A COMPARISON OF VENTILATION PRACTICES

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Ventilation techniques and requirements vary considerably between different countries. In part, the type of building and the use to which it is put play an important role in the choice of method but climate also has a substantial influence, with methods that are found to be both energy and cost effective in one environment being totally inappropriate in another. The objective of this paper is to present a summary of the various ventilation techniques in common use in European, Scandinavian and North American countries. Particular emphasis is focused on the rationale, advantages and disadvantages of each approach. In addition, calculation techniques and examples are described which enable both the cost performance and energy efficiency of ventilation systems to be analysed.

INTRODUCTION

The changing patterns in living requirements, construction practices and materials, coupled with a desire to minimise energy use, has resulted in a tendancy towards the airtight construction of buildings. In turn, there has been a growing awareness of the problems that airtightness can bring. In the home, moisture laden air - with no route of escape - adds to the risk of condensation, while in the office, as in all buildings, inadequate supplies of fresh air may contribute towards a poor level of indoor air quality.

Ventilation technology has essentially followed an evolutionary process. In cold climatic regions, comfort requirements have demanded the avoidance of draughts with the result that airtight construction has been necessary. In turn some form of purpose provided ventilation has proved to be essential. On the other hand, buildings located in less severe climates have not needed to be so rigorously constructed with the result that the natural porosity of the structure, coupled with window opening, has often provided sufficient air for ventilation purposes. More recently, this latter approach has been affected by other factors. In particular, attention has been focused on airtightness measures to reduce energy consumption, while increasing noise levels in city centre locations has attracted the building designer and occupant to mechanical ventilation.

In this paper the alternative ventilation options are reviewed and an attempt is made to indicate the rationale behind the techniques used in other countries. The applicability or suitability of each approach to the United Kingdom environment is also discussed, especially in relation to climate and cost performance.

SUMMARY OF VENTILATILION TECHNIQUES

Ventilation is principally required to dilute and disperse internally generated pollution in order to provide a climate in which occupants can live without detriment to health and comfort. Ventilation requirements vary enormously and may be specified in terms of volume/unit time/person or as an overall fresh air change rate/hour (ach). A selection of recommendations and standards for several countries is summarised in Table 1.

On an international front, much effort has been devoted to the air leakage and ventilation performance of dwellings. For such buildings, the air leakage performance is often quoted in terms of an air change rate at an artificially induced pressure, created between the inside and outside of the building, of 50

Pa. Subject to the requirements for combustion appliances, BRE Digest 306 (1) recommends that, for naturally ventilated dwellings, an air change rate of between 10 and 20 ach, at 50 Pa, is likely to correspond to an acceptable ambient ventilation rate of between 0.5 and 1.5 ach. By contrast, Swedish air leakage requirements for new dwellings (2) are set at between 1 and 3 ach at 50 Pa and Norwegian requirements are set at between 1.5 and 4 ach at 50 Pa (3). In both cases a ventilation rate of 0.5 ach is specified which, in view of the level of building airtightness, is invariably met by mechanical ventilation. In the United States proposals for building airtightness standards are under consideration (4) while the proposed minimum ventilation rate for dwellings is set at 0.35 ach (5). Essentially ventilation methods can be grouped into six categories, these being:

- adventitious natural ventilation
- purpose provided natural ventilation
- mechanical extract ventilation
- mechanical supply ventilation
- balanced mechanical ventilation
- demand controlled ventilation

The performance of each method depends critically on the leakage value of the building envelope and therefore ventilation approach must be integrated with building design.

Adventitious Ventilation

This is the most common approach to ventilation to be found in the United Kingdom. Adventitious ventilation is entirely passive and relies upon natural air leakage through gaps and cracks in the building fabric. It is the most uncontrolled form of ventilation with both the amount of air change and the direction of flow through openings being dominated by the vagaries of climate and local shelter. Over-zealous weatherstripping or the introduction of airtight construction techniques can result in inadequate ventilation. From an energy aspect, the rate of air change is extremely variable with the highest rates coinciding with extremes in weather conditions. Comfort conditions may also be impaired by uncontrollable draughts.

In addition to the United Kingdom, "adventitious" ventilation is widely used in Belgium, Germany and North America. This especially applies to dwellings and small commercial buildings.

Purpose Provided Natural Ventilation

In some countries, an attempt has been made to harness the climatic parameters driving natural ventilation to provide greater control of both bulk air movement and air change rate. As with the previous approach, air enters the building through adventitious openings or through purpose provided openings. Stacks, ventilation shafts or high level vents are then used to promote the extraction of stale air. This technique takes advantage of temperature as a natural driving force for ventilation. For reliable operation a consistent interior/exterior temperature difference is required, thus making this technique most appropriate for moderately cold climates. To ensure satisfactory operation, careful design of the stack is essential. Of particular importance is the termination of the stack above the roof in such a position as to minimise the risk of downdraughts in windy conditions. Design requirements covering the sizing and termination of stacks are contained in Swedish and French regulations (2)(6) and in Dutch specifications (7).

While this approach gives greater control over airflow than wholly "adventitious" ventilation, its performance is still dominated by weather influences. In the past, stack ventilation has been used in dwellings in much of Scandinavia, the Netherlands and Northern France. During the 1970's however, this technique began to be superseded by mechanical ventilation.

Mechanical Extract Ventilation

Much improved ventilation control is possible by replacing the ventilation stack with a mechanical extract fan. In theory it is possible to maintain a uniform air change rate almost irrespective of climate but in practice this can be affected by the need to have sufficient openings in the building to ensure that make up air freely replaces that which is extracted.

Benefits of extract ventilation include constant air change and the opportunity for waste heat recovery from the exhaust air. Particular difficulties include the risk of backdraughting from chimneys and high velocity draughts, both of which are consequences of high suction pressures. These underpressures can also exacerbate the ingress of radon and other pollutants.

Extract ventilation is used in timber frame, single family housing in Scandinavia (2) and increasingly in Canada (8). It is considered to be an advantage in such buildings because a slight underpressure assists in preventing moisture generated within the home from entering the building fabric. Extract ventilation is also a preference for industrial buildings where internal heat and pollution need to be removed at source.

Mechanical Supply

Supply ventilation is governed by the same principles as extract but in this case fresh air is mechanically driven into the space while displaced air escapes through either adventitious or purpose provided openings. This method is commonly used in conjunction with heating or cooling systems to provide tempered air to the occupied zone. It is also used in conjunction with air circulation or filtration systems to provide a steady replenishment of outdoor air. In addition, mechanical supply ventilation may be used to overpressurize zones in which the ingress of pollutant is to be avoided. Heat recovery from the exhaust air is not normally feasible since it is unlikely to be possible to collect the air at a single location. This approach is common in mechanically ventilated commercial buildings, especially in North America where air conditioning is essential.

Balanced Supply/Extract

Balanced ventilation is a combination of the previous two techniques in which separate fans and duct systems are used to provide fresh air and to extract stale air. This method is potentially capable of embodying all the advantages of extract and supply systems while minimising their disadvantages. Typically air is supplied to occupied zones and extracted from polluted areas. In the industrial environment, for example, air is supplied at low level and extracted from machine hoods or from the roof space. In the home, air is supplied to living and bedrooms and is extracted from the bathroom and kitchen.

In a truly balanced system there is no net pressure effect due to the operation of the system, thus the natural driving forces of wind and temperature can interfere with the operating performance of this approach by means of air infiltration through leakage openings in the building. Thus any adventitious openings will contribute to the overall air change rate and interfere with the intended performance of the system. A dual ventilation system also increases the installation and maintenance cost which must also be taken into consideration.

Balanced ventilation with heat recovery is used in Scandinavian apartments and commercial buildings. It is also used as an alternative to mechanical extract ventilation in single family homes.

Demand Controlled Ventilation

A more recent development in ventilation has been the introduction of demand controlled systems in which the rate of ventilation is modified according to the level of pollution. This is especially important in transiently occupied buildings such as commercial buildings, schools and theatres where large influxes of people can be sensed by an increase in carbon dioxide concentration. This technique has become well established in Japan where air quality standards require that CO_2 levels should not exceed 1000 ppm in public buildings (9). In the home humidity sensors are increasingly being used to control extract ventilation systems in an effort to minimise the risk of condensation.

VENTILATION HEAT RECOVERY

Ventilation heat recovery is a method of extracting the heat from exhaust air for re-use within the building. In the case of balanced ventilation systems, warm exhaust air is passed across the plates of a heat exchanger through which fresh supply air is passed in a counterflow direction. This process can be very efficient with as much as 70% of the "waste" heat in the exhaust streams being transferred to the incoming air supply. Some varieties of heat recovery system are also able to condense water vapour in the exhaust air and thus recover the latent heat. An alternative heat recovery technique for use with extract mechanical ventilation systems is to extract the heat from outgoing air by means of a heat pump. This may take the form of an air-to-air heat pump in which the recycled heat is used directly for space heating or an air-to-water system for use in pre-heating domestic hot water.

While from a theoretical aspect heat recovery appears to be very attractive, there are a number of reasons as to why its apparent advantages are occasionally not fully realised. Of prime consideration is system and operating cost which must be offset by a corresponding reduction in energy consumption within a reasonable payback period. Also the net efficiency of the heat recovery system is unlikely to reach ideal performance. This is partly because of a need to defrost the systems in cold weather but, principally because heat is only recovered from air ducted to the heat recovery device, exfiltration losses through adventitious openings will reduce the overall performance.

CALCULATION TECHNIQUES

Calculation techniques perform an essential role in the selection of the most appropriate ventilation for any given set of conditions. They may be used to provide information on ventilation performance, air quality and cost effectiveness (10).

The ingress of air into a building is primarily governed by the leakiness of the building shell and the magnitude of the pressure imbalance developed across envelope penetrations. It is also influenced by the distribution of leakage paths, the characteristics of flow through individual openings and by internal impedences to air flow.

The flow of air through adventitious openings in the envelope of a building can generally be approximated by the equation

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

where k = flow coefficient (m^3/s at 1 Pa)
n = flow exponent
ΔP = pressure difference across opening (Pa)

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 between 0.5 for fully turbulent flow to 1.0 for laminar flow. In practice its value for cracks and adventitious openings tends to vary between 0.6 and 0.7.

Airflow through purpose provided openings such as vents can normally be assumed to be turbulent and may be represented by the orifice equation

$$Q = C_d A \left[\frac{2}{\rho} \Delta P\right]^{\frac{1}{2}} \quad (m^3/s) \qquad (2)$$

where C_d = discharge coefficient $\simeq 0.61$
A = area of opening (m^3)

Thus, by substitution in equation [1]

$$k = C_d A \left(\frac{2}{\rho}\right)^{\frac{1}{2}} ; \; n = \tfrac{1}{2}$$

e pressure difference across the opening, ΔP, is maintained by the action of
nd, temperature and (when used) mechanical ventilation.

lative to the static pressure of the free wind, the pressure resulting from
nd impinging on the surface of a building is given by

$$P_w = \frac{\rho}{2} C_p v^2 \qquad \text{(Pa)} \qquad (3)$$

ere ρ = air density (kg/m^3)
C_p = pressure coefficient
v = wind speed at building height (m/s^1)

e wind speed at building height will, in general, be different from that
ovided by the Meteorological Office, its value being influenced by
rrounding terrain and height above ground. A correction formula is published
BS 5925 (11). The pressure coefficient, C_p, is a function of the pattern of
ow around the building. It is normally assumed to be independent of wind
eed but varies according to surrounding shielding, wind direction and
cation on the building surface. A summary of published material suitable for
e in ventilation calculations has been published (10).

e pressure difference resulting from temperature or stack action, between two
rtically displaced openings is given by

$$P_s = \rho_o g\, 273h \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}}\right] \text{(Pa)} \qquad (4)$$

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

ir infiltration and ventilation is simulated by devising a flow network in
ich flow paths between the inside and outside of the building and between
dividual zones or rooms within the building are defined (Figure 1).

deally the location, size and flow characteristics of each opening should be
efined. In practice, however, this is rarely possible and, instead, an
pproximation or an amalgamation of flow paths is almost always necessary. For
ccurate results it is essential that all sources of air infiltration are
dentified. These sources may be usefully analysed in terms of 'component'
eakages and 'background' or 'fabric' leakages.

ypical component openings include vents, stacks and chimneys. These present
he most straightforward type of building penetration to identify and include
n the flow network description. Unfortunately, identifiable sources of air
eakage often represent only a small proportion of the total infiltration
outes, with unidentifiable 'fabric' or 'background' penetrations accounting
or the remainder. This 'background' component is attributable to construction
echniques, site practices and the inadequate sealing of service penetrations,
ith the result that without careful design and construction it can have a
ominating influence on the rate of air infiltration.

n terms of flow path development, the 'background' leakage may either be
ssumed to be uniformly distributed about the surface area of the building and
hus represented in terms of "leakage"/unit area of building envelope or,
lternatively, it may be distributed according to the perimeter length of
uilding joints. This latter approach is especially useful for buildings
onstructed from a relatively small number of impermeable elements. Some
ttempt has been made to collate published air leakage data (10), however
ressure testing of components or of the entire building may be necessary to
rovide suitable data. Poor design or site practice can be expected to result
n an adverse departure from published data.

Assuming j flow paths entering a single internal zone, a flow balance must exist between the air inflow and the air outflow, i.e.

$$\sum_{i=1}^{j} Q_i = 0 \qquad (5)$$

substituting into equation [1] gives

$$\sum_{i=1}^{j} k_i \left| P_i - P_{int} \right|^{n_i} \left(\frac{P_i - P_{int}}{|P_i - P_{int}|} \right) = 0 \qquad (6)$$

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
P_{int} = internal pressure of zone
j = number of flow paths entering zone

In the case of a multi-zone building, flow balance is required for each zone. The absolute pressure difference, $|P_i - P_{int}|$, is used in the power law term and the sign of the flow direction is restored by the final term of the equation. Positive values of Q_i represent infiltrating flow and negative values represent exfiltration, i.e.

$$I = \sum_{i=1}^{j} Q_i \quad \text{for } Q_i > 0 \qquad (7)$$

Mechanical extract (or supply) ventilation is incorporated by direct inclusion in the flow balance equation, i.e.

$$\sum_{i=1}^{j} Q_i - Q_{mv} = 0 \qquad (8)$$

where Q_{mv} = mechanical ventilation rate (-ve for extract, +ve for supply)

Balanced ventilation is summed directly to the calculated infiltration rate, thus

$$\text{Total ventilation} = I + Q_{BAL} \qquad (9)$$

where Q_{BAL} = balanced ventilation rate

The calculation proceeds by iteration in which an initial guess at the internal pressure within each zone of the building is successively amended until flow balance is achieved. A general multi-zone computer coding for solving this problem is published by Walton (12).

APPLICATIONS

The following applications are based on a 2-storey dwelling or similar structure of approximately 300 m³ which may be treated as a single zone enclosure, located in an urban environment. They have been introduced to illustrate the significance of airtightness and climate on ventilation strategy. While these examples are necessarily simplistic, similar reasoning and approaches are valid for larger, more complex buildings.

Natural Ventilation

A background leakage corresponding to 10 ach at 50 Pa was distributed according to the flow network illustrated in Figure 1. By applying the concept outlined in the previous section, the corresponding ventilation characteristics for a range of weather parameters was determined (Figure 2). A ventilation rate of 0.5 ach is exceeded for building height windspeeds in excess of 4 m/s and for temperature differences in excess of 10°C. The ASHRAE minimum standard of 0.35 ach (4) is satisfied for temperature differences in excess of 10°C.

These results highlight the vulnerability of adventitious ventilation and it is difficult to recommend it as a totally suitable method. Almost certainly this approach could be improved with the use of window vents coupled with a ventilation stack or kitchen extractor fan. Additionally it would be fairly straightforward to include these additional components in the flow network and re-analyse the problem as part of the design process.

Mechanical Extract Ventilation

In Canada, a number of very airtight superinsulated dwellings known as the "R2000" homes are currently under construction in which the fabric leakage must not exceed 1.5 ach at 50 Pa (8). The corresponding natural infiltration rate is depicted in Figure 3. Clearly there is insufficient infiltration to meet ventilation needs and a mechanical ventilation rate of 0.5 ach is stipulated. In addition, where extract ventilation is fitted there is a further requirement that the system must not continuously cause a pressure difference of greater than 10 Pa (13). This has been introduced to avoid the risk of backdraughting from naturally vented furnaces. Since the fabric of the building is so airtight, the only way excess pressure can be avoided is by introducing purpose provided openings. Assuming a 300 m³ building, an air change rate of 0.5 ach corresponds to 150 m³/hr or 0.042 m³/s. Substituting into equation [2] and rearranging, yields

$$A = \frac{0.042}{0.61 \times \left[\frac{2 \quad 10}{1.29}\right]^{\frac{1}{2}}} = 0.0175 \text{ m}^2$$

where
$C_d \simeq 0.61$
$\rho \simeq 1.29$
$\Delta P \simeq 10$ Pa

Thus the necessary area of opening needed to avoid excess pressure is 0.0175 m² or 17.5 cm². This area is in addition to any fabric leakage which should only be regarded as giving a further margin of safety.

By substitution into equation [8], the flow characteristics of the mechanical ventilation configuration are presented in Figure 4. This shows a ventilation performance which is virtually independent of climatic conditions while at the same time the pressure constraint is satisfied. Such a configuration is ideal for the extremely severe Canadian winter climate where excessive air change can result in high energy losses and where the relatively low moisture content of the outdoor air means that fairly low rates of ventilation can be used to dilute internally generated moisture. The same analysis can be applied to Swedish and Norwegian homes where similar ventilation requirements are specified.

Balanced Ventilation and Air-to-Air Heat Recovery

If the efficiency of a heat recovery system for balanced ventilation is given by H_{eff}, then the overall ventilation heat loss, E_v, throughout a heating season can very approximately be given by

$$E_v = (Q_{exf} + Q_{mv}\,(1 - H_{eff}/100)) \times \rho \times S \times DD \times 24 \times 3600 \times 10^{-9} (\text{GJ})$$

$$= 0.113\,(Q_{exf} + Q_{mv}\,(1 - H_{eff}/100)) \times DD\ (\text{GJ}) \qquad (10)$$

where Q_{exf} = exfiltration rate (m^3/s)
Q_{mv} = mechanical ventilation rate (m^3/s)
H_{eff} = efficiency of heat recovery system (%)
S = specific heat of incoming air ($\simeq 1012$ J/Kg)
ρ = density of incoming air ($\simeq 1.29$ kg/m^3 at 0°C)
DD = number of degree days

If the exfiltration rate, Q_{exf}, is comparable or greater than the mechanical ventilation rate, Q_{mv}, then the introduction of mechanical ventilation with heat recovery will not only be questionable from a capital cost point-of-view, but may result in unnecessarily high ventilation rates and a consequent waste of energy. Consider the 300 m³ dwelling constructed to an air leakage specification of 10 ach at 50 Pa, in which an average air change rate of 0.7 h^{-1} (0.058 m^3/s) is required. Also assume that the average heating season's degree days are approximately 1900, corresponding to the South of England. In theory the energy demand at a constant airchange rate of 0.7 h^{-1} (0.058 m^3/s) is

$$E = 0.113 \times 0.058 \times 1900 = 12.45 \text{ GJ}$$

Assuming 70% heat recovery, the energy demand (E_{hr}) becomes

$$E_{(hr)} = 12.45\ (1 - 70/100) = 3.74 \text{ GJ}$$

However, there is an additional infiltration/exfiltration term which, from Figure 2, can be estimated to be approximately 0.5 ach (0.42 m^3/s) for winter conditions. This adds directly to the mechanical ventilation rate, equation [9], thus by substitution into equation [10].

$$E_v = 0.113\ (0.042 + 0.058\ (1 - 70/100)) \times 1900 = 12.75 \text{ GJ}$$

Consequently the theoretical heat reduction from 12.45 GJ to 3.74 GJ is just not realised. A similar exercise for the "R2000" property reveals a mean infiltration/exfiltration of about 0.1 ach (0.008 m^3/s) and therefore the overall ventilation heat loss is

$$E_v = 0.113\ (0.008 + 0.058\ (1 - 70/100)) \times 1900 = 5.45 \text{ GJ}$$

Airtightness of at least the "R2000" standard is therefore essential to achieve any significant energy saving. Obviously if the degree day range is much higher as is the case of Scandinavia and Canada then there is potential for saving much more energy.

Cost Effectivenesse

The installation and operation of a ventilation system adds to building costs. Costs include:

- initial capital expenditure on purchase and installation
- operating costs
- general maintenance charges

Where alternative strategies are feasible, a comparative 'pay back' period may be defined such that, over a given period of time, a system which perhaps incurred a greater initial expenditure will prove to be less expensive than a much cheaper system incurring a higher overall operating cost. To be cost effective, the annual energy saving of a ventilation approach must outweigh its combined operating and payback cost. The potential for the cost-effectiveness of alternative ventilation strategies will depend on the scope of energy reductions. In turn, this is a function of the overall ventilation rate and the severity of climate. Thus for a specific application, a cost-effective measure in one locality may not necessarily prove a satisfactory option somewhere else.

is costing exercise will depend on the building and on ventilation needs but comparison in energy performance of different strategies, against which ese costs will be equated, may be calculated using the principles outlined in previous examples.

SCUSSION AND CONCLUSIONS

ere are essentially two approaches to ventilation. The first is to have a atively leaky building and to allow natural or adventitious ventilation pled with window opening to satisfy most needs. The second is to adopt a tal" airtightness policy in which ventilation needs are met by alternative ns. The former technique is common in mild climatic regions including the while the latter approach is steadily finding favour in Canada and ndinavia.

n mechanical ventilation is used several methods are possible. In mercial buildings supply ventilation coupled with conditioning, filtration recirculation is popular. The building is kept slightly pressurised to vent the ingress of unconditioned air. In mechanically ventilated llings, exactly the reverse philosophy applies in which the building is kept a slightly negative pressure, by extract ventilation, to prevent internally erated moisture from entering and condensing within the fabric of the lding.

anced ventilation systems enable supply air to be preheated by the exhaust stream and heat exchange efficiencies of up to 70% are possible. However costs of such systems are relatively high and adventitious openings in the lding fabric can result in an overall poor performance. Many of these ms are in operation in Scandinavia and time will soon show whether or not are economically viable in cold climates. It is difficult to justify ir general application in low energy buildings, especially dwellings, in United Kingdom. Only where relatively large quantities of waste heat can recovered can they be justified.

of the design problems encountered in the provision of ventilation on the e of system can be analysed using relatively straightforward numerical niques. Most importantly they may be used to assess the effect of ghtness and climate on ventilation performance to determine the effect of ventilation system on building pressure distribution and to analyse the efit of heat recovery. Only by applying these methods can a full erstanding of the need to integrate ventilation technique with climate and ding construction be achieved.

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able 1 Brief summary of standards and guidelines covering ventilation and building airtightness

ublication	Coverage
rance:	
ispositions relatives a l'aeration es logements.	Ventilation systems: requirements for natural and mechanical ventilation.
apan:	
ational Building Code for ir Quality (9)	Air quality standards
orway:	
orwegian Building Regulations (3)	Domestic airtightness requirements and ventilation rates.
weden:	
wedish Building Code SBN 1980 (2)	Domestic airtightness requirements and ventilation rates.
nited Kingdom	
RE Digest 306. omestic draughtproofing: entilation considerations (1)	Domestic ventilation rates and airtightness recommendations for natural ventilation
S 5925 ode of Practice for Design of: uildings: ventilation principles nd designing for natural entilation (11)	Ventilation requirements to remove indoor pollutants, calculation methods, meteorological parameters.
nited States of America	
SHRAE Standard 119P ir leakage performance for esidential buildings (4)	Airtightness recommendations for single family dwellings.
ASHRAE Standard 62-1981 Ventilation for acceptable indoor air quality (5)	Ventilation recommendations for many varieties of building.
iscellaneous	
A review of building airtightness nd ventilation standards. IC Tech. Note 14, Air Infiltration nd Ventilation Centre, UK.	Summary of standards covering ventilation and airtightness.
uilding airtightness and ventilation. SRIA Tech. Note 5/86 (Appendices 1-3)	Comprehensive summary of international standards covering airtightness, ventilation requirements and testing methods.

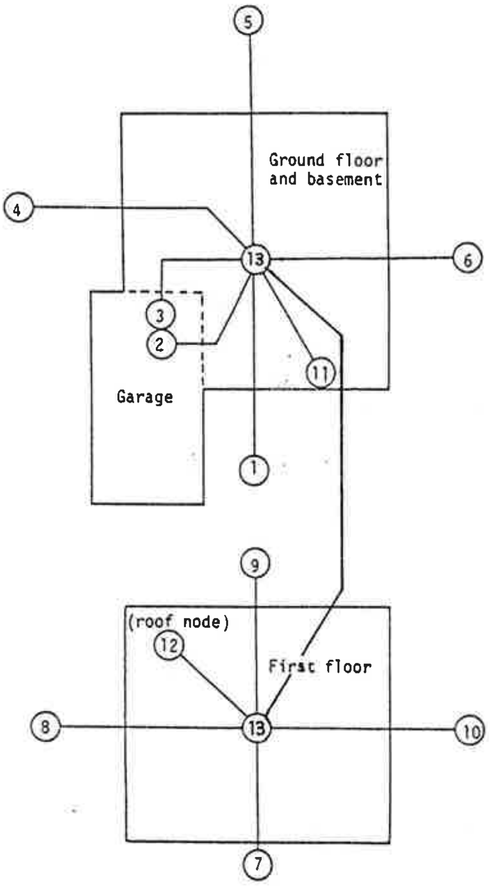

Figure 1 Simple flow path representation of a 2-storey detached dwelling

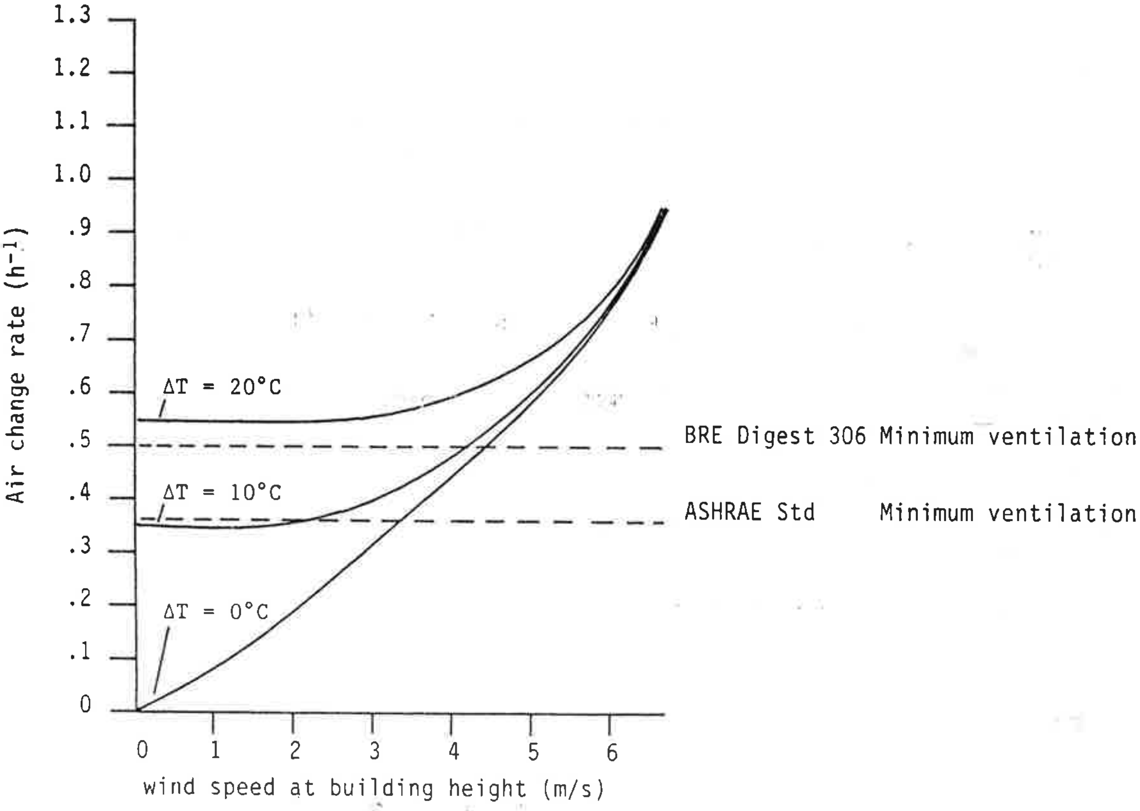

Figure 2 Infiltration performance of a moderately leaky building (10 ach at 50 Pa)

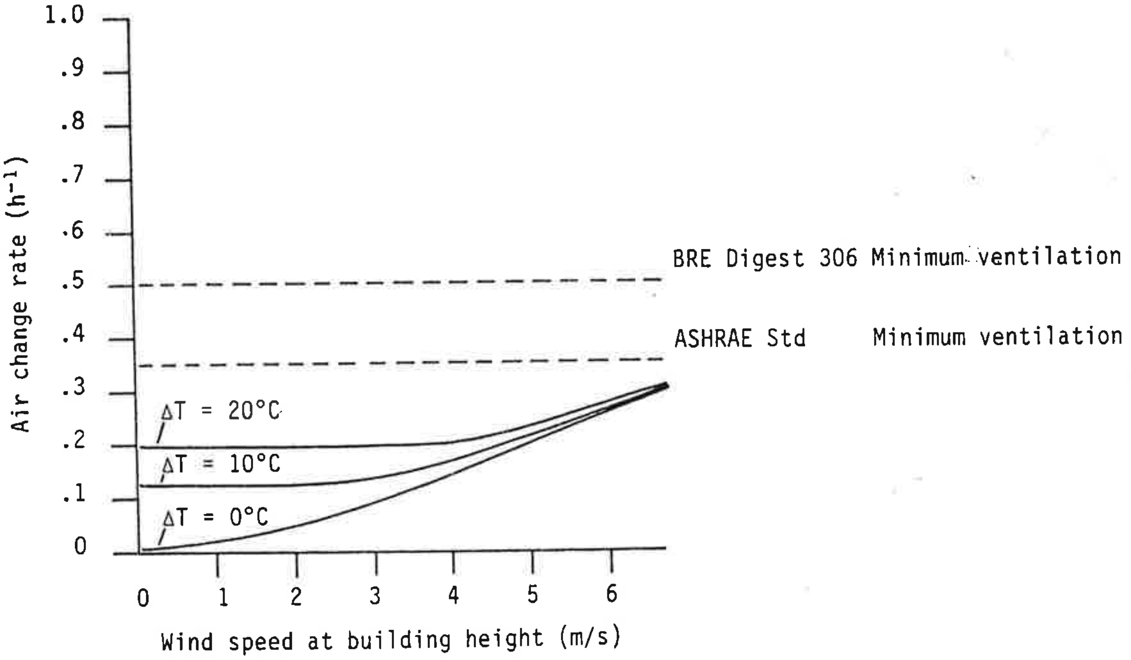

Figure 3 Infiltration performance of a "tight" building (1.5 ach at 50 Pa)

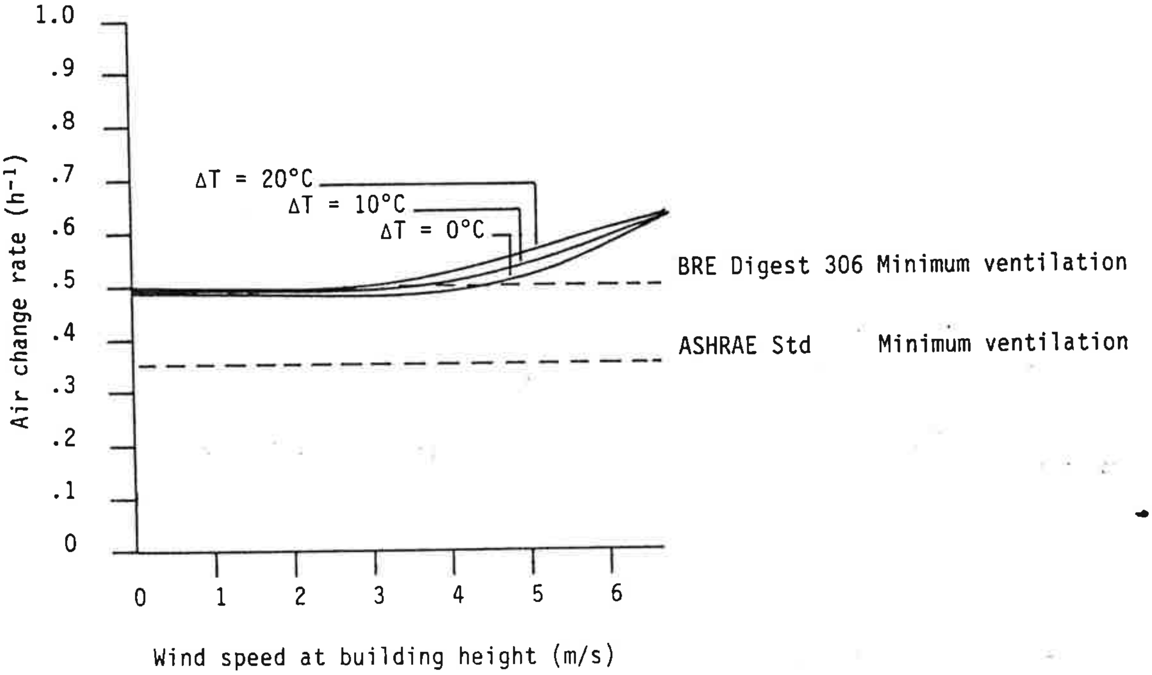

Figure 4 Mechanical extract performance for "tight" building (1.5 ach at 50 Pa, 0.5 ach extract)