patterns necessary to control pollution levels in buildings.

Any relationship between airtightness and indoor air quality is somewhat tenuous. The real problem is to design for airtightness according to ventilation approach. Buildings with no planned ventilation must have sufficient porosity to enable the adventitious passage of air into the building while mechanically ventilated buildings benefit from an overall airtight structure in which air is supplied and extracted according to requirements. These approaches to airtightness are reflected by legislative requirements or recommendations in some countries and are often dependent on climatic conditions. In Sweden and parts of Canada a move towards airtight construction with purpose provided ventilation has taken place, whereas in the United Kingdom emphasis is placed on less airtight construction. From the design point-of-view it is important to realise that airtight construction must be accompanied by an independent means of ventilation. Equally, if mechanical ventilation with heat recovery is being installed, then an airtight construction technique is essential. In practice there is an optimum range of airtightness for each type of ventilation approach which is often specified in terms of an air leakage rate at 50 Pa. Swedish requirements set a maximum leakage at 50 Pa of between 1-3 air changes/hour (ach)[2], whereas British recommendations for adventitiously ventilated dwellings are set at between 10-20 ach[3]. For the optimum performance of air-to-air balanced ventilation systems, an air change rate of less than 1 ach at 50 Pa is probably appropriate while, to avoid backdraughting or excessive draughts, an extract only ventilation system would benefit from a "fabric" leakage of about 3-4 ach at 50 Pa.

AIR INFILTRATION AND VENTILATION CALCULATION TECHNIQUES

Calculation techniques fall into two fundamental categories, these being "empirical" and "theoretical" methods. Empirical approaches are the most basic of all techniques and are only loosely based on the physical concepts of air flow. As such, their range of applicability is strictly limited and they are primarily intended for use in the sizing of heat emitters and cooling systems. Such approaches are well documented in Chapter 22 of the ASHRAE Fundamentals[4] and Part A of the CIBSE Guide[5]. In principle these methods are based on rudimentary "crackage" data, air leakage pressurization test data or a regression analysis of actual air infiltration measurements made for a known range of weather parameters. These methods have little application in the field of indoor air quality prediction, except perhaps for those based on pressurization test data, which can give valuable guidance on building airtightness and related air quality problems.

A theoretical analysis of air flow provides a much more stable foundation on which to undertake air quality simulations. Again there are various levels of complexity ranging from "simplified" theoretical techniques to multi-zone air infiltration and ventilation network methods. "Simplified" methods have been developed by Sherman et al[6] and Warren et al[7] and are intended to predict the impact on air infiltration rates of retrofit and other changes to the building envelope using the minimum number of parameters. This is achieved by simplifying the representation of flow mechanics as much as possible. The Air Infiltration and Ventilation Centre's model validation exercise[8] showed that this type of approach is very effective in predicting overall air change rates and therefore is ideally suited to energy calculations. The principal disadvantage of these methods, as regards indoor air quality analysis, is that they provide no flow path data. It is therefore not possible to use them to predict the magnitude and direction of flow through openings. Additionally these methods are only currently suitable for buildings which can be assumed to be at a single internal pressure, i.e. "single zone" buildings. Therefore they are unsuitable for multi-zone buildings such as offices, etc.

A full analytical treatment of air infiltration and ventilation is based on defining a network of flow paths through which air may pass. In order to conserve mass balance, the algebraic sum of the flow through these paths must always total zero. Under normal atmospheric conditions, the mean flow of air through an opening may generally be approximated by the power law equation

$$Q = k(\Delta P)^n \qquad (m^3/s) \qquad (1)$$

where k = flow coefficient (m^3/s at 1 Pa)

n = flow exponent

ΔP = pressure difference across opening

The coefficient, k, is related to the size of the opening and the exponent, n, characterises the flow regime. The flow exponent ranges in value from between 0.5 for fully turbulent flow to 1.0 for laminar flow. Other formulations of the flow equation are also occasionally used and for the purposes of numerical calculations can normally directly replace the power law equation.

In undertaking a calculation, the following data are required:

- surface pressure distribution
- magnitude and distribution of air flow paths

The pressure distribution drives the infiltration and ventilation process and is maintained by the actions of wind and temperature. Relative to the static pressure of the free wind, the pressure resulting from wind impingeing on the surface of a building is given by

$$p_w = \frac{\rho}{2} C_p V^2 \quad \text{(Pa)} \qquad (2)$$

where ρ = air density (kg/m^3)

C_p = pressure coefficient

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

The pressure coefficient, C_p, is an empirically derived parameter which is a function of the pattern of flow around the building. It is normally assumed to be independent of wind speed but varies according to wind direction and position on the building surface. It is also significantly affected by neighbouring obstructions, with the result that similar buildings subjected to different surroundings may be expected to exhibit markedly different pressure coefficient patterns. Accurate evaluation of this parameter is extremely difficult and analytical methods have yet to be verified. Most data come from the results of wind tunnel testing and care must be exercised to ensure that such data are appropriate to the conditions being simulated. The AIVC has prepared data tables, based on published results, for a range of building sizes subjected to various degrees of surrounding shielding[9].

The temperature or stack effect arises as a result of differences in temperature and hence air density between the interior and exterior of a building. This produces an imbalance in the pressures exerted by the internal and external air masses, thus creating a vertical pressure gradient. The pressure differences resulting from stack action, between two vertically displaced openings, is given by

$$p_s = -273\rho_o gh\left(\frac{1}{T_{int}} - \frac{1}{T_{ext}}\right) \quad \text{(Pa)} \qquad (3)$$

where ρ_o = air density at 273K and ambient pressure (Kg/m^3)

h = vertical distance between openings (m)

T_{ext} = external air temperature (K)

T_{int} = internal air temperature (K)

The consequences and significance of stack effect must be considered for a number of alternative configurations. These include

- uniform internal temperature distribution
- multizone buildings with impermeably separated vertical zones
- multizone buildings in which interconnected vertically placed zones are at different temperatures
- multizone buildings in which horizontally placed zones are at different temperatures
- large single zone structures subjected to thermal stratification
- heated fireplaces, chimneys and flues

Each of these configurations may be readily analysed using the basic stack equation[9]. The effects of wind and stack action are taken into account by superimposing the magnitude of each, taking into account both the elevation and orientation of individual openings (Figure 1).

It is essential that the flow network represents all sources of air leakage, otherwise serious errors will result. In essence these paths consist of "component" or "purpose provided" openings such as vents and chimneys, and "background" openings which result from imperfections in the building structure. The characterization of component openings is relatively straightforward but, by its very nature, the scale of background leakage is difficult to ascertain. There is a growing database of air leakage performance data for both entire buildings and components, some of which has been catalogued by the AIVC[9]. Where no other data exist or where measurements cannot be made, representative data should be applied. However, wherever possible, assumptions regarding design leakage should be verified by pressurization testing on completion of the building.

Any number of flow paths can be selected to represent leakage openings and each may be used to represent either a single opening or an amalgamation of openings. The calculation is very much simplified if the interior of the building can be assumed to be of a single uniform pressure (Figure 2), otherwise the building must be represented by a multi-zone network (Figure 3). In the latter case, an internal flow network must also be defined. Having established the flow network, equation (1) is applied to each path. For a single zone, mass flow balance is given by

$$\sum_{i=1}^{j} \rho_i Q_i = 0 \qquad \text{(kg/s)} \qquad (4)$$

where ρ_i = density of air flowing through i'th flow path (kg/m^3)

Q_i = volumetric flow rate (m^3/s)

By substitution of the above in the power law form of the flow equation (equation (1)), the condition of mass balance becomes

$$\sum_{i=1}^{j} \underbrace{\rho_i k_i}_{\textit{Term 1}} \underbrace{|p_i - p_{int}|^{n_i}}_{\textit{Term 2}} \underbrace{\left(\frac{p_i - p_{int}}{|p_i - p_{int}|}\right)}_{\textit{Term 3}} = 0 \qquad (5)$$

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

P_{int} = internal pressure

ρ_i = density of air mass in the i'th flow path

The infiltration air density, ρ_i, is given by that of the outside air while for the exfiltrating air it is given by that of the internal air mass. If the density difference between the internal and external air masses is negligible in comparison to the magnitude of the overall density of air, i.e. when the internal/external temperature difference is less than approximately 20°C, then Term 1 of equation (5) may be ignored. The problem then becomes one of balancing the volume flow rate rather than the mass flow rate. Term 2 expresses the absolute value of the internal/external pressure difference across each opening and is applied to avoid exponentiating a negative number when $P_i < P_{int}$. Term 3 restores the sign of the flow direction which was lost in the previous term.

The internal pressure is determined by numerical iteration such that a flow balance is attained. In the case of a multi-zone network, equation (5) is applied to each zone. Mechanical ventilation is most easily incorporated by expanding the mass balance equation (equation (4) to give

$$\sum_{i=1}^{j} \rho_i Q_i + \rho_i Q_{mv} = 0 \qquad (kg/s) \qquad (6)$$

The numerical solution of these equations is normally very easy to execute and this approach offers many advantages. From an air quality aspect, the technique indicates where air enters or leaves a building. It also enables the rate and direction of flow through each opening to be quantified and shows how the flow rate is influenced by mechanical ventilation. Additionally it determines the pressure difference across openings. This is a very important parameter since it can be used to estimate the propagation of pollutants across a boundary, e.g. radon ingress through a basement slab. Since the flow rate into or out of individual zones is also determined, the mean pollutant concentration can be calculated for any given starting concentration or pollutant discharge rate. As a consequence, this approach is extremely powerful and is an essential element towards any building air quality prediction study.

INDOOR AIR QUALITY CALCULATIONS

Subject to the uniform mixing of pollutants within each zone of the building, the concentration of a contaminant in a leaky enclosure is given at any instant in time by the continuity equation[10]

$$\underbrace{\frac{Vol \times dC_{int}}{dt}}_{Term\ 1} + \underbrace{mQ\,(C_{ext} - C_{in})}_{Term\ 2} = \underbrace{(S - \lambda)}_{Term\ 3} \qquad (mass/time) \qquad (7)$$

where Vol = volume of enclosure (m^3)

λ = rate of chemical or physical decay of pollutant (mass/s)

m = empirical mixing factor (varies from 0 to 1, m=1 is equivalent to perfect mixing)

C_{int} = internal concentration of pollutant ($mass/m^3$)

C_{ext} = external concentration of pollutant ($mass/m^3$)

Q = ventilation rate (m^3/s)

S = total rate of emission of pollutant (from all sources)

The above equation may be solved when any six of the seven parameters are known and, in practice, a solution is normally made possible by eliminating some parameters altogether. Two formulations of the continuity equation may be readily analysed and will enable approximate pollution concentrations to be determined for many situations.

The first considers the constant emission of a pollutant, for example the emission of formaldehyde or radon within a building. Assuming a steady state air exchange rate, the internal concentration of pollutant will eventually reach equilibrium. Thus Term 1 of equation (7) will tend to zero and the equilibrium concentration will be given by

$$(C_{int} - C_{ext}) = \frac{(S - \lambda)}{mQ} \qquad (8)$$

In the case of formaldehyde, there will be no physical or chemical degredation, neither will there be an external component. Therefore both λ and C_{ext} are equal to zero. If perfect mixing is assumed (m=1) the internal equilibrium concentration becomes

$$C_{int} = \frac{S}{Q} \qquad (9)$$

Radon experiences physical decay, hence

$$C_{int} = \frac{S - \lambda}{Q} \qquad (10)$$

where λ = decay rate

Once the emission of a pollutant ceases, the emission rate, S, becomes zero and the pollutant concentration decays as a function of time. Eliminating Term 3 from equation (7) and integrating yields

$$C_t = C_{t_o} e^{-Q/vt} \qquad (11)$$

where C_t = pollution concentration at time (t) after cessation of pollutant emission (t_o)

C_{t_o} = equilibrium pollutant concentration

VENTILATION EFFECTIVENESS

For many applications, ventilation requirements are expressed in the form of an hourly air change rate. Additionally it is often necessary to have an indication of interzonal air flow rates and knowledge of the air flow direction at boundary and other openings. All these requirements are met by the preceeding techniques and very often this is sufficient for the development of ventilation design solutions. However, implicit in this numerical analysis is the assumption of perfect mixing within each zone. In practice the behaviour of internal air movement is not straightforward and much can happen to prevent this "ideal" mixing pattern. The degree to which a ventilation system fulfills ventilation requirements is often described in terms of "ventilation effectiveness" or "ventilation efficiency".

Poor ventilation effectiveness is likely to occur in instances where convective currents create circulatory or preferential air flow patterns leaving zones in which air is effectively trapped. This problem is further aggravated by the improper siting of supply and exhaust terminals. The degree and nature of mixing is frequently described in terms of ventilation efficiency in which three extremes of mixing characteristics are defined[11]. The first and most "efficient" is known as "plug flow" or "piston flow" in which fresh air displaces contaminated air directly. The second is "perfect mixing" in which incoming air continuously and uniformly mixes with the interior air mass. The final extreme is that of total short-circuiting. This condition is represented by the complete interception of supply air by the exhaust air register without any mixing with the interior air mass. An example based on the results of Sandberg [11] is illustrated in Figure 4 for the ventilation efficiency of two ventilation configurations, each providing the same nominal air change rate in an occupied zone. The figure also illustrates a line of "perfect" mixing as assumed in numerical prediction techniques.

Some experimental data and design information on the optimum layout of ventilation systems is available but for buildings with demanding ventilation requirements, it is often necessary to undertake experimental design studies. Calculation techniques based on general two- and three-dimensional air movement algorithms are now becoming available to ease this design burden [12]. The numerical problem is essentially one of firstly determining the pattern of air movement within a room or zone and secondly predicting the transport of pollutant within that zone. This leads to a high level of numerical complexity incorporating the transient equations of momentum, energy and mass transfer. The availability, performance and suitability of air movement and ventilation effectiveness algorithms are currently being assessed by the Air Infiltration and Ventilation Centre.

CONCLUSION AND DISCUSSION

Numerical techniques provide a valuable tool for ventilation and air quality studies. Over recent years the development of these techniques has reached the point where they are now available to the designer, either through direct use or via a consulting link.

Essentially three levels of numerical technique are available, each with a distinct purpose. Air infiltration and ventilation modelling presents the designer with basic airchange predictions and identifies air inflow and outflow routes for any combination of wind and temperature. It may also be used to assess the pressure regime within each zone of the building and to predict the effect of mechanical ventilation on air flow distribution. Basic infiltration and ventilation modelling provides the foundation on which air quality modelling can proceed. Interzonal air movement and air change predictions are a vital pre-requisite to air quality algorithms.

Air quality models provide the investigator with information on average pollutant concentrations within rooms and on the transfer of pollutant from one zone to another. The response to transient emissions, external pollution and any physical or chemical degredation of a pollutant may also be analysed using these methods.

Room air movement models provide the user with air velocity field predictions, mixing characteristics and temperature and pollutant distributions within individual zones. This is a very specialist area of modelling, demanding very precise boundary data. This level of calculation technique is reserved for specific applications such as industrial ventilation problems or research analysis calculations.

Although playing an important function in the design process, numerical methods will only interpret or project the ideas of the designer and are of little value in themselves in producing a design solution. The key parameters for consideration at the design stag are the required rate of ventilation, the proposed ventilation approach and the overall value of building airtightness. These parameters must be carefully considered by the designer, who should then use the calculation techniques outlined to identify any shortcomings in the proposed approach.

The AIVC has compiled a calculation techniques guide[9] which covers many of the items outlined in this paper. It also contains a basic database of air leakage and wind pressure data for use in the calculation of air infiltration and ventilation.

REFERENCES

1. Louden, A.G.
   The effect of ventilation and building design factors on the risk of condensation and mould growth in dwellings.
   Archit. Journal, May 1971, Vol.153, p1149-1159

2. Swedish Building Code SBN 1980
   Chapter 33: Thermal insulation and airtightness (revised 1980). Building Regulations 1969.
   Royal Ministry of Local Government and Labour.

3. Building Research Establishment (UK) Digest 306
   Domestic draught proofing: ventilation considerations
   February 1986

4. ASHRAE Fundamentals, Chapter 22
   American Society of Heating, Refrigerating and Air Conditioning Engineers
   1985

5. CIBSE Guide Section A4: Air Infiltration
The Chartered Institution of Building Services Engineers
1976

6. Sherman, M.H. and Grimsrud, D.T.
Measurement of infiltration using fan pressurization and weather data
Proceedings, 1st AIC Conference, UK, 1980

7. Warren, P.R. and Webb, B.C.
The relationship between tracer gas and pressurization techniques in dwellings
Proceedings, 1st AIC Conference, UK, 1980

8. Liddament, M.W. and Allen, C.
The validation and comparison of mathematical models of air infiltration
Technical Note AIC-TN-11-83, Air Infiltration and Ventilation Centre, September 1983.

9. Liddament, M.W.
Air infiltration calculation techniques - an applications guide
AIC-AG-1-86, Air Infiltration and Ventilation Centre, June 1986

10. Harrje, D.

11. Sandberg, M.
Definition of ventilation efficiency and the efficiency of mechanical ventilation
Proceedings, 3rd AIC Conference, UK, 1983

12. Whittle, G.E.
Computation of air movement and convective heat transfer within buildings
International Journal of Ambient Energy, Vol.7, No.3, 1986
(to be published)

Figure 1: Single zone representation

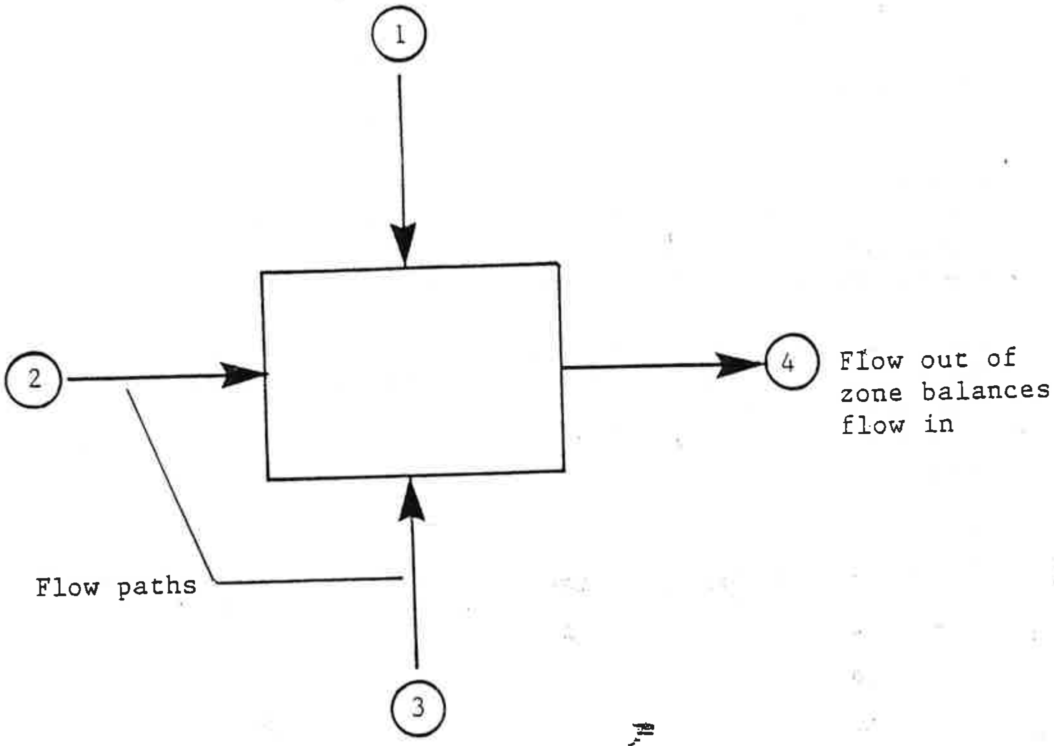
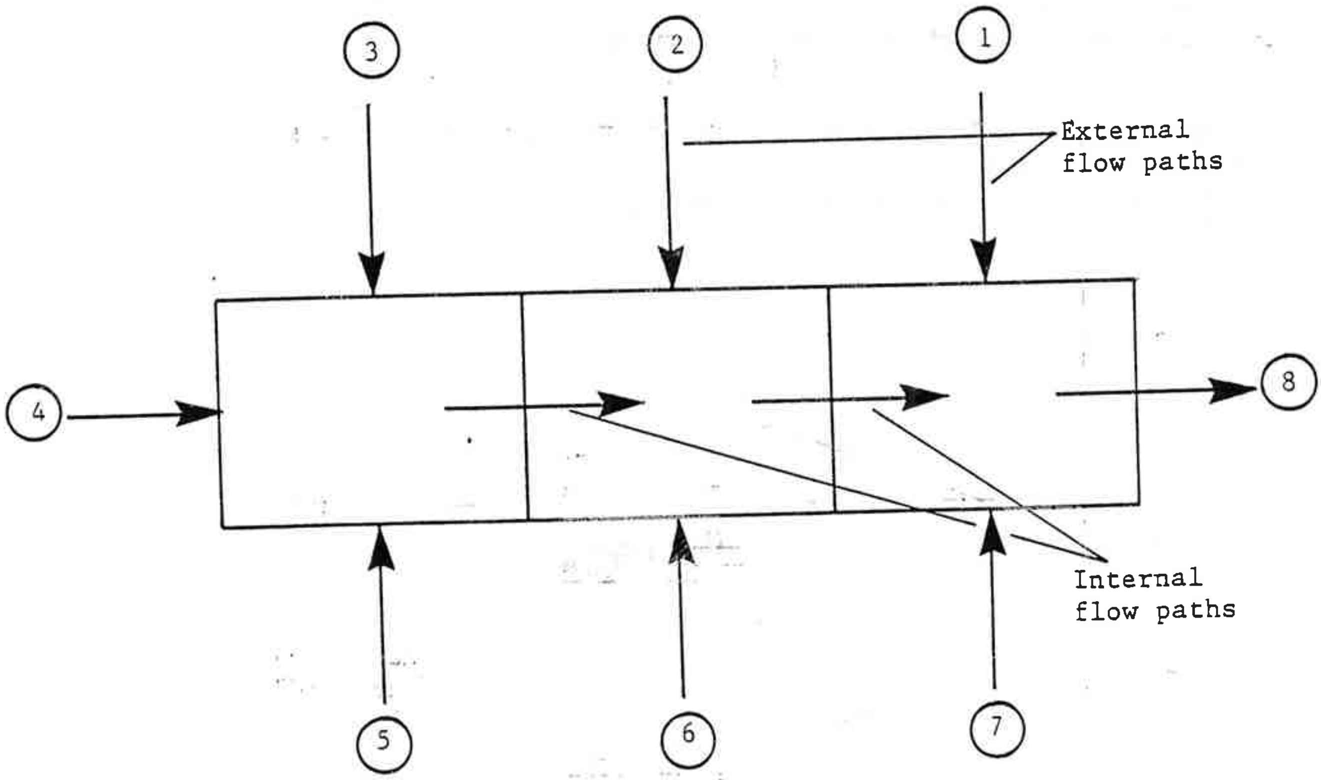
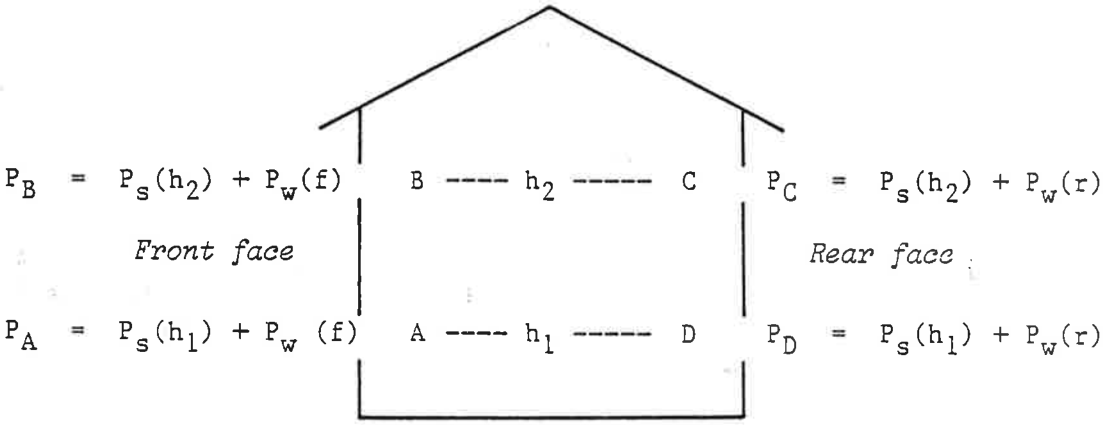


Figure 2: Multi zone representation



(i) Flow into and out of each zone must balance.
(ii) Total flow into and out of building must balance.

Figure 3: Combined wind and stack pressure distribution for openings in the facade of a low rise building *(assuming uniform wind pressure on each face)*



$P_s(h_1)$ = Stack pressure at height h_1
$P_s(h_2)$ = Stack pressure at height h_2
$P_w(f)$ = Wind pressure, front face
$P_w(r)$ = Wind pressure, rear face

Figure 4: Ventilation efficiency of occupied zone for alternative ventilation configurations