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Ventilation Technology in Large Non-Domestic Buildings

AIVC

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.
To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
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XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques*
XVIII	Demand Controlled Ventilating Systems*

XIX Low Slope Roof Systems*
XX Air Flow Patterns within Buildings*
XXI Thermal Modelling*
XXII Energy Efficient Communities*
XXIII Multizone Air Flow Modelling (COMIS)*
XXIV Heat Air and Moisture Transfer in Envelopes*
XXV Real Time HEVAC Simulation*
XXVI Energy Efficient Ventilation of Large Enclosures*
XXVII Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII Low Energy Cooling Systems
XXIX Daylight in Buildings
XXX Bringing Simulation to Application
XXXI Energy Related Environmental Impact of Buildings
XXXII Integral Building Envelope Performance Assessment
XXXIII Advanced Local Energy Planning
XXXIV Computer-aided Evaluation of HVAC System Performance
XXXV Design of Energy Efficient Hybrid Ventilation (HYBVENT)

Annex V Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.
The Participants in this task are Belgium, Canada, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

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1. Introduction

1.1 Scope

Most people spend a large proportion of their working and leisure time inside large enclosures or buildings other than their 'home'. These non-domestic buildings cover a very wide range of sizes and functions. The recreation building for some people is the workplace for others, and their perceptions of the environment may therefore be quite different. The time spent in such buildings by any one individual may vary from a transitory few minutes to a long, perhaps sedentary, working day. The buildings may at times be crowded to capacity with people and at other times be empty.

More ventilation than is necessary may be expensive to install and extravagant in energy, on the other hand inadequate ventilation can be at best unpleasant and at times actually harmful both to the building and the occupants. Ideally the ventilation of the building should follow the usage pattern for comfort, health and economic reasons.

This Technical Note is about ventilation of large non-domestic buildings. It describes current ventilation practice and also looks into the future. Designers, building owners and policy makers will be told what is done and why, while researchers are provided with a framework on which to hang future projects.

Atria, auditoria, sports halls, enclosed shopping malls and offices are examples of the type of space considered. A characteristic of many of these spaces, other than offices, is that they are so large, and the occupied part is so small in comparison, that avoiding draughts and limiting energy use may be as important a consideration as supplying sufficient fresh air for health and comfort. Buoyancy effects, driven by insolation and heat sources relating to people and their activities, frequently result in significant vertical air-streams especially where there are large expanses of cold glazed facade.

1.2 Purpose

This Technical Note is an introduction to the way in which large buildings are ventilated in order to provide a starting point for useful dialogue between those who design buildings and those who use them.

Chapter 2 relates ventilation to the removal of pollution from occupied spaces in buildings.

Chapter 3 shows how the choice between *mechanical* or *natural* ventilation affects the whole character of the building, but also that a *mixed-mode* approach may make it possible to combine the best of both methods.

Chapter 4 shows how these ventilation options translate when applied to different types of building.

Chapter 5 is concerned with making the ventilating process 'efficient' - the art of good air distribution.

Chapter 6 considers the needs and expectations of the user of the building. Is the person in the building comfortable and is the ventilation system user-friendly?

Chapter 7 considers the energy implications of ventilation decisions.

Chapter 8 then shows how these decisions are arrived at and which are out of the decision makers' control.

Chapter 9 then relates these decisions to a design process which is controlled by needs and constraints. Ways of checking design proposals by calculation ('modelling') are briefly reviewed.

Chapter 10 explores how the system can be checked after it has been built and commissioned.

Chapter 11 summarises the present status of ventilation strategies for large buildings and tries to indicate where the most likely changes may occur.

1.3 Chance or Choice?

There are still many buildings in which ventilation is left to chance in the sense that the users of the building are required to open or close windows or vents according to their needs. This may be successful for indoor air quality but is unlikely to be energy efficient. Most people in a building are unaware of the ventilation system, until it goes wrong.

Ventilation is about removing pollutants and achieving satisfactory 'air quality'. The pollutants arise from the people and their activities and also from the building itself. Having first minimised the sources, the rest of the pollution has to be removed by purging the building with 'fresh' air; this is ventilation.

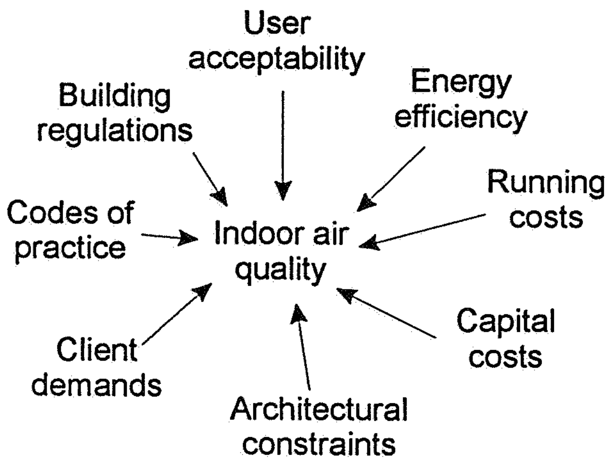
Ventilation strategies vary according to whether the air is driven through the building by forces arising from the weather or by fans. The building size and function will influence the type of approach. Since the fresh air coming into the building may have to be heated or cooled the energy implications become more significant the larger the building.

Some options are closed at the decision stage by the climate and building location; but many decisions made at the design stage have implications for both the well-being of the occupants and the energy consumption, which may be difficult to change later. The design process is a balancing act between building regulations and codes of practice, architectural constraints, initial and running costs, energy efficiency and the demands of the client.

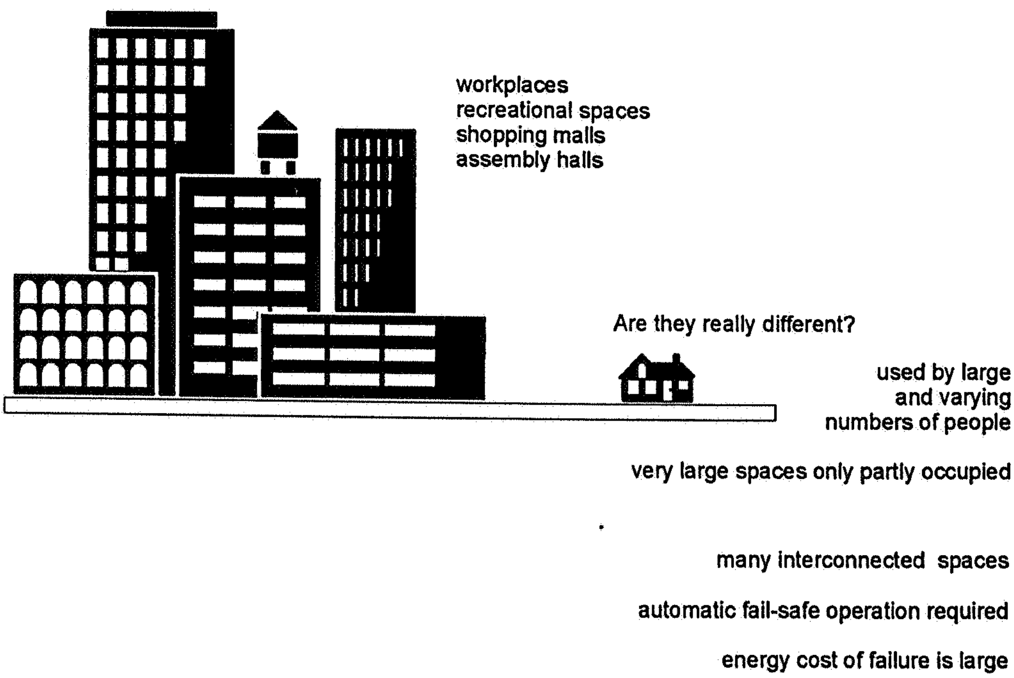
Ventilation design implies the achievement of controllable, or at least predictable air flows. However, unless a building is unusually air-tight, a lot of ventilation occurs as unseen, unplanned air movement through fortuitous gaps in the building envelope. Among many other draw-backs this so-called infiltration increases the energy bill without any benefit to the people using the building. A 'build tight, ventilate right' approach minimises unplanned air flows and ventilates in a planned way according to needs.

Some aspects of the performance of ventilation systems can be predicted by calculation but in many cases scale modelling may be justified. Commissioning and performance testing are necessary stages in achieving the required indoor climate and checking that it has been achieved.

This note relates to large non-domestic buildings where the energy and health implications of wrong decisions and poor designs can be large and expensive and where the aim is to provide acceptable indoor air quality and satisfy as far as possible all the constraints imposed by:



1.4 What is a Large Non-Domestic Building?



2. Background

2.1 Why Ventilate?

The primary aim of ventilation is to provide a clean, healthy and comfortable atmosphere in a building for the people who use it and work there. The main sources of pollution are generally inside the building except in cities, close to busy roads and near sources of industrial pollution.

2.2 What Pollutants Are Present in Buildings?

Odours are the most immediate indication of poor air quality. Ventilation standards have hitherto normally been based on diluting body odours but other sources of pollution such as building materials, furnishings and cleaning compounds are now recognised as equally significant. These sources must be identified and controlled before an effective ventilation strategy can be applied.

Tobacco smoke is an 'optional' indoor air contaminant which can be controlled at source by prohibiting smoking. If smoking is allowed, very much higher ventilation rates have to be specified than for any of the other people-produced contaminants in non-industrial buildings.

Moisture is a major consideration in ventilation of houses but its removal is unlikely to be a primary reason for ventilating large non-domestic buildings except in special cases such as:

- swimming pool halls
- certain art galleries and museums
- in climates which experience high outdoor humidity in summer
- assembly halls (high load of moisture from people).

Carbon dioxide is an odourless gaseous product of respiration. Its removal is seldom the main reason for ventilating large buildings but, being easily measured, it can be used as an indicator for other occupancy-related contaminants to control a ventilation system. This is appropriate where the number of people in a building is very variable and the energy cost of excessive ventilation is sufficiently high to justify the extra complexity and capital cost of 'demand control'.

Surplus heat in large non-domestic buildings can be considered as a pollutant which can be removed by ventilation. Therefore cooling to minimise summer overheating is likely to have a strong influence on the ventilation strategy.

Smoke removal requirements in the event of an accidental fire may impose requirements and constraints on the ventilation of large enclosures. However, separate systems, such as pressurised stair lobbies and dedicated smoke extracts, are often provided for the removal of smoke in the event of fire.

2.3 How to Ventilate?

Ventilation is the art of causing 'fresh' air to flow through the occupied parts of a building, without draughts or stagnation, in such a way that thermal comfort and acceptable indoor air quality are achieved and maintained, together with the removal of odorous or harmful airborne materials. The basis of every ventilation strategy is:

to supply fresh air where it is needed
and
to remove pollutants where they are produced.

The main choices relate to how much mechanical complexity is necessary, desirable or acceptable to enable the building to perform its function and to satisfy the aspirations and budget constraints of the architect, owner and user.

2.4 What Are the Options for Ventilating?

Methods of ventilation will be described in more detail later, but essentially they relate to whether natural forces (wind and temperature differences) or electrically operated fans are used to move air into or out of the building:

Natural ventilation is apparently the simplest and cheapest option but also the most difficult to predict and control, since the driving forces, and thus the air flow rates, vary with the weather.

Mechanical exhaust ventilation uses fans to remove polluted air. The route taken by the outside 'fresh' air entering the building to replace the air removed should be planned so that it services the places where it is most needed, but this, unfortunately, is often left to chance.

Mechanical balanced ventilation uses fans to bring the fresh air into the building as well as to remove stale air from the building. This allows fresh air to be supplied close to, or directed towards, the people thus achieving the best air quality where the need is greatest.

Mixed mode refers to using a combination of mechanical and natural ventilation strategies when requirements vary at different times or locations in the building.

Comfort cooling is often part of a mechanical ventilation system if cooling is required to achieve comfortable conditions. This becomes **air-conditioning** when humidity control is also included.

2.5 How Much Ventilation?

Standards and Codes of Practice generally recommend fresh air ventilation rates per person in the region of 7-10 litres/second (Limb 1994a), based on body odour experiments carried out in the 1930s (Yaglou 1937). More recent work (Fanger 1995) has shown that ventilation requirements depend on the quantity and nature of a much wider range of pollutants, many of which arise from building and furnishing materials. Many common pollutants are unpleasant rather than harmful but there are a few pollutants such as CO which are odourless and harmful, so it is necessary to identify likely pollutants. For spaces with pollutant sources other than people it is necessary to ventilate for the most demanding contaminant.

2.6 Large Enclosures

When the ventilated space is 'large' the effect on air quality of intermittent bursts of pollution is much less than in a 'small' space. The pollutant concentration experienced in a ventilated space represents the net result of the balance between supply and removal rates of that pollutant. Under conditions of complete mixing, the steady state concentration of pollutant is independent of the volume of the space, but the time taken to reach that equilibrium concentration is longer in larger spaces.

Starting with an initially 'clean' space into which a pollutant is released, the concentration will never reach this maximum level if the source of pollution ceases soon enough. The effect this has on the ventilation rate required to maintain pollutants below a certain level when the source of pollution is intermittent is illustrated in Figure 2.1 (adapted from BSI 1980). For example a lecture theatre having a design ventilation rate, for continuous occupancy, of one air change per hour (i.e. turnover time = 1 hour) but used for only alternate hours (polluting time fraction = 0.5) could be operated at 0.6 air changes per hour without the air quality passing the design value.

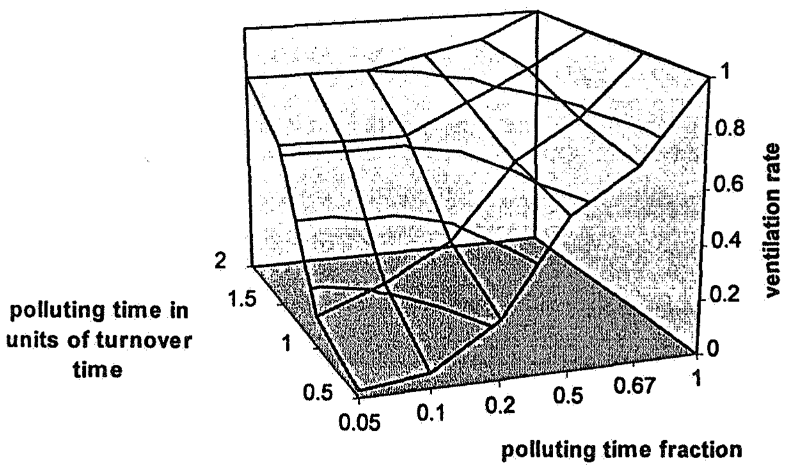


Figure 2.1 Permitted reduction in ventilation for intermittent emission of pollution

3. Overview of Current Practice

3.1 General

There are essentially two methods of supplying fresh air to the people in a building and removing stale air:

- **natural ventilation**
- **mechanical ventilation**

It is also possible to have a combination of the two ('mixed mode') and each category covers a wide range of options.

The choice depends on the size and type of building, together with its surroundings, and will be addressed in Chapter 8. There is no unique solution for a given building or building type and decision makers may be influenced by fashion and perceived status which are unrelated to air quality and comfort.

Natural ventilation provides a cheap and simple approach for small buildings in a number of countries with temperate climates. It can also be used in quite large buildings by the application of some ingenuity, especially where the climate is benign and where occasional uncomfortable conditions are acceptable. Figure 3.1 shows an example of a natural ventilation system in a fairly large building (Cohen 1996).

Since wind and temperature differences are the driving forces causing air flows through the building there may be times, even in the best designs, when ventilation is insufficient to satisfy comfort needs and some overheating may occur in summer. Choosing natural ventilation may involve making a judgement on the significance of these periods of discomfort (Willis 1995).

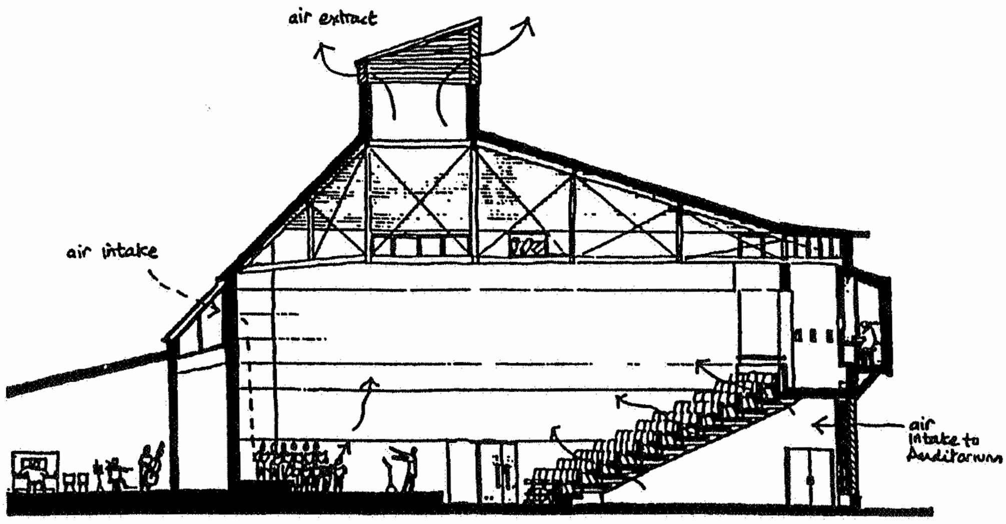


Figure 3.1 Natural ventilation of a large building

Unplanned natural ventilation through fortuitous openings which inevitably occur in a building shell is called 'infiltration'. The associated variable and uncontrollable exfiltration can result in very large energy costs in large buildings, which cannot easily be predicted or reduced; therefore whatever ventilation strategy is adopted unplanned leakage should be minimised by appropriate design and construction techniques.

Mechanical ventilation uses fans to move the air and can therefore be applied to virtually any building. This approach is intrinsically more versatile and controllable than natural ventilation. A well designed and operated system will maintain a chosen ventilation pattern which is independent of the weather and responds to the needs of the people in the building. The best systems are very successful in maintaining a predictable and comfortable environment (Dickson 1992) but there is a significant minority of installations which fall short of this ideal through design, construction, operation or maintenance faults and result in a higher incidence of 'Sick Building Syndrome' (SBS) complaints than in naturally ventilated buildings (Wilson 1987). However, more recent research shows that management style may be as important as engineering design in reducing SBS (Whitley 1995).

Mixed mode represents an attempt to achieve the perceived benefits of natural ventilation with the controllability of a mechanical system. Natural ventilation is used when or where possible, from both an energy and comfort point of view, changing over to mechanical at times or in parts of the building where natural ventilation is not satisfactory. This approach may be combined with solar shading, high building thermal mass and night time cooling to extend the time during which natural ventilation can produce comfortable conditions.

Air-conditioning is an extension of mechanical ventilation with the ability to heat, cool, humidify and dehumidify the incoming fresh air. It permits closer control of the comfort conditions in a building than can be achieved by other methods of ventilation. Comfort cooling is used where overheating would otherwise occur and full air-conditioning where close control of both temperature and humidity is necessary. In large deep plan commercial buildings, internal heat gains may impose a requirement for cooling throughout the year.

The choice between mechanical or natural ventilation depends on many factors some of which may appear to be conflicting. The advantages and disadvantages of each strategy:

- natural ventilation
- mechanical extract + natural supply
- mechanical extract and supply

are summarised in Table 3.1.

Table 3.1 Natural and mechanical ventilation compared.

	Ventilation Strategy		
factor	**natural**	**mechanical extract natural supply**	**mechanical extract mechanical supply**
climate	weather dependent rate and route especially at low wind speeds	less weather dependent but natural fresh air route is still weather dependent	rate and route almost weather independent
building shape	difficult for low and/or deep plan buildings	deep plan buildings will require fresh air supply ducts	applicable to any shape and size of building
space occupied	sometimes very little, but certain designs require high ceilings or large ducts (for low pressure drops) which occupy a lot of space	space is needed for plant and ducts (which may be larger than for a fully mechanical system)	space is needed for plant and ducts
complexity	openings can be manually operated in simple systems, automatic control of certain systems may be complex	depends on degree of automatic control desired	complex automatic control can permit operation without user intervention
maintenance	little required	requires regular maintenance	requires regular maintenance
heat recovery	generally not possible	possible (e.g. air to water)	easily done
air filtration	not possible	limited possibilities	very easy
capital cost	generally lower	generally higher	generally higher
running costs	generally lower but unplanned excessive ventilation can result in high heating costs	generally mid-way between natural and fully mechanical due to fan power requirement	generally higher due to fan power required to drive system, but demand control and heat recovery can reduce running costs
user reaction	generally liked, especially if openable windows are available to user	probably acceptable if fresh air route well planned and in not too cold climates	risk of being less popular especially if windows are absent or permanently closed
ease of control	user intervention usually required	user intervention may be required for fresh air route control	potentially easy to control automatically
indoor air quality	variable, depending on the user and the weather	may be variable if fresh air route varies with the weather	predictable, relatively weather and user independent
summer overheating	very likely since active cooling not possible	very likely since active cooling not possible	easily avoided but cooling may be required
isolation from outside pollution	none, development underway	none, development underway	can be done
environmental impact	perceived as being 'environmentally friendly'	probably seen as a good compromise	depends on how much energy is used by the fans

3.2 Role of Natural Ventilation

Natural ventilation provides an economic and relatively simple way of ventilating a wide range of non-domestic buildings in temperate climates. Table 3.2 summarises the various options, which are illustrated schematically in Figure 3.2. To be successful, the ventilation must be planned and not 'just happen'. Its importance must be recognised at the initial stages of the design process, before decisions are made which might make it unworkable, since the building envelope itself is a critical component of the ventilation system. The relation of the new building to surrounding buildings affects the wind pressure distribution over the building shell and therefore the ventilation rate. If the external environment is noisy or smelly, natural ventilation is not appropriate using techniques known today. Designing natural ventilation should involve different degrees of calculations. Hitherto, good design tools have been scarce. However, development of such tools is underway (e.g. Svensson, 1997).

Table 3.2 Natural ventilation strategies

strategy	attributes
single sided single opening	depends on wind turbulence to work - effective to a depth of about 2 x ceiling height
single sided multiple opening	driven by both wind and stack (temperature) effect - effective to a depth of about 2.5 x ceiling height
cross-ventilation	usually wind-driven - effective up to a building width of about 5 x ceiling height
wind scoop cross-ventilation	captures wind at high level to enhance cross-ventilation
ducted flow cross-ventilation	ducts dimensions need to be large because driving pressures are low
passive stack ventilation	vertical ducts provide high level exhaust to draw air out of the building
chimney stack ventilation	operation depends on chimney being warmer than ambient, possibility of using solar warming
atrium stack ventilation	the 'chimney' is attractive usable space, permits ventilation to a depth of 5 x ceiling height all round and permits use of daylight. High temperatures at top
double facade ventilation	either a special form of solar chimney for extract air or as a solar pre-heater for supply air
mechanically assisted	<u>mechanical supply</u> to ensure good distribution of fresh air combined with natural exhaust <u>mechanical extract</u> where there are significant sources of internal pollution combined with natural supply

Natural ventilation is often successful for large spaces where the enclosed volume provides a fresh air reservoir or pollutant buffer and the height provides the driving force for buoyancy driven stack ventilation. A glazed atrium is a commonly used device for assisting ventilation in this way while providing an attractive indoor space.

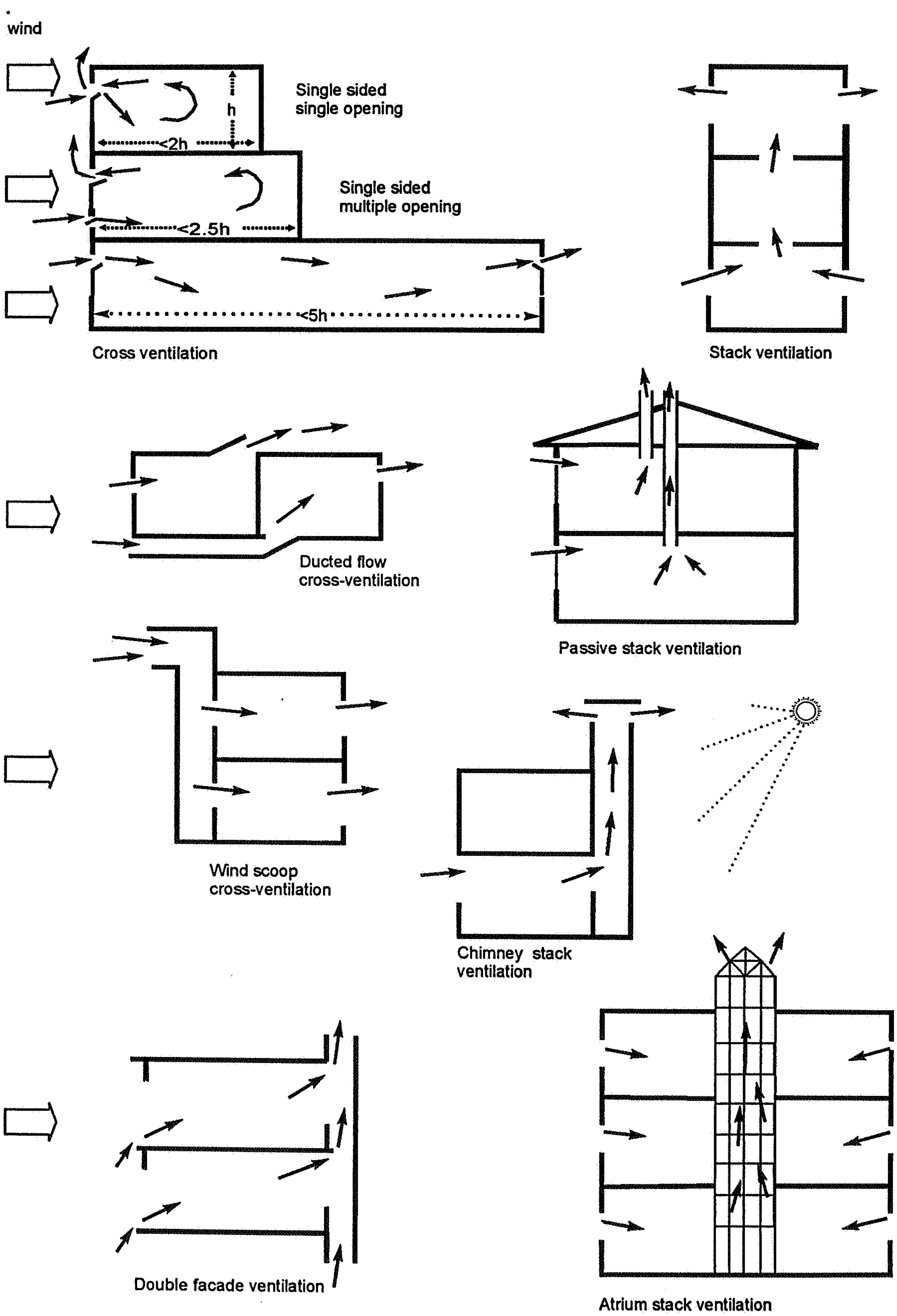


Figure 3.2 Natural ventilation strategies schematic

The cooling capability of natural ventilation is limited by the small temperature difference between inside and outside air at the times when most cooling is likely to be required. Whether overheating occurs in summer depends on both the degree of protection from insolation and on the internal heat sources. The thermal mass of the building is also significant since it determines how quickly these heat sources, if intermittent, raise the temperature. Air flow rates up to ten times that required for respiration and health may be required to provide summer cooling in a typical naturally ventilated commercial building. Peak cooling loads in commercial buildings are generally in the range 30-100Wm^{-2}. For northern European climates natural ventilation can be considered for cooling loads in the range 10-35Wm^{-2} (Irving 1996).

3.3 Role of Mechanical Ventilation

A mechanical system is likely to be necessary if:

- the internal heat gains are unusually large
- solar overheating would otherwise occur, due to poor solar control strategies
- the building is too deep for natural cross-ventilation
- the outside environment is polluted or noisy
- heat recovery is a key issue.

The air flow rate and pattern of a mechanical system is much more predictable than for natural ventilation but the cooling effect, for the same air flow, is no better and in practice may be worse due to the heat produced by the fan motors. However, techniques such as night-time cooling may be used more readily, especially in large office buildings which are unoccupied at night and used intensively during the working day.

Since a mechanical ventilation system includes electrically operated fans and dampers it is possible to incorporate demand control using, for example, a CO_2 sensor so that the ventilating air flow is matched to the number of people in the space thus avoiding over-ventilation and the consequent extra energy costs.

Heat recovery from the outgoing warm stale air to preheat the incoming fresh air during winter is very easily incorporated into a mechanical supply and extract system (Irving 1994).

3.4 Role of Air-Conditioning

Comfort cooling can be incorporated into a mechanical ventilation system which has a fan-driven air supply. When such an all-air system includes heating, cooling, filtration and moisture control it is known as 'air-conditioning'. In principle, ventilation and conditioning of spaces of any size and shape is feasible to provide comfort conditions whatever the climate.

The cooling effect in an occupied space can be achieved by circulating air, water or refrigerant around the building to appropriate terminal devices near the occupants.

The main options for active cooling are: (Limb 1994 b).

- **Chilled water** to local induction units, fan coil units or radiant panels in the ceiling.

- **All air systems** of various types:
  ⇒ fixed flow rate, variable temperature ducted air to suit the building cooling or heating requirements + terminal reheat
  ⇒ variable air volume (VAV) supplies ducted air at a fixed temperature to special terminal devices which vary the air flow rate locally to suit thermal (but not air quality) requirements
  ⇒ dual duct air flow system which blends cold and warm air at the air supply terminals to provide local temperature requirements.

- **Refrigerant based systems** in which room air is driven locally by a fan across a heat pump evaporator in the room linked to a remote condenser. Ventilation is separate.

- **Evaporative cooling** is an alternative to heat pump systems in hot dry climates where the mid-day Summer relative humidity is less than 40% (Liddament 1996 b).

The ways in which moving air is used for cooling are essentially by ventilation of the whole space or by spot cooling directed at the people.

This will be discussed in Chapter 5.

3.5 Influence of Climate and Environment

The need for heating, cooling and dehumidification of the incoming fresh air will depend on the outdoor climate. The main factor is how hot and humid the weather is in summer. Essentially it is not possible to cool the inside of a building to a lower temperature than the outside air by ventilation alone, in which case comfort cooling will be necessary to achieve acceptable conditions.

If the moisture content of the outside air is greater than that required inside then full air-conditioning is required since the outside air must be dehumidified. This is further discussed in Chapter 7.

3.6 Summary

The driving force for natural ventilation is the weather. In general the ventilation rate will be higher in cold or windy weather. It provides a relatively simple fail-safe method of ventilating a wide range of buildings in moderate climates and where a high degree of building user interaction with the system is acceptable.

A mechanical extract + natural supply system can provide a more predictable ventilation rate and route while a system with both mechanical supply and extract can provide weather independent ventilation for any type of building.

4. Specific Building Types

4.1 Introduction

The ventilation strategy depends on the type of building and its function, in particular the number of people and what they are doing. The aim is to provide, in an energy efficient way:

- good indoor air quality and comfort
- safe removal of airborne contaminants
- satisfactory distribution of fresh air without draughts
- a satisfied client.

4.2 Offices and Commercial Buildings

These buildings include multi-storey office blocks with a mixture of cellular and open plan working areas. The occupancy is generally one or more persons per $10m^2$ of floor area during the day and unoccupied at night and weekends. Moisture production is generally low and the main pollution sources are the building itself, the people working there, their equipment and the pollutants (including heat) arising from its use. Outdoor sources of pollution and noise, e.g. from traffic, may also be significant in towns and cities. The main considerations usually revolve round the achievement of acceptable indoor air quality in winter, when ventilation rates are minimised to save energy, and providing sufficient ventilation to avoid overheating in summer.

Small offices accommodating two or three people within a large building are similar to those in a smaller building and natural ventilation via openable windows would normally be feasible unless the outside air is polluted, or where the climate is extreme.

Large open plan offices shared by tens or even hundreds of people usually require comfort cooling due to the large internal heat gains from people, lights, equipment and the sun.

Openable windows for natural ventilation under user control are liked by most people and fewer sick building type complaints would be expected, but this type of strategy becomes increasingly inappropriate in large offices because of difficulties in fresh air distribution to parts of the office remote from the windows. However, if there is sufficient freedom to design the building accordingly, then natural ventilation is possible even for quite large offices in temperate climates, particularly where:
internal heat gains are moderate ($\sim 30W/m^2$)

- the building is narrow plan (depth ≤ 5 x ceiling height)
- an atrium or stack effect chimney is planned
- night cooling is feasible
- the outside environment is neither dirty nor noisy.

The provision of large thermal mass and external solar shading, Figure 4.1, to reduce summer overheating can be considered as part of the ventilation strategy. In climates where the summers are hot and humid, natural ventilation cannot provide sufficient cooling or moisture control, air-conditioning will be the only option. However a mixed mode approach with seasonal changeover may be possible.

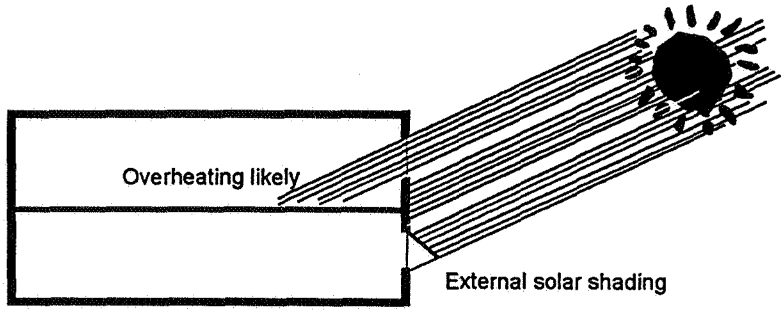


Figure 4.1 External solar shading

Mechanical ventilation uses fans and ducts to take fresh air into the occupied parts of a building and remove stale air. The air supply can reach the people via ceiling 'diffusers' to provide mixing ventilation, Figure 4.2, or through the floor or near-floor located air terminal devices, Figure 4.3, to provide non-mixing or displacement ventilation. In a deep plan office it is likely that cooling will be required all the year round in the centre with heating or cooling at the perimeter depending on the season. The people who are remote from the windows may feel cut-off from the outside world and are likely to be very sensitive to the thermal environment and especially critical of draughts.

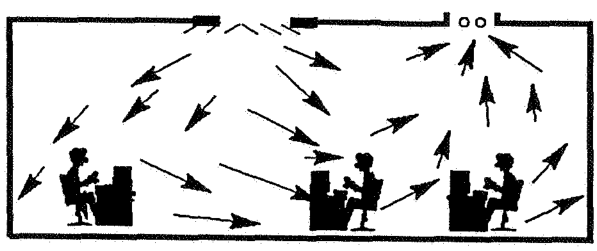


Figure 4.2 Mixing ventilation with air supply and extract through the ceiling

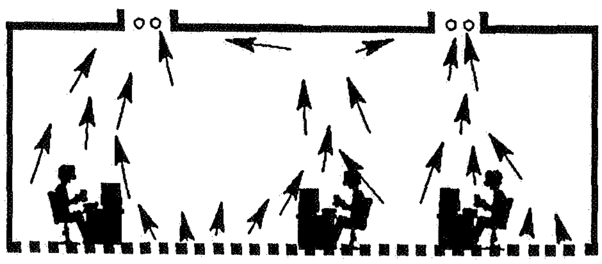


Figure 4.3 Displacement ventilation with air supply through the floor

A conventional air-conditioning system is usually used for heating and cooling as well as purely ventilation, and consequently the air flow rate is likely to be far greater than is necessary for supplying fresh air only. The normally adopted solution to avoid excessive energy loss is to recirculate a large proportion, typically up to 80%, of the air from the building, Figure 4.4.

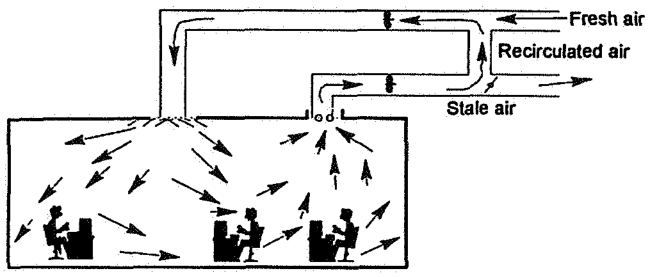


Figure 4.4 Air supplied to occupied space may be a mixture of recirculated and fresh air

An alternative approach is to completely separate the ventilating and heating or cooling functions. This is quite easy for heating but not quite so simple for cooling. One possible solution is the chilled ceiling or beam, Figure 4.5, which is the cooling equivalent of the hot water radiator and can provide sufficient cooling capability for most conventional offices thus permitting the ventilation system to supply fresh air only and therefore be much smaller and cheaper (Dickson 1994). The cooling performance of this and other similar chilled water or refrigerant based systems is limited by the requirement that the surface temperature of the cooling device must be above the dew point temperature of the air in the room, otherwise moisture will condense on the cool surfaces and may drip into the space or cause staining.

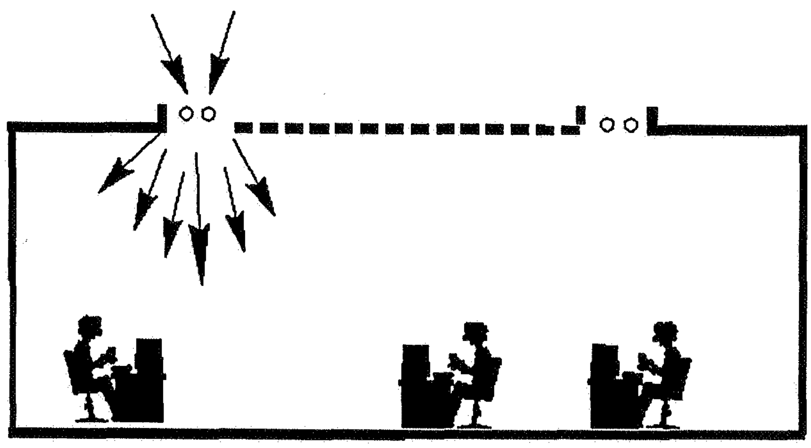


Figure 4.5 Chilled beam provides cooling independent of the ventilation system

There have been recent moves in many countries to conserve energy by minimising the use of air-conditioning (Willis 1995). Some quite large office buildings have been commissioned which rely on wind scoops or buoyancy driven chimneys (Aiulfi 1996) to provide extract ventilation with purpose provided controllable openings for the fresh air supply, Figure 4.6. Each building is a one-off design and there is very little data so far on how successful they are. Most rely on acceptance of the adaptive comfort theory (Nicol 1995) which proposes that people will accept temperatures above the normally accepted comfort band for limited times when it is very hot outside.

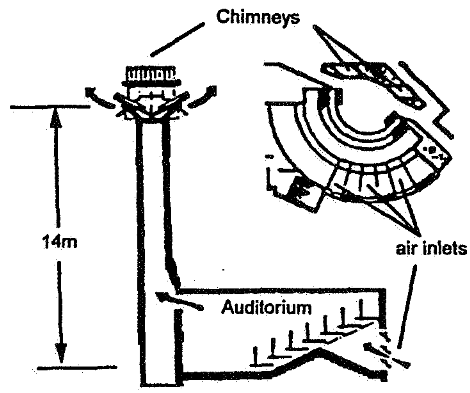


Figure 4.6 Chimney-ventilated auditorium

4.3 Shopping Malls and Atria

The atrium is now a common feature of office buildings, hotels, hospitals and shopping malls. The atrium may be used as an entrance hall or as an architectural feature with no specified purpose. It is characterised by large glass walls and roof resulting in possibly large swings in temperature due to daytime insolation and rapid night-time cooling. A further attribute is a large unobstructed vertical dimension which can result in large temperature gradients due to stratification. All sides and roof may be glazed or the side walls may be adjacent buildings with either closed or open access to the atrium space at different heights. Typical volumes are in the range 1000 to 100,000 m^3, with height up to 80m. The part of the enclosure just under the roof acts as a natural reservoir for warm air which may be naturally or mechanically vented to outdoors depending on requirements. Air curtains can be used for separating occupied floors from the atrium space and for avoiding upward air flow (Yoshino 1995).

The probability of cold down-draughts from large glazed facades and condensation on the cold glass must be addressed, typically by providing a warm air flow up the glass. An alternative approach for avoiding down-draughts (Heiselberg 1995) is to subdivide the glazed area by horizontal obstructions which reduces the height of individual glazed areas.

Many atria are sealed and mechanically ventilated, but this may be undesirable from an energy viewpoint and unnecessary for effective ventilation. The atrium can be utilised as part of the flow path for natural ventilation into or from adjacent rooms. Within the atrium itself, openings only at the top will tend to result in mixing ventilation and a relatively uniform vertical temperature distribution within the atrium. If openings are also provided at the bottom then buoyancy forces will result in displacement type ventilation with the air at low level being close to outside ambient temperature and warmer air at high levels which will be appropriate for summer cooling situations. In temperate climates, natural ventilation in this way will be able to prevent overheating in summer by providing a high air change rate (30 ac/h) provided that both low level inlets and high level outlets are feasible. This would be especially effective if combined with solar shading. Care is needed to avoid draughts where the air comes into the building.

Air quality within an atrium is generally not an issue since the ventilation rates are high and the space is large; control of energy flow and comfort temperatures are more significant. A high ventilation efficiency must be aimed for in the occupied zone without a large air exchange rate in the rest of the volume which would result in excessive energy consumption. Air velocities in the occupied zone must be low enough to avoid draughts. The possible ingress of traffic fumes must be addressed if the outdoor air inlets are near ground level.

Shopping malls are in many cases simply extended atria. In temperate climates they may be open at both ends and thus naturally ventilated. Air quality is not usually a concern because of the large volume. In cold climates the shopping centres will normally be totally enclosed and open to many of the shops. They are then very similar to exhibition halls and other large enclosures. Provision for smoke clearance after an accidental fire will be an essential part of the ventilation strategy in an atrium or shopping mall (Morgan 1990). If a shop catches fire the smoke rises in a plume to the ceiling, entraining air from the immediate surroundings, which increases the plume volume and cools it down, Figure 4.7. The shop fills with smoke from the ceiling downwards. The smoke then spills out of the shop into the mall. Whether the mall is open or closed at the end, smoke will return into the mall, by being drawn back towards the fire. The solution, which will have implications for ventilation of the mall under normal conditions is:

- a high ceiling forming a deep smoke reservoir
- mechanical or buoyancy driven natural extraction within the reservoir
- low level supply of replacement fresh air.

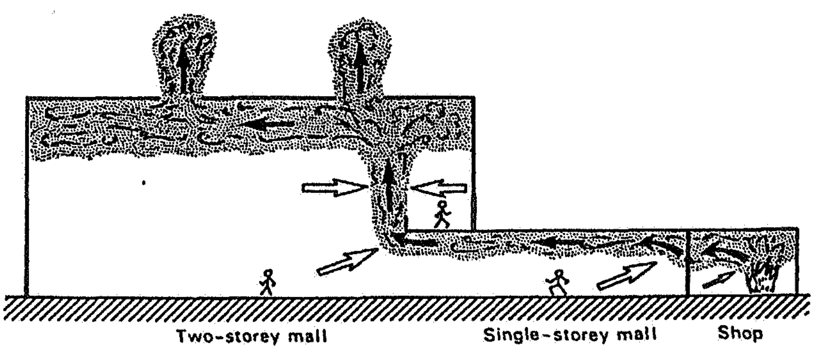


Figure 4.7 Smoke spread in a shopping mall

4.4 Auditoria and Assembly Halls

Buildings such as auditoria, congress halls and theatres are characterised by intermittent extreme occupancy patterns being at times very densely populated and at other times nearly empty. These types of building are appropriate for demand-controlled mechanical ventilation using, for example, carbon dioxide concentration as an indicator of occupancy.

Auditoria are usually mechanically ventilated by a balanced supply and extract system of either a mixing or displacement type. An ideal strategy is a displacement system which supplies air at 2-3°C below room temperature under the seats with extract at high level. Ventilation for thermal comfort may be more demanding than for odour removal, since the internal heat load from all the people is large and will therefore determine the required air flow rate.

The base ventilation rate when the building is unoccupied needs to be the air flow required to remove odours arising from building and furnishing materials. Pre-ventilation to clear accumulated pollutants should be arranged after shut-down periods such as week-ends.

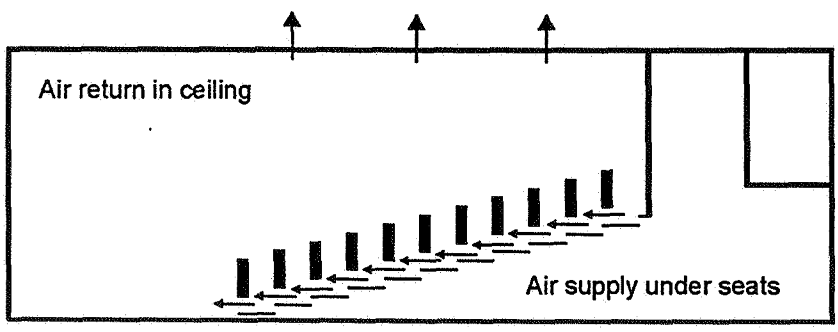


Figure 4.8 Mechanically ventilated lecture hall at NTH Trondheim

Figure 4.8 shows a 320 seat auditorium at the University of Trondheim (Drangsholt 1992) which has a volume of 1600 m^3 and is surrounded by other rooms on 3 sides with an atrium on the fourth side. It is mechanically ventilated with air at 18°C supplied under the seats with exhaust through the ceiling. The maximum ventilating flow rate is $2.8m^3/s$ representing 8.7 l/s per person. The fan speed which is controlled from the concentration of carbon dioxide in the exhaust air stream, increases the ventilation rate from a base value of $0.8m^3/s$ whenever the carbon dioxide concentration exceeds the set point, normally 800-1200ppm.

A Law Court is a particular challenge for natural ventilation since the need for privacy and security limit the options available for windows. A successful solution (Walker 1991) supplied air through an underfloor ventilation duct with controllable vents at roof level, the air flow being buoyancy-driven, Figure 4.9.

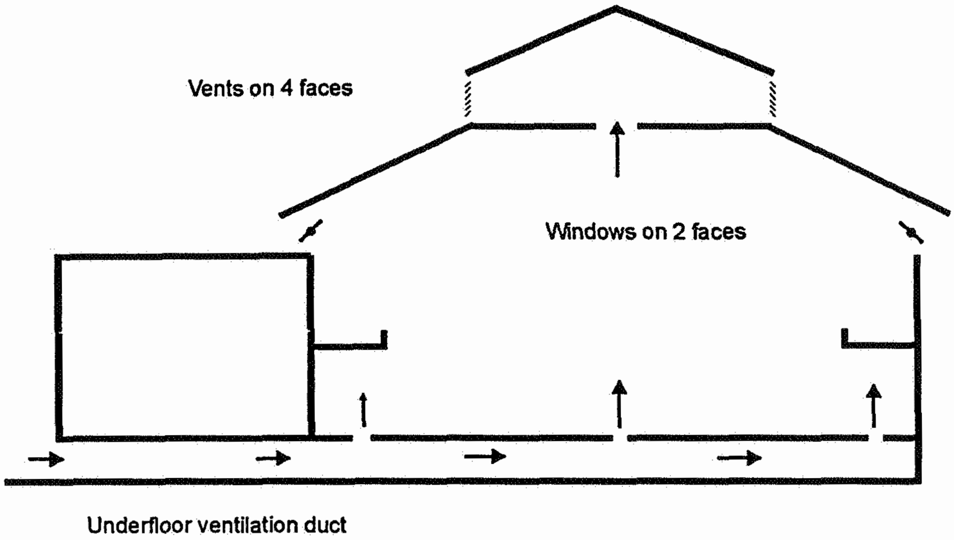


Figure 4.9 Naturally Ventilated Law Court in UK.

4.5 Recreational/Multi-Purpose Complexes

Many large enclosures are little more than protection from the weather and provision of a large lit enclosed space. They can often have quite simple ventilation systems, especially if there is no need for heating.

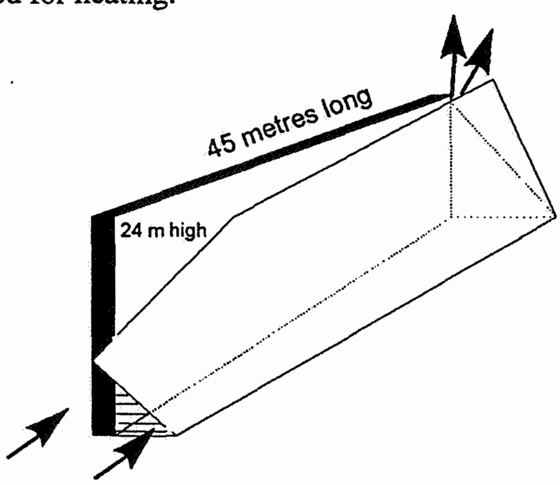


Figure 4.10 Danish Pavilion at Seville 1992

An example of such a system for a large enclosure was the Danish pavilion at the 1992 World Exhibition in Seville (Nielsen 1995) which consisted of a west facing air-conditioned steel framed building 45 x 2.5 x 24m high with an east facing externally water-cooled fibreglass 'sail' leaning against it forming an enclosure 10m wide by 45m long having a triangular cross section rising to a height of about 18m, Figure 4.10. The north and south walls were mainly glass with gaps in the south wall supported exposed cooling elements while an extract fan in the top north end of the room drew air in through the cooling elements and through the occupied zone. The design air flow rate for the fan was 10 m³/s which corresponds to over 30l/s of fresh air per person, but the main function of the fan was for cooling by drawing air through the cooling elements and removing the warm air above the occupied zone of the pavilion. Owing to the relatively high air temperature in the hall, air speeds up to 1m/s were acceptable.

The Jeppensen Terminal Building (Tjelflaat 1995) at Denver International Airport, USA, Figure 4.11, is the largest enclosed tensile roofed structure in the world (as at 1995). It is 300m long with a tent-like roof covering an area of 23000m². The central part of the building comprises the Great Hall, 64 x 274m flanked by 24m wide perimeter spaces under sloping reinforced pvc roofs. The building is naturally lit through the translucent roof. Ventilation of the hall is by horizontal air jets from the sides which results in a displacement mode with stratification when cooling and a mixing system when heating. The air system supplies air at a fixed flow rate of 253m³/s with up to 30% of fresh air, equivalent to 7 l/s per person, controlled by CO_2 sensors in the occupied zone. The air exhausts through roof vents, without heat recovery. Due to solar heating and occupancy gains, heating is required for only 2-3 weeks per year.

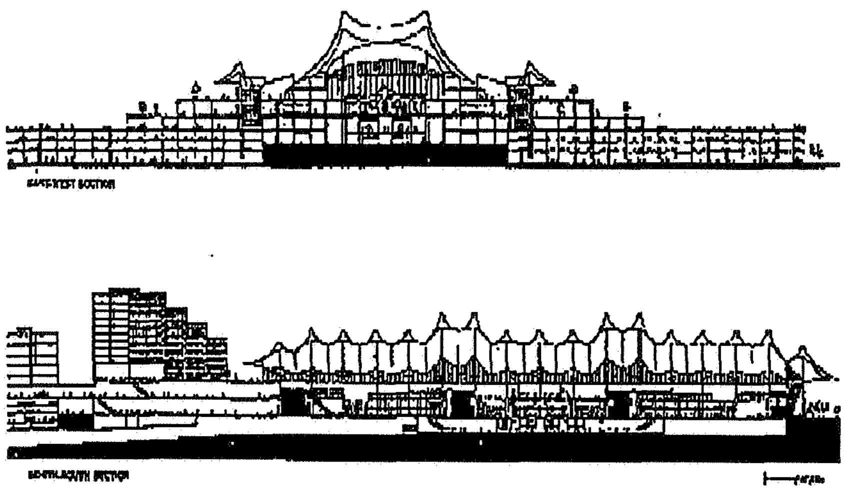


Figure 4.11 Denver International Airport terminal building

4.6 Warehouse and Factory Halls

Natural ventilation in through windows at low level and out through roof vents, Figure 4.12, is a common configuration for warehouses and other utilitarian buildings, especially if there are heat sources in the working area and ventilation is needed to avoid overheating. In warehouses humidity control may be important (Bennett 1995) which will require mechanical ventilation to be installed.

It is imperative that localised sources of pollution are provided with local extract so that the air quality in the occupied parts of the enclosure is acceptable. An air flow route into the building must be provided for fresh air to replace the air removed by the extract fan. In many cases, the amount of air needed for an industrial process is an order of magnitude higher than that for the people working in the factories.

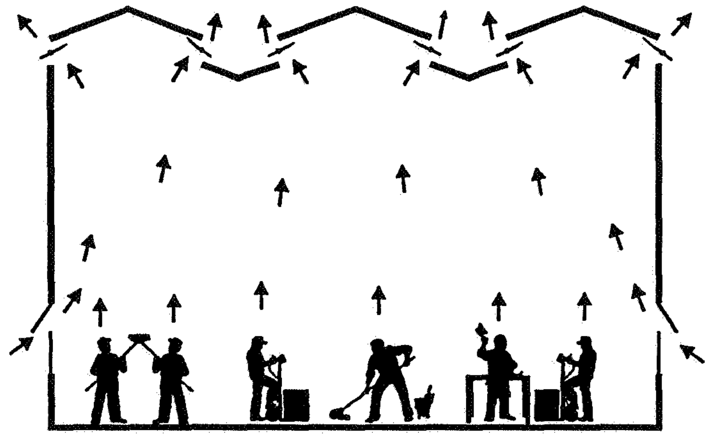


Figure 4.12 Naturally ventilated factory hall

Large single cell factory buildings and aircraft hangars tend to be very leaky (Perera 1990) although more recently built structures are less leaky than old ones. Very little can be done to tighten an existing building but new buildings should be constructed to be as tight as possible with purpose-built natural ventilation openings. Measured infiltration rates are typically several air changes per hour (Ashley 1986, Lawrence 1987).

Door opening can be a major problem if the doors are large and open for a long time and air curtains ought to be considered (van der Maas 1995, Strongin 1993). For such leaky buildings the main problem is over-ventilation which will result in excessive energy consumption in the heating season.

4.7 Museums and Archives

Archival material such as papers and books can act as a sink for pollution rather than a source. The ventilation system may bring outdoor pollutants such as SO_2, NO_2 and O_3 into the building. These pollutants attack the paper at concentrations far below those of concern to public health as indicated in Table 4.1. Although the damage rate is slow, because it takes place over many years, the result is very serious.

Since paper absorbs the pollutants, their concentrations measured in the indoor air may be misleadingly low, and the air leaving the galleries and storerooms may be less polluted than the air entering the space from outside, through the ventilation system (Lanting 1990). A typical air-conditioning system for an archive would contain a fine dust filter in the fresh air intake, a steam humidifier in the supply duct and dampers to proportion the amount of fresh and recirculated air. The humidifier may remove a large proportion of SO_2 but NO_2 and O_3 pass through the HVAC system almost unaffected.

In storerooms, where occupancy is minimal, the adoption of a high proportion of air recycle (~90%) will generally improve the air quality provided that there are no significant sources of indoor pollution.

Table 4.1 Guideline and measured pollutant concentrations (24 hour average)

pollutant	guideline value for archives (Lanting 1990)µg/m³	guideline value for people (WHO) µg/m³	max daily mean in cities (Europe) (WHO) µg/m³
SO_2	2.5	350 (1 hour)	250-500
NO_2	5	400 (1 hour) 150(24 hour)	400-1000
O_3	2	150-200 (1 hour)	40-400

4.8 Schools

School classrooms are occupied intermittently and at times densely. They may be simple single storey buildings with 100 occupants or quite large multi-storey buildings with 1000 or more occupants. Many are naturally ventilated but the occupancy pattern lends itself to demand controlled mechanical ventilation with either an exhaust only or supply + exhaust mechanical system.

The demand control can be achieved either by using the carbon dioxide concentration in the extracted air to control fresh air flow rates (Mansson 1992) or, more simply and in the case of a natural system, by using occupancy sensors which open and close local air dampers depending on whether anyone is in the room, (Norell 1993). The main polluting sources are the people and therefore non-localised; a mixing system can be used but a displacement system will usually provide better indoor air quality.

Cooling requirements and comfort (reduction of glare) will benefit from external solar shading. The occupancy pattern is also appropriate for the use of night cooling. Since occupancy is intermittent it may be possible to combine a mechanical system with the facility to air the rooms between occupancies at a rather high rate by opening windows for a relatively short time.

4.9 Parking Garages

Cars are sources of carbon monoxide, nitrogen oxides, particulates from diesel engines and other less pernicious but odorous pollutants. While most people spend only a very brief time in parking garages, people who work in them and those in traffic queues may be in the contaminated space for much longer times. Car parks may be underground, at ground level or multi-storey. Natural ventilation can be used for all except underground car parks, which require mechanical ventilation. It has the advantage of simplicity and cannot fail catastrophically. Openings in opposite outside walls provide cross ventilation. Most Codes of Practice recommend about 5% of the floor area as free opening, with as much of the opening as possible near floor level and no part of the floor more than 30m from a ventilated side (Limb 1994b).

National codes should be consulted for guidance relating to mechanically ventilated car parks. Typical requirements are an extract rate of 6-10 air changes per hour, with extract openings at both high and low level and located to avoid stale air pockets, together with CO detection linked to an alarm and standby fans having a secure power supply. Attendants' pay kiosks should have a fresh air supply and over-pressure.

Traffic routes into and out of the car park which have been planned to discourage the formation of stationary traffic queues can help to avoid build up of CO.

The possibility of the car park exhaust air contaminating neighbouring properties is real. Stack effect operating in stair wells and lift shafts can provide an unintended route for contaminants to travel from a basement car park into a building above, resulting in serious indoor pollution.

Large scale bus garages are characterised by high ceilings and periods of intense activity. Buoyancy effects are significant in removing exhaust fumes which can be boosted by mechanical extraction at roof level, with fresh air inlets at low level placed to avoid short circuiting. Heat recovery to reduce the heating costs of the building and demand control of ventilation rate should be considered. Local extracts at servicing bays are also desirable.

4.10 Summary

Mechanical ventilation is generally the first choice for large non-domestic buildings since it is predictable and controllable. Often the requirement for comfort cooling will be met more easily using mechanical ventilation or full air-conditioning.

However, particularly in temperate climates the need for air-conditioning is increasingly being questioned for energy reasons and large naturally ventilated buildings are appearing which provide acceptable comfort conditions without using fans or refrigerant cooling systems.

The function of the building may impose overriding conditions on the design. Since archival material acts as a sink for pollutants frequently found in towns, an air-conditioning system with minimum fresh air supply will be best. On the other hand a parking garage is more likely to be fail-safe if naturally ventilated.

5. Air Distribution for Good Design

5.1 The Art of Ventilation

Ventilation is the art of moving air without it appearing to move and removing pollution without anyone realising that the air is polluted.

5.2 Contaminant Removal

The air flow **route** is more critical than the **rate** for effective removal of contaminants. The fundamental rules for good design apply to all sizes of building:

- **Control sources:** major effort must be directed at avoiding, removing and reducing all possible sources of pollution
- **Local extract:** for those sources which cannot be removed, the ventilation extracts should be as close to them as possible
- **Targeted fresh air:** supply fresh air where it is needed
- **Planned air flow route:** from less contaminated towards more contaminated regions, with no short circuiting

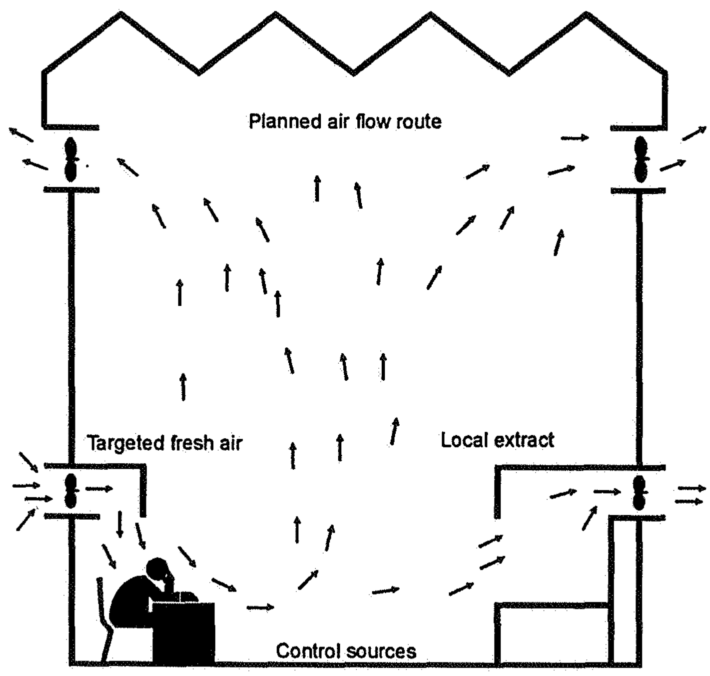


Figure 5.1 Planned air distribution: supply fresh air where it is needed and remove contamination where it is produced

The location and nature of the air supply openings determine the air distribution pattern and are therefore more significant than the extract openings. In general, warm air is best supplied at low level whereas cool air can be supplied horizontally near the ceiling or from low velocity outlets near the floor.

Air projected into a space entrains room air with the result that the volume of air in motion increases and its speed decreases. Moving air tends to adhere to any surface and be deflected away from the surface by obstructions. An air jet initially travels in the direction it was projected but buoyancy forces determine the final trajectory.

In a large open space with no physical barriers a jet will continue in its original direction until buoyancy forces take over, the room air pattern will then be dominated by convection arising from warm or cold surfaces and thermal sources such as people and equipment.

The air return opening affects the air only in its immediate vicinity because suction is omni-directional and therefore the suction effect falls off very rapidly. This does not mean that the location of the extract is unimportant but only that it has very little effect on the air flow pattern in the room. Extracts must be close to the contaminant sources for effective removal of pollutants before they mix with all the air in the room.

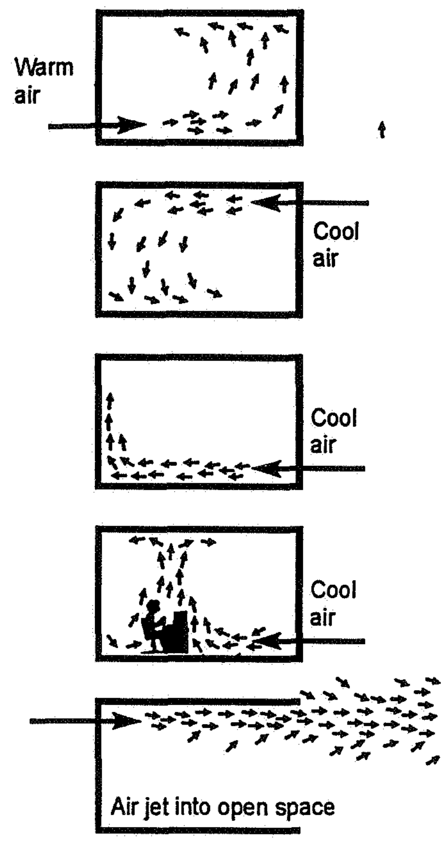


Figure 5.2 The effect of different air supply options on the air flow pattern in a room

5.3 Heat Removal

The same guidelines apply for removing heat as for removing odours and chemical pollutants. Removing, or minimising, sources of heat associated with:

- people
- lighting
- the equipment they are using
- sun shining through windows
- solar heating of the building structure

is the first priority.

To prevent heat entering the occupied space unnecessarily:

- extract air through air-handling light fittings
- position the extract where the room air is warmest
- install external shading coupled with moderate glazed areas particularly on south facades.

Non mixing ventilation patterns should be adopted, from cooler towards warmer parts of the room. The return outlet should extract the warmest air in the space when cooling.

Cooling loads of the order 100 W/m^2 are frequently assumed for design calculations whereas 30 W/m^2 is more realistic in many commercial offices. The tendency for the building itself to act as a solar collector can be approached at the design stage by orientation, thermal insulation and surface treatment. However, if the outside temperature is always higher than the indoor comfort temperature there is no possibility of using outdoor air to provide cooling (unless the air is dry enough to consider some form of evaporative cooling).

If a low outside air temperature occurs at night then designing the building so that it can be cooled overnight could be considered as a design option to limit the daytime cooling requirement. A daytime temperature reduction of about 3°C (Irving 1996) can be achieved in a heavyweight building by providing high rates of ventilation at night.

In temperate climates where the outdoor temperature is higher than the comfort temperature for only relatively short periods then cooling can often be achieved by ventilation, at possibly a fairly high rate, with outside air. Cross-ventilation and chimney ventilation will be more likely to succeed than single-sided ventilation.

The humidity of the outside air will also influence the ability to provide cooling. If the climate is both very hot and very humid then there may be no other option other than to provide air-conditioning in the form of mechanical cooling.

5.4 Ventilation Efficiency

In a large enclosure, especially of a prestige or artistic character, the possible locations for air supply and exhaust terminals may be influenced more by architectural than by aerodynamic considerations. This should be resisted since it is very difficult to change at a later date. The most likely mistake is to have the air supply terminals so far from the people that high air speeds have to be used, resulting in draughts or short-circuiting of the fresh air direct to the air extract, thus missing out the people, unless the system is unusually well commissioned.

The route travelled by the ventilating air and the amount of mixing have a profound influence on the control of contaminant spread within the space being ventilated. The concept of ventilation efficiency describes how successfully the contamination is removed in relation to the 'standard' condition of complete mixing. It is possible for air to pass through the ventilated space without encountering the occupants or pollutants at all, this could reasonably be called zero ventilation efficiency. In this situation the ventilation would be completely useless since the occupants would receive no benefit at all from the fresh air supplied and pollutants would not be removed. A highly efficient ventilation system is exemplified by local air supply such that the occupant is bathed in fresh air and therefore gains maximum benefit. Most practical situations lie somewhere in between these two examples.

5.5 Displacement versus Dilution Ventilation

Complete mixing and no mixing can be considered as two extremes of the ventilation process. Dilution of contaminants by efficient mixing with 'fresh air' accompanied by removal of the contaminated mixture is how many traditional ventilation systems work; the location of the supply and extract are relatively unimportant since the air quality is 'the same' throughout the space. Alternatively, the air can be introduced in such a way that mixing is discouraged and the clean air drives, or displaces, the contaminated air before it like a piston in a cylinder. In this case the location of the supply and extract are critical but the air quality close to where the fresh air enters the building is potentially much better.

Traditionally most ventilation is closer to the mixing pattern than displacement, perhaps modified by local extract where there are known local sources of pollution.

Displacement ventilation is buoyancy driven by heat sources in the room. Air, slightly cooler than room temperature is delivered to the room at very low speed and close to the floor. The result is a lake of cool fresh air at floor level which is entrained by the rising convective plumes arising from heat sources such as people and equipment.

This can result in large vertical gradients of temperature and contaminants which can often be used to advantage for contaminant and heat removal from large enclosures such as atria. When the rising warm air finds its surroundings to be at the same temperature it stops rising and there then exists a mixed zone at high level which can be arranged to be above the occupied zone by appropriate choice of air extract rate.

If air is supplied by a displacement ventilation system at a temperature lower than about 19°C then there is a high risk of people suffering from cold feet. This restriction on the air supply temperature limits the cooling capability to less than about 20W/m^2 in a typical office building.

In large buildings, the opportunities for exploiting convective driving forces are greater and a high ceiling can provide a reservoir for pollution. However, the high ceiling also provides a reservoir for warm air, which may be undesirable in the heating season and some form of destratifier should be considered.

6. User Considerations

6.1 User Friendliness and Control

The most successful ventilation system would be invisible. It should provide 'fresh' air silently without draughts or stuffiness.

Studies of sick building syndrome (SBS) have indicated that perception of greater control over ventilation, lighting and temperature is associated with decreased symptom prevalence (Wilson 1987). In many recreational and public buildings the users would not expect to have control over the environment but in offices the people working there are very likely to demand a high degree of control and to feel 'uncomfortable' and suffer real 'sickness' symptoms even when the comfort conditions are apparently within accepted limits.

Control over ventilation is most easily seen in relation to opening windows but in offices occupied by more than 2 or 3 people, individual variability and different distances from the window make it quite difficult to satisfy everybody. Control must be real, but it can be through a responsive management where complaints about the environment are seen to be acted upon quickly.

Task ventilation in the form of local workstation control or the 'environmental desk' is a possible solution (Arens 1990). By using a central system to provide fresh air and a background thermal environment with control of temperature and air flow pattern provided at each desk, by a configuration similar to that found in cars, each person can set their own local comfort condition without affecting the other people in the office.

6.2 Draughts

Ventilation involves air movement which frequently causes draughts. A refreshing breeze in summer may be a cold draught in winter. Cold air may be perceived as draughty even if it is not moving. Air speeds below 0.1m/s are unlikely to be felt as draughty unless the air temperature is below about 18°C. Air at speeds greater than 0.2m/s is very likely to be considered draughty unless a cooling sensation is desirable.

Sensations of draughtiness will depend on the type of building. People in theatres and auditoria are likely to be as critical as office staff, whereas in shopping malls and similar spaces where people are milling around, draughtiness is likely to be far less critical. In atria where there is a large quantity of air flowing into the enclosure at ground level draughts are likely. Whereas air speeds greater than about 0.2 to 0.3 m/s should be avoided there are situations where higher speeds are acceptable. The Danish Pavilion at Seville (Nielsen 1995) was an exhibition hall where the air speed in the occupied zone was 0.6m/s at about 26°C air temperature.

People are believed to be more tolerant of draughts in naturally ventilated buildings since they appreciate the cause of the air movement, and the moving air is perceived as fresh. In an air-conditioned building any draught sensation will be perceived as coming from the air-conditioning system, uncontrollable and therefore unacceptable.

6.3 Noise

Air movement is likely to be associated with noise, ranging from the rustling of leaves in a turbulent breeze to the drone of a fan in a mechanically ventilated building. In many large buildings such as recreational and shopping complexes it is fairly unlikely that a ventilation system designed and constructed according to normal practice would be the main source of annoying noise. In auditoria and assembly halls much lower background noise levels will be specified which will have to be met by effective silencers, ductwork designed for minimum noise generation and choice of low noise air supply terminals. Table 6.1 summarises the noise sources relating to ventilation of large buildings.

Proposed standards (CEN 1994) for maximum noise levels generated by ventilation equipment are 30-40 dB(A) depending on the 'quality' of indoor environment desired. If it is possible for the user to control the ventilation equipment then it is proposed that noise levels can be 5 dB(A) higher than for a centrally controlled system.

Natural ventilation is in itself virtually silent but permits intrusion of external noises. The most common outdoor source of noise is road traffic. Some wind noise may also occur but is unlikely to be annoying.

6.4 Maintenance

There is a lot of evidence that poor maintenance is responsible for many of the shortcomings associated with ventilation systems and the more complex the system the more serious the problem. The first step in maintenance is commissioning, i.e. setting the system running and adjusting the fluid flows. Most national professional organisations have a standard Commissioning Code which is essentially a check list.

The first stage of commissioning is to ensure that the design air flows exist within the ventilation system; this is relatively straightforward, though time consuming in a large system. The second stage is to check that the resulting effect in the room is what was intended.

Natural systems appear to require virtually no maintenance. However it is necessary to ensure that vents or opening windows are appropriate and easily operable. On the other hand, mechanical ventilation systems need to be commissioned and maintained by skilled staff. Fans, ducts and heat exchangers must have access for cleaning. Filters can act as pollution sources if not changed in time.

Table 6.1 Ventilation-related noise sources

ventilation strategy	noise source	character of noise	solution or precaution
natural	traffic	variable, annoying	acoustic treatment of air inlets and outlets
	wind	variable	generally acceptable
	activities of others	distracting	re-plan traffic routes; move desks
	printers	dot matrix printers were very noisy	laser and ink-jet are much quieter
	copiers	distracting	move to separate room
mechanical	outside	variable	air tight building with attenuators in HVAC system
	inside	as for natural	
	fans	humming transmitted along the ducts	reduce fan speed. duct noise attenuators
	air flow in ducts	turbulence	avoid obstructions, dampers and sharp bends; maintain air speed less than 4 m/s in uninsulated ductwork
	air terminals	turbulence	refer to manufacturers' data
	cross-talk via ducts	voices and other noises from adjacent rooms	acoustic treatment of ceiling plenum and interconnecting ductwork

7. Energy Considerations

7.1 Ventilation Heat Loss

The fresh ventilating air coming into a building in the heating season is colder than the air leaving the building and the energy required to heat this air is the ventilation heat loss which is likely to be much greater than the heat loss by conduction through the walls and roof.

Since the size and locations of leakage sites on a building shell are not generally known, the consequent exfiltration heat loss due to accidental ventilation is very difficult to predict.

It is possible to measure the leakage of a building by a pressurisation test using a large mobile fan which blows air into the building through a door or window opening (Perera 1989). A number of mobile test facilities exist which can test buildings up to an enclosed volume of about 20,000 m^3, depending on their air leakage characteristics.

The results can be used to predict air change rates for mean weather conditions and thence the ventilation heat loss.

7.2 Heat Recovery

The simplest way to reduce the ventilation heat loss is to use the outgoing warm air to preheat the incoming fresh air. The larger the building, the more worthwhile this is likely to be. Heat recovery options are shown in Table 7.1.

Passive systems use plate heat exchangers, as part of a balanced mechanical ventilation system; these are simple and allow complete separation of the outgoing and incoming air streams. Typical temperature efficiencies are 50-80%.

Thermal wheels have higher efficiencies (up to 85%) and also can recover moisture. They are likely to appear to be the best option for maximum energy savings, but this must be balanced against the inevitable cross-contamination and the maintenance implications of moving parts together with a matrix which may clog and require cleaning.

Heat pumps provide even more options but at increased capital costs and complexity. They permit the recovered heat to be used by a hot water system.

Any economic assessment of heat recovery should take into account that investment in heat recovery provides savings for the life of the system which may be 15-30 years. Heat recovery is most worthwhile for a tight building in a cold climate and least attractive for a leaky building in a mild climate (Irving 1994) mainly due to the relationship between the fan power required to drive the system and the amount of heat recovered.

Table 7.1 Heat recovery options

name	description	advantages	disadvantages	where to use?
run-around coils	a pair of finned heat exchangers linked by a water/glycol circuit	supply and exhaust air streams need not be next to each other	relatively low efficiency	retrofitting
plate heat exchangers	a stack of plates separated by air gaps through which the air streams pass	simple with no moving parts low maintenance	supply and exhaust ducts must be adjacent summer bypass needed	any building where incoming fresh air has to be heated
thermal wheels	a revolving cylinder containing a matrix through which the air flows pass, with transfer of heat	high efficiency can transfer latent as well as sensible heat	supply and exhaust ducts must be adjacent some cross-contamination is inevitable maintenance	any building where incoming fresh air has to be heated unless strict standards of air quality are required
heat pumps	transfer heat from one fluid to another by the vapour compression cycle or absorption cycle	very efficient (high Coefficient of Performance) good for latent heat recovery	cost mechanical complexity	any building, especially when combined with a plate heat exchanger

7.3 Heating and Cooling Loads

The energy cost of ventilation relates to whether the air supplied to the occupied spaces is warmer or colder than the fresh air coming into the building. Energy is also required to remove moisture so if the ventilating air is too humid the cooling load will be that much greater. Humidification is often used in practice when the outside air is very dry but opinions vary about how necessary or desirable this is (Reinikainen 1990).

The overall picture can be appreciated by reference to the psychrometric chart, Figure 7.1, which is a visual presentation of the possible characteristics of an air/water vapour mixture. The chart refers to outside air, which may have to be heated, cooled or dehumidified to satisfy indoor comfort requirements, it is assumed for illustration that outside air needs to be heated if it is below 18°C, cooled if warmer than 25.5°C and dehumidified if the moisture content is greater than that corresponding to 40%RH at 25.5°C.

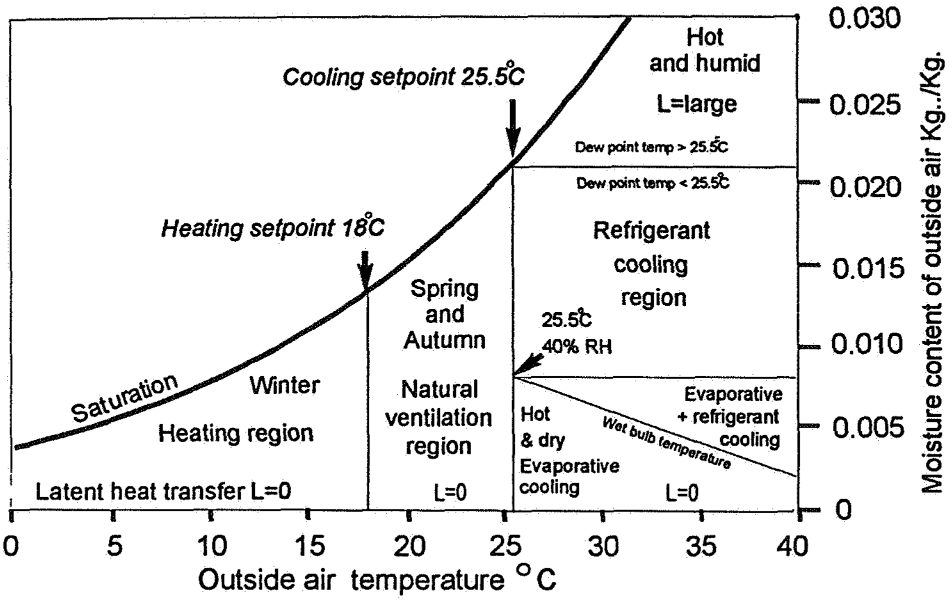


Figure 7.1 Heating and cooling regimes on the psychrometric chart

The energy required to achieve the desired indoor conditions can be calculated for any chosen climate (Colliver 1995) from the temperature and moisture content changes experienced by the incoming fresh air. From hourly weather data the annual heating and cooling energy requirements for sites in America and Europe are given in Figure 7.2. It is seen that in the hot humid climate of south east USA the energy required to dehumidify the air, referred to as "latent cooling energy", is up to ten times as great as the "sensible cooling energy" which is required to lower the temperature without moisture control.

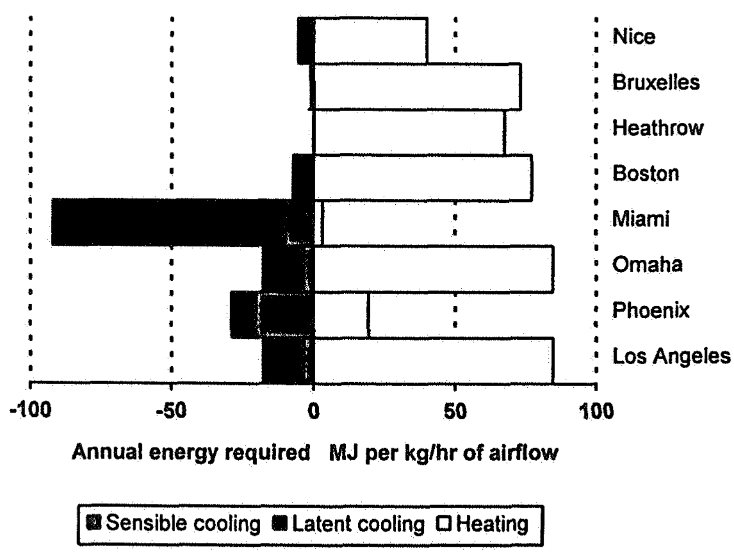


Figure 7.2 Heating and cooling energy related to climate

In very large enclosures (Murakami 1992) it becomes desirable to limit the air-conditioned part of the building to the occupied zones only, to save energy. Cool air naturally flows to the floor and so low velocity supply of cool air at low level will be appropriate. Options for local heating are air supply under seats, floor heating, radiant heating or a carefully sized and targeted warm air jets directed towards the people. A simulation procedure such as CFD may be necessary to find what air flow rates and temperatures are necessary to provide comfort conditions.

7.4 Night Cooling

In climates where the night time air temperature is lower than the comfort temperature the cooling capability required from the ventilation system during the day can be reduced by cooling a building overnight and thus using the thermal mass of the building to store the night 'coolth'. The overnight cooling can be achieved either by open windows and vents, i.e. the normal ventilation route, or by purpose provided air ducts in the structure (e.g. 'Termodeck' which uses a ducted floor construction). It is essential that the parts of the building which are cooled are in good thermal contact with the air supplied to the occupied space or with the occupied space itself and not separated from it by, for example, suspended floors and ceilings.

Windows left open at night for cooling purposes may be closed by cleaners or for security reasons thus thwarting the aim of the system. In any case some form of automatic control system is desirable to ensure that the building is not cooled too much overnight which would result in temperature at the beginning of the occupancy period being too low, and also to prevent the ingress of rain. If fans are used to drive the night time ventilation then the energy cost of the fan operation must be balanced against the cooling advantage obtained. An optimum start control system is desirable to limit the time during which the fans are running and also to confine it to the later part of the night.

7.5 Building Geometry

The shape of a building influences the ventilation characteristics by its height, influencing stack effect ventilation, and its shape in relation to the prevailing wind speed and direction which affects wind-induced ventilation. Wind pressures may oppose or assist buoyancy forces resulting, at times, in reversal of intended flows. Wind pressures on the surface of the building depend on the building form and on the nature of the surroundings. In this sense the design of the ventilation system begins as soon as the architect decides what shape the building will be (Alexander 1996). These are decisions which are very difficult to change once the building is built. Orientation can influence the cooling load since solar gains through west facing glazing (afternoon sun) are more likely to cause overheating than south facing glazing (sun high in the sky). East facing glazing (morning sun) is likely to give rise to overheating only if the building is of very lightweight construction. Solar shading can save on the cooling load. In temperate climates naturally ventilated buildings use less energy, forcing the building to be narrow plan. For a medium to deep plan building in a temperate climate it should be possible to adopt a mixed mode approach in which the perimeter operates, in the appropriate season, as a naturally ventilated space with openable windows, in conjunction with air-conditioning for internal spaces. The provision of an atrium may not necessarily reduce energy consumption. To ensure that the energy consumption is not increased it is important that:

- the atrium does not cut down on daylighting reaching the adjacent office spaces
- natural ventilation of the surrounding rooms should be possible
- shading and high rates of ventilation prevent overheating in summer.

7.6 Building Function

The activities carried out in the building affect the energy use, for example a swimming pool will consume more energy per m^2 than an office. Some offices may have an abnormal number of computers and associated equipment making mechanical cooling obligatory. The way the building is used by the occupants will be very significant and much of the wide variation in energy consumption can be attributed to occupant interaction with the ventilation system. The management also have a role here in ensuring that the building is maintained, that everything works and that people are listened to.

7.7 Control

Mechanical ventilation systems will generally be controlled automatically by varying, for example, the fan speeds in response to the signal from an appropriate sensor situated either in the occupied space or in the extract air duct. This 'demand control' (Mansson 1992) must be such that reducing the ventilating air flow results in a reduction in energy consumption. In situations where 'free-cooling' is available (outside air cooler than indoor air) then the air flow rate required to take advantage of free cooling must take precedence. The most common driving pollutant for ventilation control is CO_2. This is likely to be appropriate for schools, auditoria and offices which are characterised by the people using the spaces being the main source of pollution. Normally a control value of around 1000ppm CO_2 will be used with the ventilation falling to a baseline value relating to the pollution produced by the building materials and furnishings when the CO_2 level is below 1000ppm. It must be ensured that the controller algorithm controls for the most demanding condition, i.e. the system must not reduce the ventilation so much because the CO_2 level is low if this makes the achievement of thermal comfort impossible as a result of the cooling effect of the ventilating air flow being insufficient.

Electrically operated vents can be used for control of natural ventilation. These are generally temperature-controlled where night cooling is an important part of the ventilation strategy or in a large building or atrium where removal of warm air through high level vents is necessary to avoid summer overheating. A minimum opening position for the ventilation openings will have to be defined depending on the fresh air needs of the occupants according to accepted guidelines (i.e. ~10 l/s per person).

8. Decision Process

8.1 Objectives

The ventilation strategy is an integral part of the building design which influences both the energy efficiency and the user satisfaction. It is important to identify those decisions which are very difficult to change and those which can be modified later as the building use patterns develop. An integrated design process is required whereby 'unexpected' knock-on effects are avoided. For example the ventilation plan for a new large building may be affected by decisions relating to size, shape, orientation and structure while having implications for thermal comfort and energy use.

The most obvious decision to be made is 'natural or mechanical?', which can be broadened out to four options:

- mechanical ventilation with cooling
- mechanical ventilation without cooling
- natural ventilation
- mixed mode.

The developer or landlord may want 'air-conditioning' so that a higher rent can be justified whereas the user may prefer openable windows to keep the workers happy. An air-conditioned building will be easier to design than mixed mode or naturally ventilated; the operating simplicity of a naturally ventilated building is a reward for more time and effort spent at the briefing and design stage.

8.2 Designer Decision List

Ventilation system design is influenced by many factors, only some of which are within the control of the designer. In order of irreversibility, with the most difficult to change first:

Climate

is critical, but outside the control of the decision maker:

If summers are:	**you will need:**
hot and humid	Mech vent + cooling + dehumidification
hot and dry	Mech vent + cooling
hot days, cool nights	Nat vent + night cooling
seldom uncomfortably hot	Nat vent should be considered
If winters are:	
very cold	Mech vent with heat recovery
seldom much below 0°C	Nat vent should be considered

Location

is also probably decided before the client even approaches the design team.

Is the outside air clean enough to be used indoors (i.e. free from traffic or industrial pollution)?	If not, discard natural ventilation
Is the outside noisy (e.g. close to a busy road or airport)?	If yes, discard natural ventilation
Does the shape of the site force a deep plan, or very high, building?	Natural ventilation will be difficult
Will the surroundings influence the wind pattern?	Natural ventilation may be unpredictable

Function

will influence the size and shape of the internal spaces and also the ventilation requirements.

What ventilation rate does 10l/s per person make?	This is your first estimate of the required fresh air ventilation rate
Is occupancy intermittent?	Seriously consider demand control
What level of management skills are available?	Complicated systems need to be well managed
Is there a lot of IT equipment?	Consider local extract for printers and copiers, and energy-saving equipment
Is the management happy for people to fiddle with the controls?	If not, specify demand control
Are there hazardous pollutants present, and what happens if a mechanical system fails?	Car parks for example may be more 'fail-safe' with a well-designed natural system than with mechanical ventilation

Special needs of the client

will also influence the ventilation system, possibly indirectly.

Open plan or cellular offices?	How does the function of office influence the ventilation system?
Is an atrium specified?	Can it be used as part of the ventilation system!
What image?	Is air-conditioning really necessary?
What are their expectations?	Prestige/ functional
What type of workers?	Clerical/professional/highly motivated
What type of management?	Effective/ laissez faire
Budget available	Natural ventilation is cheaper

Control strategy

will be important for both user satisfaction and energy consumption. The occupant needs sufficient control which is ergonomically convenient and easily understood. A default energy-conserving average comfort mode is also highly desirable.

Since preferred comfort conditions vary between individuals, it is never possible to please everyone in a centrally controlled building. Ideally each person should be able to control their own immediate environment; this may be practical in offices occupied by two or three people but in a large open plan office an effective management structure is required to ensure that the occupants' views are heard together with a responsive control system to make it possible to change conditions in a predictable way.

Architecture

of the building can be aimed at easing the ventilation problem:

Is cooling required?	Attend to solar shading, specifying low energy equipment
Does the building have to be tall?	This may preclude natural ventilation
Can the building be made airtight?	Pay attention to construction details
Does the building have to be wider than 10 m?	If so, natural ventilation may not be feasible
Are openable windows required?	These can affect the performance of a mechanical cooling system

8.3 User Decision List

The designer's brief will reflect the user's needs which relate to the building in use:

Comfort and productivity of the workforce are the user's main concern. Air-conditioned buildings require good management to achieve their potential of reliable and predictable environmental conditions. However the more advanced and larger naturally ventilated buildings may require even more skilled management (Leaman 1995) in ensuring that the intervention of workers, cleaners and security staff does not defeat the aims of the design for example in relation to window opening for night cooling.

Capital costs are of little concern to the user except as reflected in the rent. The developer will want the best return on their investment and may be reluctant to increase the initial cost to save running costs during the life of the building.

Maintenance costs relate to the complexity of the building and so will be least for a naturally ventilated building and higher for an air-conditioned building. Reliability relates to maintenance costs. Natural ventilation systems are less dependable in maintaining adequate ventilation since the rate is weather dependent, but the effect on air quality and morale of a poor air-conditioning system is more traumatic.

Energy costs may be small compared with salary costs in many commercial buildings, but energy costs are likely to increase in real terms. In temperate climates naturally ventilated buildings consume less energy than air-conditioned per m^2 of floor space. Mechanical ventilation with heat recovery has hitherto been considered economically viable mainly in Scandinavia and Canada, but it is often cost-effective in other countries such as Germany, Holland and France.

Control aspirations depend on the function of the building. Office workers generally expect to have some effective control whereas the people in theatres, shopping malls and exhibition halls would never expect to have any hands-on control of the thermal environment, although they would like someone to complain to if it is not acceptable. Natural ventilation often has the perception of more control but the actual control available is insufficient to achieve normally accepted comfort standards.

To air-condition or not? The answer should be definitely yes only if the climate, shape and function of the building demand it.

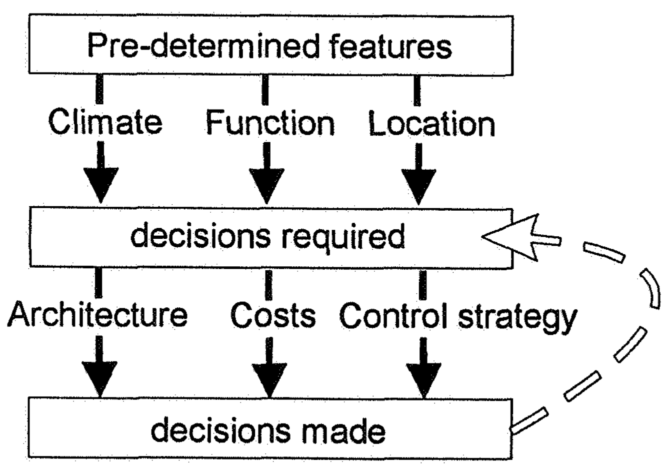
8.4 Criterion for Success

Buildings are for the people who use them. Are they satisfied? Will they still be satisfied in 1 year, 10 years, 50 years?

For a given building there is no unique set of decisions which will guarantee success. In a more complex building there is more to go wrong and more management skills are required to ensure that it succeeds. However this is not a reason for stagnation in ventilation system design but it does mean that the type of system must relate to the type of user.

8.5 Summary

The decision-making process can be summarised thus:



9. Design Process

9.1 General

The aim of the design process is to obtain a certain environmental air quality in the building within the constraints imposed by the client, building codes and good engineering practice.

The ventilation design process is inevitably based on professional judgement satisfying:

- relevant legislation
- health and comfort requirements
  - ⇒ what people do in the building?
  - ⇒ how many people in what area and volume?
- pollutant removal
  - ⇒ body odours, CO_2, moisture
  - ⇒ office equipment
- cooling needs
  - ⇒ number of people
  - ⇒ number of printers and photocopiers
- architectural constraints or aspirations
  - ⇒ open plan or cellular?
  - ⇒ ceiling height
  - ⇒ windows and shading
- cost constraints
- energy efficiency

The ventilation process comprises a **rate** and a **route** for the air flow. Air flows cannot be observed directly and in any case are likely to vary in space and time. Mechanical systems in principle permit both rate and route to be planned whereas designing for natural ventilation is largely empirical.

9.2 Building Tightness

The design of the building itself is an integral part of the ventilation system design. It is a general rule that buildings should be as tight as possible so that, for both energy and comfort reasons, ventilation can be planned and controlled - the 'build tight, ventilate right' approach (Perera 1995).

Air leakage (infiltration) through fortuitous gaps in the building structure is generally unplanned, unpredictable and uncontrollable. It is also very difficult to find and seal these leakage sites in an existing building. The building must therefore be designed and constructed to be as air-tight as possible and the designer must communicate to the builder the importance of, and ways of, achieving this objective.

While building tightness is measurable by the 'fan-pressurisation method' (Perera 1990), this is not generally useful as a tool for producing a tight building since the building has to be built before it can be tested. The technique does however allow standards of tightness to be defined (and checked) and for the effectiveness of various sealing strategies to be compared, particularly by researchers. Where air tightness standards exist in current national codes they generally refer only to dwellings (AIVC Technical Note 43).

Practical guidance on how to construct a tight building is sparse. In general, a continuous polyethylene vapour barrier will result in a tight wall structure whereas brick or block walls tend to be leaky unless sealed by being wet-plastered. Leakage sites are generally associated with edges, corners and the joints between dissimilar materials such as wood and masonry. Sealing techniques need to be as durable as the materials being sealed and must survive relative movement between structural elements where this may take place.

9.3 Materials Used

The building itself may also be a source of pollution and so low-polluting construction and furnishing materials must be specified since it is much more efficient in every sense to omit a source of pollution than to remove the pollutant from the air in the building.

However, the data required to make an informed choice of materials is not readily available, but a recent European collaborative project has taken the first steps in providing a database of materials and their emissions and considerable research work is in progress to measure pollutant emissions from building components and materials (Clausen 1997).

With the aim of minimising sources of pollution the building should be designed to be easily cleaned. Dust collecting on ledges and other horizontal surfaces and the possibility of mould growth on condensation sites which may be out of sight but nevertheless in contact with the occupied space can add to the ventilation needed to provide acceptable air quality.

9.4 Procedure

Liddament (1996) has considered ventilation system design in terms of needs, constraints and design variables. This is illustrated in Figure 9.1. The needs of comfort and acceptable IAQ have to be achieved at an acceptable cost and reliability by choosing appropriate values of the design variables subject to a number of constraints some of which are natural and others imposed. There is no unique solution.

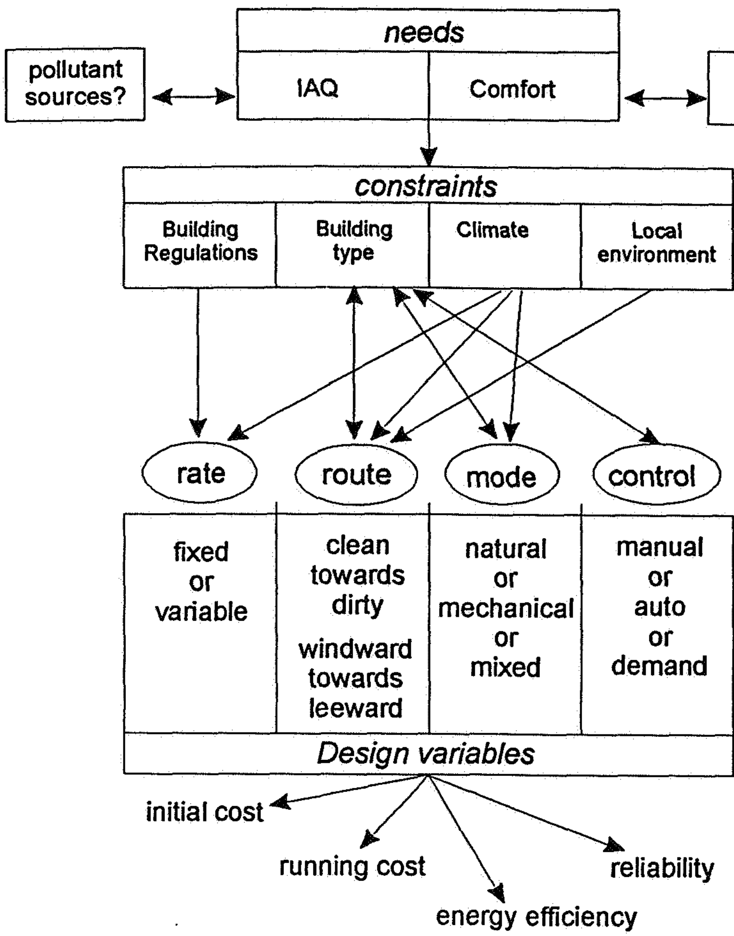


Figure 9.1 The design process in terms of needs, constraints and design variables

9.5 Route

The ventilation of large enclosures is a very open subject and there are no specific design procedures other than an extension of the principles applied to the ventilation of smaller spaces.

The ventilating route should be from less contaminated towards more contaminated places and the extract should be where the air is most contaminated. This is more easily achieved for a mechanical system.

Natural ventilation relies on wind and buoyancy forces to drive air through deliberate or fortuitous openings in the structure. The air flow route will change with the weather and the implications of this on the indoor air quality must be considered.

Wind induced ventilation acts across the building, although wind induced single-sided ventilation occurs due to turbulence. Temperature or buoyancy induced ventilation (stack effect) encourages air to enter the building at low levels and leave the building at high level. There has to be a possible air route within the building from inflow openings, through the occupied spaces, to the outflow openings.

Once the intended flow strategy is decided the design steps are to select and locate:

- inlet devices
- outlet devices
- flow-path elements

The flow components must then be sized to achieve the required air flow under the driving pressures calculated from weather data and building geometry.

Night ventilation for cooling may require different flow paths from day-time ventilation for air quality, particularly if the aim is to cool the structure.

9.6 Ventilation Rate

The ventilation requirements may vary from space to space within the building depending on the number of people and what they are doing. The ventilation rate must be chosen to achieve acceptable air quality without excessive energy use. Current guidelines are generally in the range 0.5-1 ac/h or 7-10 l/s of fresh air per person (Limb 1994c). Summer ventilation for cooling will require much larger rates.

Ventilation at higher than the minimum rate has an energy penalty in the heating season whereas in the cooling season the rate may be increased to utilise 'free cooling' using outside air if this is cooler than the inside temperature.

9.7 Control

The ventilation rate can be controlled by the people using the space opening or closing windows, or it may be completely handed over to an 'air quality sensor' linked to fans and dampers. The larger the building, the more likely it is that automatic control is appropriate, for comfort, energy and practical reasons.

Manual control must be user-friendly and easy to understand with sufficient feedback that the effect of any action is clear to the person initiating the action.

Automatic control requires a decision on what to use as the control parameter. While the aim of the ventilation system may be to reduce odours to an acceptable level, the easiest pollutants to predict are moisture and carbon dioxide. They are both easily measured and are therefore frequently used to control ventilation systems. Carbon dioxide is appropriate when the main pollutants are believed to arise from the occupants, moisture control is used when moisture producing activities occur in the building. If summer overheating is the main reason for ventilating, then temperature sensors may be appropriate to control ventilation openings.

9.8 Scale Models

The testing of ventilation principles on scale models is cheaper and more practical than full scale tests. Flow visualisation e.g. using smoke makes physical models useful tools for illustrating concepts. Most scale models use air as the fluid but this is not essential and highly successful studies have been carried out using salt bath models in which differences in density between salt solutions permit buoyancy driven flows to be simulated on a laboratory scale (Kiel 1986).

Are scale tests valid? A similar flow will be obtained in a full size enclosure and scale model (Nielsen 1993) if the dimensionless boundary conditions and certain dimensionless numbers (Archimedes, Reynolds and Prandtl) are the same, but this is not practically possible. However in turbulent flow conditions it is feasible to make valid model experiments by keeping only the Archimedes number (the ratio of buoyancy to momentum forces) constant.

The Danish Pavilion (Nielsen 1995) was modelled at 1/10 scale. The height of the end wall inlet device was taken as the characteristic length and the supply air flow divided by the area of the inlet device as the reference velocity. The modelling exercise showed that the air velocity in the occupied zone was similar to the face velocity at the inlet, scarcely varying with distance from the inlet and the air velocity decreased with height, which was confirmed by smoke tests which showed that cool incoming air moved horizontally along the floor. The model also showed that alternative locations for the return opening and a non-uniform temperature distribution on the supply device had no effect on the air velocities. On site measurements on the completed building were in agreement with the predictions of air speeds of 0.6m/s in the occupied zone.

Models for wind tunnel testing to establish wind pressure coefficients on the outside of buildings do not have to satisfy these scaling criteria since averaged pressures do not vary substantially with changes in length scales. However the arrangement in the wind tunnel should be such that (Perera 1988),

- the velocity in the air stream increases with height similarly to that in the atmospheric boundary layer flowing over a terrain similar to the site
- the distribution of scales of turbulence in the wind tunnel is similar to that in full scale
- the size of the turbulent eddies is reduced to match the model size.

The scale of the model will be dictated by the amount of detail that needs to be modelled and the practicalities of placing the surface pressure tappings. A scale of 1:150 was used for the Crown Court at Canterbury, UK.

9.9 Mathematical Models

In order to calculate the resulting air flows into and out of a building the location and size of the leakage paths is required. For all but the simplest buildings in open surroundings, the determination of surface wind pressure coefficients will require wind tunnel tests. The total leakage and the air flow paths are likely to be unknown, and a 'best guess' will have to suffice perhaps based on pressurisation test data for similar buildings. Since the air pressure inside the building is not known, an iterative procedure can be used to find the unique value of internal air pressure which will satisfy a mass balance for inflow and outflow of ventilating air. The ventilating air flows can then be calculated for any chosen wind speed and direction.

Relating calculated ventilation rates to likely actual rates requires a knowledge of the frequency of different weather conditions on the actual site as defined by wind speed, wind direction and outside air temperature.

9.10 CFD

Computational Fluid Dynamics (CFD), by enabling the solution of thousands of simultaneous fluid flow equations, makes it possible to calculate flow and temperature patterns in a space, and produce attractive and convincing flow diagrams. Figure 9.2 (Cohen 1996) shows the naturally ventilated auditorium of Figure 3.1. It can also predict pollutant distributions and allows different ventilation strategies to be compared more quickly and cheaply than by building physical models. While there remain some uncertainties about some of the details of the procedures such as turbulence modelling, natural convective heat transfer at surfaces and treatment of radiation it is widely accepted that CFD codes can predict room air movement with sufficient realism to be useful in design practice (Schild 1995) provided that sound engineering judgement is exercised in their interpretation.

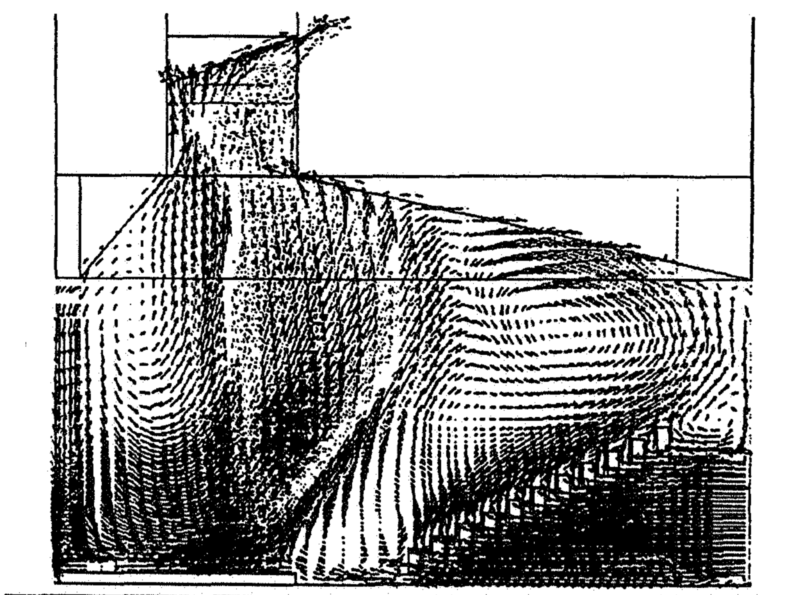


Figure 9.2 CFD air flow modelling

For very large enclosures such as atria CFD permits possible problems of draughts and thermal discomfort to be identified and avoided at the design stage. However, infiltration driven by wind and stack effects is not easy to model. As an example (Kato 1995) a tall narrow glass-covered atrium (30 x 14 x 130m high) sandwiched between a pair of high rise (~30 storey) buildings was modelled in three dimensions. The atrium was open to the adjacent offices spaces which were air-conditioned. Open bridges cross the void space at every floor. The CFD grid of cells for calculation was 50 x 32 x 220 = 352000 and each solution took 50 hours to converge. The CFD analysis coupled with a long wave radiation exchange simulation, to model the effect of solar heating, showed that while, in summer, ventilation of the upper part of the atrium is effective in preventing overheating, in winter large scale recirculation in the atrium results in a strong downdraught at the bottom of the cooled side of the atrium.

If a 2-dimensional simulation is adequate then it will be much quicker and cheaper than 3-dimensional. As an example, the Danish Pavilion was the subject of a 2-dimensional CFD simulation at full-scale along a vertical section parallel to the long length. The unidirectional air flow in the main part of the hall found in the scale model was confirmed as was the height of maximum velocity and the magnitude of the velocities.

9.11 Multi-Zone Modelling

Real buildings are subdivided into interconnecting spaces, many of which also connect to outside. Such multi-zone modelling can also be used to investigate the effect of window and vent opening and predicting air flow rates in natural ventilation ducts. When coupled to a thermal model they can predict heat loss and temperature distributions in a complex building.

One such model is COMIS (Conjunction Of Multizone Infiltration Specialists) which solves a network of equations representing air flows between individual rooms of a building and between inside and outside (Liddament 1996). The flow paths between zones may be purpose-provided such as doors, windows and vents or they may be the accidental gaps that occur in most buildings. These air leakage flow paths are the input data to the programme and the validity of the prediction will be very dependent on how well the leakage paths can be defined. These programs are becoming more user-friendly by incorporating databases of leakage data within the software packages.

9.12 Role of Computer Modelling

Calculation methods are much cheaper and quicker than physical models for checking the performance of ventilation systems which have yet to be built. They also permit checking of performance in all weather conditions.

Pollutant concentrations and energy use can be estimated.

The main problems are associated with defining the input data but this is becoming less of a problem as more data is collected. A useful summary of calculation methods is given in the AIVC Guide to Energy Efficient Ventilation (Liddament 1996).

10. Performance Measurements

10.1 General

It may be surprisingly difficult to determine whether a ventilation system is working as intended. Air movement can be seen only by using a visual tracer such as smoke. Air speeds within buildings are very low and constantly varying in speed and direction. Flow measurements in ducts are time consuming and subject to large uncertainties. The measurement of actual ventilation rates requires time consuming and skill-requiring tracer gas measurements. There are many different spaces that exchange air with each other and with outside. In large enclosures conditions are unlikely to be uniform throughout the space, so where does one place the measuring device?

The main questions to be answered are:
- Are the required ventilation rates being achieved?
- Is the fresh air coming into the space being used efficiently?
- Are contaminants being removed effectively?

10.2 Commissioning

The first opportunity to find out whether the system can be made to work is the commissioning stage, sadly often curtailed through lack of time.

The main requirements are:

- The system should be clean
- Ductwork should not leak
- All the individual components should work
- Airflows to each terminal should be as designed
- The room air flow pattern should be as envisaged
- There should be no draughts
- Air temperatures should be acceptable
- Documentation should be comprehensive and complete.

In a mechanical system most of the effort will be addressed at setting the air flow rate and pattern at each terminal. For a natural ventilation system, check that all openable vents move freely and use a smoke tracer to check flow direction.

10.3 Flow Visualisation

The quickest and also one of the best ways to check out a system is by a 'smoke test'. It permits identification in a qualitative way of what is going on. Video and still camera recording is feasible, and for best results the smoke should be back-lit against a dark background, Figure 10.1.

Smoke is available from one-off candles or from portable generators. It is convenient and quick but very soon it obscures the detail which it is aimed at showing. It can deposit dirt and be unpleasant for the operatives and is not applicable to occupied buildings except in very small quantities.

Alternative indicators used mainly by researchers include:

- Soap bubbles blown with a helium-air mixture to give neutral buoyancy have been used in full scale laboratory tests (Carpenter 1972). These have a longer useful life than smoke and lend themselves well to photographic recording, but are rather messy in real buildings.
- Neutrally buoyant balloons are clean and lend themselves to tracking procedures using multiple video cameras (Alexander 1994). They have been successful in following air movement in large spaces for several tens of minutes and indicating air velocities and regions of recirculation and stagnation.

Figure 10.1 Smoke test in an office

10.4 Tracer Gas Measurements

The only way to measure the actual amount of fresh air reaching the people in a building is by use of tracer gases. The simplest techniques are based on measuring the dilution rate of a tracer gas which has been uniformly mixed with the air in the room. For details refer to the AIVC Measurement Techniques Guide (Charlesworth 1988).

These techniques have evolved into ways of measuring local air exchange efficiencies, the spread of pollutants and complex air flow patterns within buildings using multiple tracer gases. The measuring techniques are used mainly by researchers since they are time-consuming and intrusive.

The PFT (Per Fluorocarbon Tracer) technique uses small (30mm x 6mm diameter) continuously emitting sources which are placed in the building for several hours, days or weeks. The resulting tracer concentration in the building, which is related to the ventilation rate, is measured using tracer adsorption tubes. This provides a measure of the mean ventilation rate over the duration of the test. The method is applicable to large and multicell buildings (Stymne 1991).

Tracer gas measurements are expensive and often inconclusive. An acceptable quick and simple test is to monitor the carbon dioxide concentration in the return air or in the room over a few hours or even days. Concentrations much above 1000ppm indicate inadequate ventilation. The rate of CO_2 decay when all the people leave the building provides a way of measuring the ventilation rate with very simple apparatus.

10.5 Air Flow Rate Measurements

The traditional way of measuring air flow rate in a duct is the so-called Pitot traverse. In practice, it is often difficult to obtain well -behaved flow conditions due to bends and obstructions in the ductwork and although uncertainties of 5-10% may be claimed, errors of $\pm$ 30% are quite likely under real conditions.

Dilution of a tracer gas is a more reliable technique for measuring flow rates in ducts but the equipment is more complicated and rather specialised. For more details on individual techniques refer to AIVC Technical Note 34 (Roulet 1991).

Flow hoods can be used at air terminals, but the pressure drop introduced by the device can change the flow rate which is being measured. Zero pressure drop flow hoods are available with a small fan which is adjusted to give zero pressure drop across the device and hence measures the true flow (ACIN 1986). Leakage testing by a fan pressurisation does not directly measure ventilation rate but is a useful step in the estimation of infiltration rates for existing buildings up to a volume of about 10,000m^3 (Perera 1990).

10.6 Questionnaires

The most sensitive and important measuring instrument for finding out whether a system is performing OK is to ask the people using the building, using a self-completion questionnaire. In many ways it is also the simplest.

Questionnaires are generally aimed at measuring the incidence of Sick Building Symptoms (lethargy, headaches, eye and respiratory symptoms) where a symptom is counted if it has been experienced twice or more in the previous twelve months and the symptoms disappear soon after leaving the building. An example of a suitable questionnaire is that used in the UK for a major sick building investigation (Wilson 1987).

11. Overview

11.1 General

The objective of a ventilation strategy is to provide the users of the building with a comfortable and healthy environment appropriate to the tasks carried out in the building. All possible sources of pollution, both within and outside the building, must be identified and all possible steps taken to minimise the generation of these pollutants - this is referred to as "source control".

The next step is to decide what are acceptable concentrations of the remaining pollutants and, if the production rate is known, calculate the required ventilation rate. This is an idealised scenario which can seldom be applied in its entirety, since pollutant emission data is sparse, and in many cases the design ventilation rate will be based on past experience and empirical data.

The choice between natural or mechanical ventilation will depend on how critical the indoor environmental conditions are, the pollutant source strengths (including thermal) and on the geographical situation.

Historically, natural ventilation traditions exist in all countries with more complex strategies evolving to address local climatic and lifestyle needs. Natural ventilation systems may suffice for narrow low buildings in temperate climates. Mechanical ventilation, made possible by the introduction of electrically driven fans, permits control of both the rate and route of ventilating air flows almost independent of the climate. Heat recovery from the stale warm outgoing air is feasible if the space is mechanically ventilated.

In climates with relatively mild winters and cool summers, there are moves away from 'unnecessary' air-conditioning and towards natural ventilation for both health and energy reasons. However, the rapid growth of computers and associated hardware has resulted in a cooling requirement all the year round which natural ventilation has difficulty coping with. A further confounding factor is that external pollution from traffic and internal pollution from building materials have both increased.

11.2 Energy Efficiency

Approximately 30% of the energy supplied to a building is dissipated in the outgoing ventilating air flows. As building standards improve thermally this proportion increases. Energy conservation is highly desirable politically and economically and so it is likely that energy-efficient ventilation systems will be seen as the norm. However the effect on health and comfort has to be considered (Liddament 1996) if saving energy results in lower ventilation rates.

A well-designed heat recovery ventilation system installed in a tight building can recover up to 80% of the energy which would otherwise be thrown away. Heat recovery techniques for natural ventilation are difficult because of the low driving pressures but will be developed (Schultz 1994) as part of the move away from mechanical systems.

11.3 Control

Improved control is technically feasible and desirable for both energy and user satisfaction reasons. Demand control using electronic noses and air quality sensors will provide better indoor environments while minimising energy costs. Office workers are believed to work better when they can control their local comfort conditions (Kroner 1994) and this is likely to be seen as both desirable and feasible.

11.4 Natural Ventilation

In temperate climates air-conditioning is becoming seen as wasteful of energy and not always providing an environment which is perceived to be healthy. Improvements in computer modelling techniques are now making it easier to design more ambitious naturally ventilated buildings. It is likely that a mixed-mode approach will be the best way forward for many buildings with the mechanical facility being used only when necessary.

11.5 Non-Mixing Ventilation

Large enclosures naturally stratify and the mixing ventilation systems so common in smaller spaces are no longer appropriate. Localised targeted fresh air supply and extract ventilation coupled with displacement type flow patterns and possibly air curtains to form 'environmental islands' within large spaces will replace fully mixed systems providing an improved environment at lower energy cost.

11.6 System Design

As computer modelling techniques become more accessible the evaluation of unusual solutions to new ventilation problems becomes less uncertain. The move towards natural ventilation in temperate climates is likely to continue, particularly if thermal loads decrease owing to advances in information technology equipment.

11.7 Where Now?

Some very large enclosures have been postulated where the aim is to control the climate. One Japanese author (Murakami 1992) is predicting structures accommodating 100,000 people as 'indoor cities'. But the immediate need is for an energy efficient ventilation strategy for 'normal' buildings. Accepting that designing for efficient ventilation is part of the architecture of the building is the most important starting point.

Buildings must be designed to ensure that a fresh air route into the occupied part of the building is planned and controllable and that stale or polluted air is removed without contaminating clean air. A lot of ventilation is associated with removing surplus heat, therefore the problems associated with providing ventilation are easier if:

- computers and associated machinery automatically switch over to standby mode when not in use
- solar shading is designed into the external structure of the building
- low energy lighting is installed which is switched off when not required.

Not all steps forward in ventilation are made by engineers and architects. One of the most significant recent events resulting in improved indoor air quality in many public and commercial buildings has been the introduction of 'no smoking' policies.

Legislation is likely to be aimed at saving energy, which may conflict with the requirements for acceptable indoor air quality if this results in lower fresh air ventilation rates. The response of the engineer must be to improve the ventilation efficiency thus obtaining better conditions with less fresh air. This is both a design and a control challenge, but fortunately the tools available are becoming better, cheaper and more accessible.

11.8 Build Tight-Ventilate Right

Large non-domestic buildings are often used intermittently and the environmental control is frequently not in the hands of the end users. Mistakes in design and operation are potentially expensive in energy and lost productivity. Whatever ventilation strategy is adopted the building shell needs to be sufficiently air-tight that infiltration, as an energy cost, is negligible. The rate and route of the ventilating air flows can then be matched to the needs of the end users in a predictable and controllable way.

12. References

ACIN, *Flow Finder Model 153 for measurement of air flows at grilles*, ACIN, 1986.

Aiulfi D, van der Maas J, Natural ventilation in an auditorium: the role of thermal storage in the energy consumption and comfort of De Montfort University auditorium, *Roomvent '96 Proceedings*, Volume 2, pp 291-298, 1996.

Alexander D K, Jones P J, Jenkins H, Harries N, Tracking air movement in rooms, Air Infiltration and Ventilation Centre, *15th AIVC Conference Proceedings*, Volume 2, pp483-492, 1994.

Alexander D, Jenkins H, Jones P, The effects of building form on the natural ventilation of commercial buildings, Air Infiltration and Ventilation Centre, *17th AIVC Conference Proceedings*, Volume 2, pp 571-578, 1996.

Arens E A, Bauman F S, Johnston L P, Zhang H, Tests of localized ventilation systems in a new controlled environment chamber, Air Infiltration and Ventilation Centre, *11th AIVC Conference Proceedings*, Volume 1, pp 99-130," 1990.

Ashley J A, Lagus P L, Air infiltration measurements in large military aircraft hangars, *ASTM Special Technical Publication* 904, p120-134, 1986.

Bennett K M, Efficient humidification in buildings, Building Services Research and Information Association, *BSRIA Application Guide* AG 10/94.1, 1995.

British Standards Institution, Code of Practice for design of buildings : ventilation principles and designing for natural ventilation, BS 5925:1980.

Carpenter G A, Moulsley L J, Randall J M, Ventilation investigations using a section of a livestock building and air flow visualisation by bubbles, *J Agric Engng Res*, Vol 17, pp323-331, 1972.

CEN, Ventilation for buildings - Design criteria for the indoor environment, CEN pr ENV 1 752, 1994.

Charlesworth P S, Air exchange rate and airtightness measurement techniques- an applications guide, *AIVC Technical Guide 2*, 1988.

Clausen Geo, de Oliveira Fernandes E. (editors). European data base on indoor air pollution sources in buildings. *E C JOULE II Programme* (Energy Conservation and Utilisation) Final report in preparation 1997.

Cohen RR, Davies R M, Standeven M A, Natural ventilation design for a concert hall, , Air Infiltration and Ventilation Centre, *17th AIVC Conference*,Vol 2, pp468-475, 1992.

Colliver D G, Energy requirements for conditioning of ventilating air, , Air Infiltration and Ventilation Centre, *Technical Note 47*, 1995.

Dickson D, A testing time for chilled ceilings, *Building Services*, June 1994.

Dickson D, Collins P, Healthy building: an energy efficient air conditioned office with good indoor air quality, Air Infiltration and Ventilation Centre, *13th AIVC Conference*, pp23-31, 1992.

Drangsholt F, Lecture Hall at NTH Trondheim (Norway), Demand Control Ventilation Systems Case Studies, pp157-177, *International Energy Agency Annex 18*, 1992.

Fanger P O, International trends in ventilation standards, *Healthy Buildings 95*, Milan, pp 257-263, 1995.

Heiselberg P, Overby H, Bjorn E, Energy efficient measures to avoid downdraft from large glazed facades, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

Irving S J, Air to air heat recovery in ventilation, Air Infiltration and Ventilation Centre, AIVC *Technical Note 45*, 1994.

Irving S, Ventilation and cooling, Air Infiltration and Ventilation Centre, *Technical Note Draft, 1996.*

Kato S, Murakami S, Shoya S, Hanyu F, Zeng J, CFD analysis of flow and temperature fields in atrium with ceiling height of 130m, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

Kiel D E, Wilson D J, Gravity driven flows through open doors, Air Infiltration and Ventilation Centre, *7th AIVC Conference*, p15.1-15.15, 1986.

Kroner W M, Stark-Martin J A, Environmentally responsive workstations and office-worker productivity, *ASHRAE Transactions*, Vol 100, Pt 2, preprint, 1994.

Lanting R W, Air pollution in archives and museums: its pathways and control, *Indoor Air '90*, Volume 3, pp 665-670, 1990.

Lawrence G V, Waters J R, Measurements of infiltration and air movement in five large single-cell buildings, Air Infiltration and Ventilation Centre, *8th AIVC Conference*, p2.1-2.18, 1987.

Leaman A, Cohen R, Jackman P, Which ventilation system?, *Building Services*, February, pp 37-39, 1995.

Liddament M, Annex 23 Multi-Zone Air Flow Modelling (COMIS), *Air Infiltration Review, Vol 17*, No 4, pp10-12, 1996 a.

Liddament, M, A Guide to Energy Efficient Ventilation, Air Infiltration and Ventilation Centre, 1996 b.

Limb M, Ventilation and Building Airtightness: an International Comparison of Standards, Codes of Practice and Regulations, *Air Infiltration and Ventilation Centre, Technical Note 43*, 1994 a.

Limb M, Garage Ventilation: An annotated bibliography, Air Infiltration and Ventilation Centre, 1994 b.

Limb M, Current ventilation and air conditioning systems and strategies, , Air Infiltration and Ventilation Centre, *Technical Note 42*, 1994 c.

Mansson L G, Svennberg S, Demand Controlled Ventilating Systems Source Book, *IEA Annex 18*, 1992.

Morgan H, Gardner J P, Design principles for smoke ventilation in enclosed shopping centres, *Building Research Establishment* report, BR 186, 1990

Murakami S, Prediction, analysis and design for indoor climate in large enclosures, *Third International Conference*, Aalborg, Denmark, Volume 1, pp 1-30, September 2-4, 1992.

Murakami S, Prediction, analysis and design for indoor climate in large enclosures, *Roomvent '92*, Volume 1, pp 1-30, 1992.

Nicol F, Humphreys M, Sykes O, Roaf S (Editors), Standards for thermal comfort: indoor air temperature standards for the 21st century, UK, *Chapman and Hall*, 1995.

Nielsen P V, Airflow in a world exposition pavilion studied by scale-model experiments and computational fluid dynamics, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

Nielsen P V, Airflow in a world exposition pavilion studied by scale-model experiments and computational fluid dynamics, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

Nielsen P V, Model experiments for the determination of airflow in large spaces, *Indoor Air 93*, Volume 5, pp 253-258, 1993.

Norell 1993, Demand-controlled ventilation in a school, Demand Controlled Ventilation Systems Case Studies, *IEA Annex 18*, pp 137-153, 1993

Perera M D A E S, Shaw M R, Treadaway K, Naturally ventilating UK non-domestic buildings: status and future policy, Indoor Air Quality, Ventilation and Energy Conservation in Buildings , *Second International Conference*, Volume I, pp273-280, 1995.

Perera M D A E S, Tull R G, Envelope leakiness of large, naturally ventilated buildings, Air Infiltration and Ventilation Centre, *10th AIVC Conference*, Volume 1, pp413-428 1990.

Perera M D A E S, Walker R R, Tull R G, Natural ventilation for crown court: developing statistical assessment techniques at the design stage, , Air Infiltration and Ventilation Centre, *9th AIVC Conference*, 1988.

Reinikainen L, Jaakola J J K, Seppanen O, The effect of humidification on symptoms and environment of complaints in office workers, an experimental study, *Helsinki University of Technology, Finland, HVAC-Laboratory, Series B26*, February 1990.

Roulet C-A, Vandaele L, Air flow patterns within buildings: measurement techniques, Air Infiltration and Ventilation Centre, *Technical Note 34*, 1991.

Schild P G, Tjelflaat P O, Aiulfi D, Guidelines for CFD modeling of atria, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

Schultz J M, Saxhof B, Natural ventilation with heat recovery, *Air Infiltration Review*, Vol 15, No 4, 1994.

Strongin A S, Aerodynamic protection of hangars against cold ingress through apertures, *Building Serv Eng Res Technol*, Vol 14, No 1, pp 13-16, 1993.

Stymne H, Eliasson A, A new passive tracer gas technique for ventilation measurements, *12th AIVC Conference*, Ottawa , 24-27 September 1991.

Tjelflaat P, DIA - Jeppesen Terminal Building, Annex 26 seventh expert meeting in Dresden, October 10, 1995.

van der Maas J, Schaelin A, Application of air flow models to aircraft hangars with very large openings, Air Infiltration and Ventilation Centre, *16th AIVC Conference*, Volume 1, pp 127, 1995.

Walker R R, Perera MDAES, Designing for natural ventilation: law courts, *CIBSE National Conference*, UK, pp 201-205, 1991.

Whitley T, Makin , Dickson D, Organisational and job factors in sick building syndrome: a critique and some suggestions for future research, *Healthy Buildings 95*, pp 1469-1474, 1995.

Willis S, Fordham M, Bordass B, Avoiding or minimising the use of air-conditioning, *BRECSU, UK*, 1995.

Willis S, Keeping control of comfort, *Building Services*, February 1995, p 43.

Wilson S, Hedge A, The office environment survey: a study of building sickness, *Building Use Studies Ltd*, London, 1987.

Yaglou C P, Witheridge W N, Ventilation Requirements (part 2), *Ashrae Trans*, Vol 43, pp 423-436, 1937.

Yoshino H, Ito K, Aozasa K, Trends in thermal environmental design of atrium buildings in Japan, *Ashrae Transactions*, Vol 101, Pt 2, preprint, 1995.

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