INTERNATIONAL ENERGY AGENCY
Energy conservation in buildings and
community systems programme

Technical Note AIVC 57

Residential Ventilation

Air Infiltration and Ventilation Centre
Operating Agent and Management
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Residential Ventilation

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Belgium, France, Greece, the Netherlands, Norway and the United States of America.

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 in 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 also 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 *
XII	Windows and Fenestration *
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 Ventilation 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 Residential 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 Systems Performance *
XXXV	Design of Energy Hybrid Ventilation (HYBVENT)
XXXVI	Retrofitting of Educational Buildings
XXXVII	Low Exergy Systems for Heating and Cooling of Buildings
XXXVIII	Solar Sustainable Housing
XXXIX	High Performance Insulation systems (HiPTI)
XXXX	Commissioning Building HVAC Systems for Improved Energy Performance

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, France, Greece, Netherlands, Norway, and the United States of America.

Disclaimer

Executive Summary

Ventilation is required to provide to remove or dilute pollutants and incidentally meets metabolic oxygen requirements for occupants. In addition ventilation may also be required to provide oxygen for combustion devices and as a means of summer cooling.

It is estimated that, within the OECD countries, around 28EJ of energy is consumed in residential dwellings, of which around 12EJ is associated with ventilation. Calculations suggest that it may be possible to reduce this energy consumption associated with ventilation to less than 1EJ. It is therefore important to ensure that the need for ventilation within dwellings is met with the minimum of energy consumption.

A wide range of systems are used to provide ventilation in dwellings. Each system has advantages and disadvantages and therefore the applicability of any one system will depend on a number of local factors such as climate or standards.

Work undertaken as part of Annex 27 has found that natural ventilation remains the most common ventilation method in OECD countries. Countries with cold climates have a more rigorous approach to building air tightness and ventilation systems that offer good control such as balanced mechanical systems with heat recovery. Milder and moderate climates favour ventilation systems with less control, usually natural. However, there is now a move towards reducing energy consumption by the use of more controlled ventilation methods.

Ventilation and thermal standards will have a significant influence on the energy consumption of ventilation systems. Ventilation standards usually aim to provide the minimum ventilation for metabolic needs and the removal of major indoor pollutants such as moisture. Thermal standards can cover, fabric conduction losses, heating and cooling plant performance and infiltration losses.

Infiltration can have a detrimental effect on both energy consumption and ventilation effectiveness, hence indoor air quality and comfort. Each method of ventilation operates most effectively if the building envelope is constructed to the appropriate air tightness standard for the chosen ventilation method.

Indoor air quality must not be sacrificed in pursuit of reductions in energy consumption. There are a wide range of pollutants, which are derived from an equally extensive number of sources. Source control is the most effect way to avoid problems and regulations aim to achieve this for may major external pollution sources and some internal sources. Other sources can be avoided by correct specification and design. For those sources that cannot be completely avoided, such as moisture production, dilution by ventilation is the only alternative.

Occupant behaviour has been shown to have a significant impact on energy consumption. Annex 8 investigations indicated that occupants used windows to influence indoor air quality and thermal comfort, but with little conscious attempt to minimise energy consumption. Other studies have indicated that there is a correlation between health problems and dissatisfaction with the ventilation system. Calculations have suggested that occupant window opening may increase average ventilation rates by 0.32 ach for natural systems and 0.34 ach for mechanical systems, while studies in Japan suggest that as much as 87% of the total air change rate may be due to occupant behaviour. A set of occupant guidance to provide good indoor air quality and thermal comfort without excessive energy consumption has been provided in AIVC Technical Note 53.

Other design issue that need to be considered when designing ventilation systems include safety, avoidance of external pollution and re-entrainment of extract air, noise, visual appearance, build ability, reliability and cost.

Commissioning for residential ventilation systems is not currently common, but could have a significant impact on system performance. The Swedish Boverket procedure is the only practical performance-orientated approach for system checking currently in use. Work is however, being carried out in Europe as part of the European Commission’s Joule programme (TIPVENT) and in the USA by The Energy Performance of Buildings Group at Berkeley Laboratories.

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1 Introduction

Ventilation is the exchange of stale polluted air with fresh, relatively clean, air (usually from outside). This air change can occur via incidental air paths in the building fabric (usually referred to as infiltration) or via purpose provided routes (usually referred to as ventilation).

Ventilation is required for a number of reasons; to remove pollutants from the indoor environment, to provide oxygen for combustion devices and to provide oxygen for human metabolism.

When ventilation occurs energy will also be transferred between the building and the external environment. It is estimated that ventilation losses are around 33% for the combined residential and service building sectors for 13 OECD countries.

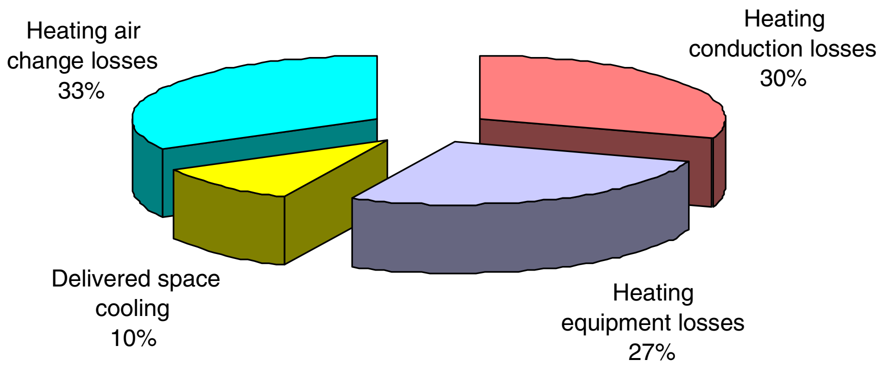

Figure 1.1: Dissipation of Delivered Space Conditioning Energy in the Service and Residential Sectors

Conflicting requirements therefore exist for ventilation between the need to provide fresh air and the need to minimise energy consumption.

This Technical Note aims to provide information on residential ventilation systems and how they can be applied to meet the conflicting needs of fresh air and minimised energy consumption.

As well as considering energy consumption, indoor air quality, occupant interaction with the ventilation system, safety, siting of inlets, comfort, noise, visual appearance, reliability and commissioning are also covered.

2 Ventilation Systems

2.1 Introduction

A wide range of systems are used to provide ventilation in dwellings. Each system has advantages and disadvantages and therefore the applicability of any one system will depend on a number of local factors such as climate or standards.

In all cases ventilation is required to provide metabolic oxygen for occupants and to remove or dilute pollutants. In addition ventilation may also be required to provide oxygen for combustion devices and as a means of summer cooling.

Systems are usually designed to provide a low background level of ventilation to meet the first two of these needs, with some form of boost facility for times when pollutant production is high. This boost facility can often provide for summer cooling as well as pollutant removal. Combustion devices usually require additional provision over and above that for occupants.

2.2 Natural Ventilation

2.2.1 Driving Forces

Natural ventilation relies on two driving forces, wind and temperature difference. Both these forces are variable over time and location and therefore make control of ventilation rates difficult.

Wind striking a building will cause some areas of the building to have a positive pressure and some to have a negative pressure. When suitable paths are offered through the building air will flow from high to low pressure areas.

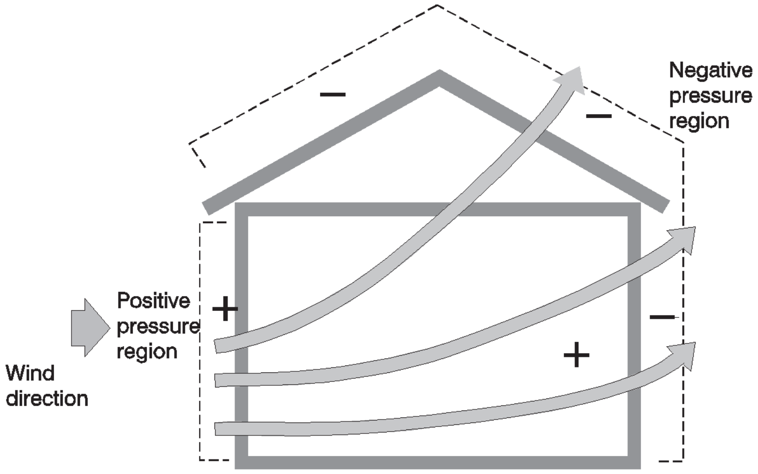

Figure 2.1: Wind Driven Flow

Stack driven airflow uses temperature difference, usually between inside and outside air. Typically air will flow into the building at low level and out of the building at high level. There will be some point within the building where there is no pressure difference, referred to as the neutral pressure level, the position of which will be determined by resistance to flow and temperature differences.

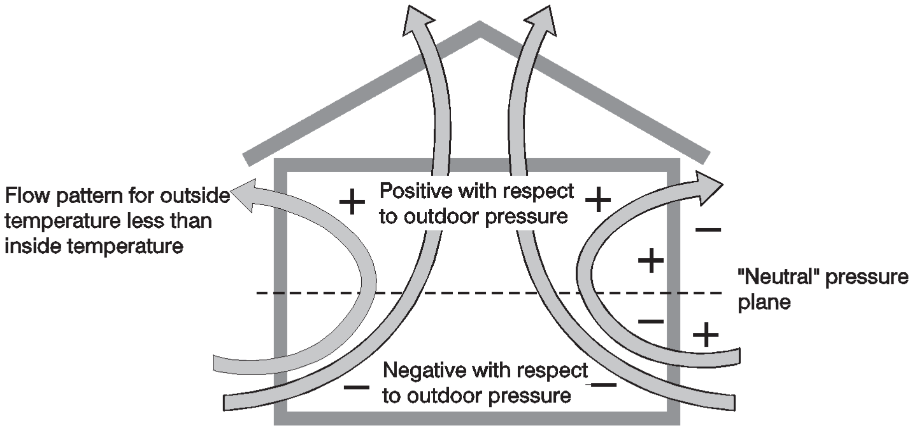

Figure 2.2: Stack Driven Flow

These two driving forces can act together, increasing ventilation rates, or in opposition, thus reducing ventilation rates. The distribution of ventilation may therefore vary with the relative strength of each driving force.

The wind can provide relatively high driving forces compared to stack forces. Figure 2.3 shows that for wind speeds in excess of 3 m/s wind forces will start to dominate natural ventilation systems.

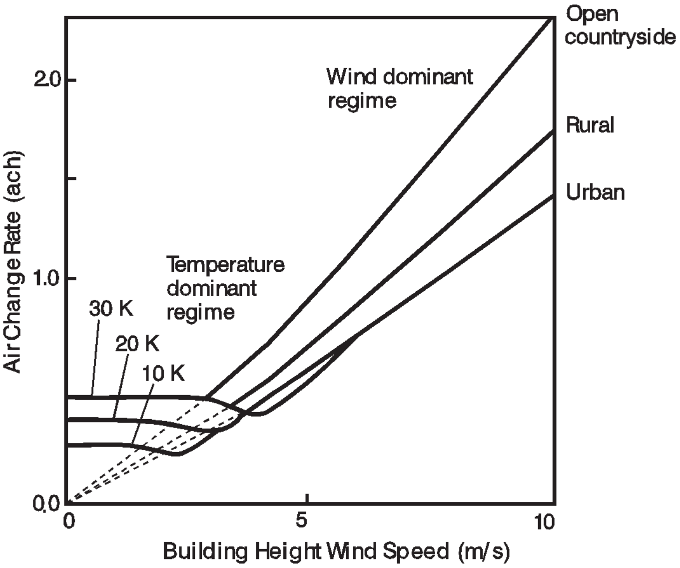

Figure 2.3: Relative Dominance of Wind & Stack Driving Forces

2.2.2 Window Airing

The most basic natural ventilation system relies on infiltration through a leaky building envelope to provide background ventilation with openable windows to provide increased ventilation rates when required.

This offers a very simple and low cost solution to providing ventilation but offers very poor control. Over-ventilation often occurs during the heating season when winds and temperature differences are high leading to higher than necessary space heating energy consumption or discomfort due to cold draughts. During the summer months ventilation rates may be too low due to low wind and temperature differences, leading to high internal temperatures.

This type of system is rarely used to meet minimum ventilation needs in new dwellings but a significant number of existing dwellings still rely on it.

2.2.3 Purpose-Provided

A development of the basic window airing ventilation system is to construct a more airtight building envelope and then provide controllable ventilation openings. These purpose-provided openings can be in the form of trickle vents, hit & miss ventilators or suitably designed windows and are used to provide background ventilation. Window airing is then used to provide increased ventilation rates.

The main advantage of this type of system is the reduction of over-ventilation during the heating season. However, the system is still subject to the relatively poor control offered by dependence on non-consistent natural driving forces.

2.2.4 Passive Stack

Passive stack ventilation is designed to provide better control over ventilation while still relying on natural driving forces.

Passive stacks are incorporated into the building structure to extract air, usually from wet rooms such as bathrooms and kitchens. Fresh air is supplied via purpose provided openings such as trickle vents. The stacks are terminated in the negative pressure region above the roof to utilise wind pressure. Thus airflow is driven up the stack by a combination of inside/outside temperature difference and wind.

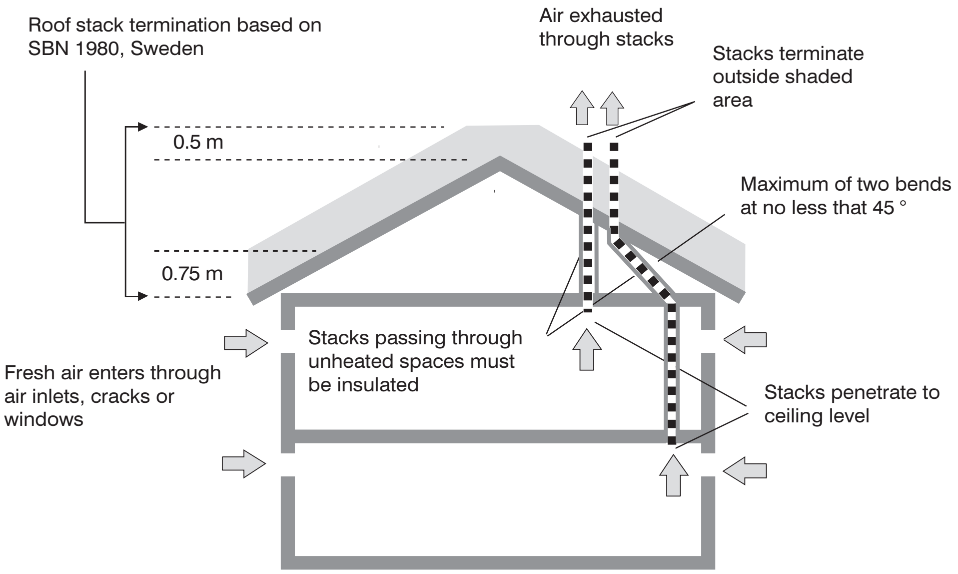

Figure 2.4: Typical Passive Stack Ventilation System Configuration

It is still not possible to achieve uniform ventilation rates with this type of system. Rather they are designed to meet an average ventilation demand.

The driving forces involved are small. It is therefore necessary to ensure that the stacks are design for minimum resistance to ensure adequate ventilation. Good design practice indicates that separate stacks are required for each room from which air is to be extracted. Typical duct diameters are 100mm to 150mm and should have no more that two bends of

45^o or less. Any ductwork that runs through an unheated space should be insulated [BRE IP21/89 in the UK].

2.3 Mechanical Ventilation

Mechanical systems offer much better control over ventilation rates compared to natural ventilation. However, additional energy is required to transport air around the system.

2.3.1 Mechanical Extract

Local mechanical extract is often used in rooms with high moisture or odour production, as a means of rapid purge. Usually these local fans are installed in addition to other natural ventilation mechanisms.

With central mechanical extract, air is extracted from the building creating a negative pressure. This negative pressure induces the flow of fresh ‘make-up’ air into the building via gaps, cracks or purpose provided openings. Air is extracted from wet rooms, bathrooms and kitchens, to prevent moisture migrating from these rooms throughout the building. The ventilation rate can often be increased during times of high moisture production.

Extract systems must avoid creating high negative pressures within the building as this can lead to back-draughts from soil stacks and open flue heating devices.

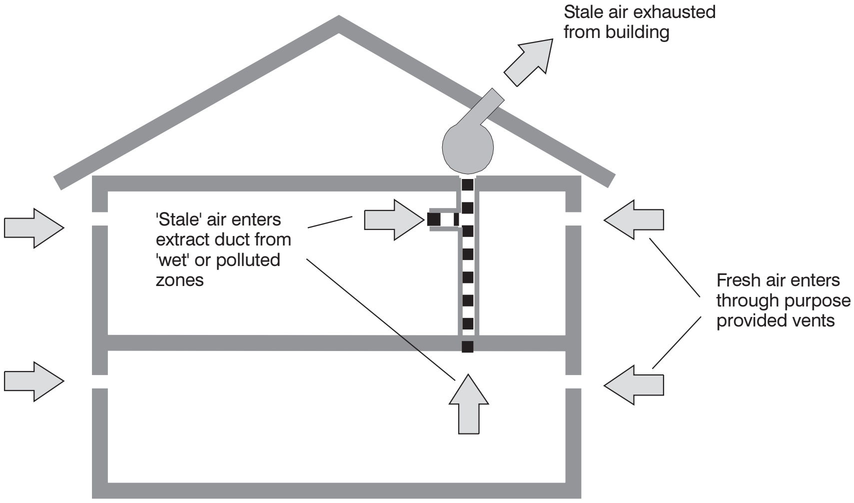

Figure 2.5: Typical Mechanical Extract System Configuration

2.3.2 Mechanical Supply

Mechanical supply systems are similar to central mechanical extract. Air is supplied by a ducted fan causing a positive pressure within the building. This forces stale exhaust air out of the building via gaps, cracks or purpose provided openings. For single-family dwellings air is often taken from loft spaces as a simple pre-heat.

This type of system has been generally considered inappropriate for dwellings as it causes moist air to be forced through, with the attendant possibility of damage to the building fabric. However, it does offer the advantages of being able to filter and pre-heat supply air.

There has been an increase in interest in recent years in the UK in its use as a simple retrofit option.

2.3.3 Balanced

A balanced system consists of an independent supply and extract system. The supply system capacity is commonly 90-95% of the extract system to produce a slight depressurisation of the dwelling. This slight depressurisation prevents moisture being forced into the dwelling structure.

The supply system provides fresh air to the habitable rooms, living room, dining room and bedrooms, with the extract system removing stale exhaust air from the wet rooms, kitchens, bathrooms and toilets. These systems often operate 24 hours per day with boost facility on the extract side for times of high moisture production.

Balanced systems are often fitted with a heat exchanger for recovering heat from the extract air and using it to preheat the supply air. Commonly these heat exchangers are combined with the supply and extract fan in a single unit. Heat recovery efficiencies of 70% are achievable, but the performance of these units is very sensitive to building air tightness.

The advantages of balanced mechanical ventilation systems include: moisture removal at source, pre-filtration of supply air and the potential for heat recovery. Disadvantages include: operating costs, capital costs, noise and maintenance needs.

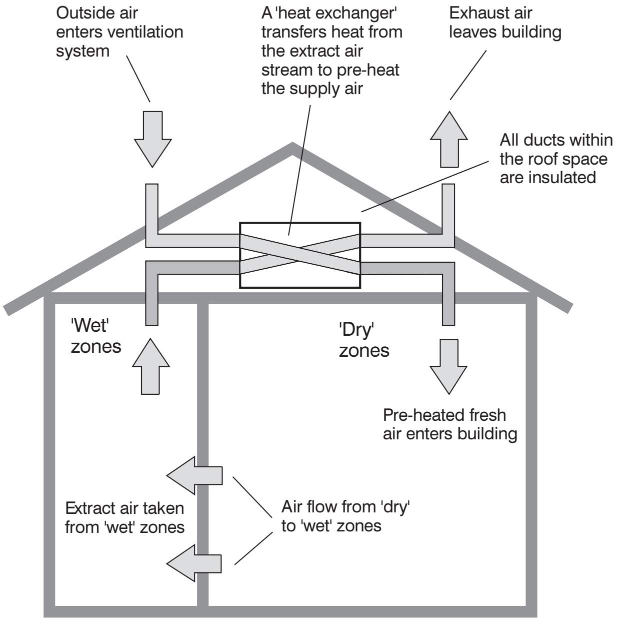

Figure 2.6: Typical Balanced Mechanical System configuration with Heat Recovery

2.4 Prevalence of System Types

Work undertaken, as part of IEA ECBCS Annex 27 [Månsson, 1995], has found that natural ventilation of one type or another, often with additional local fan(s), remains the most common ventilation method in OECD countries. Table 2.1 indicates, for each of the ventilation systems, the proportion used in different countries for existing single and multi-family dwellings.

Mechanical systems are more prevalent in countries with cold climates. However, even here balanced systems make up a relatively small percentage of the total installed systems.

Natural ventilation with additional kitchen extract fans is common in single-family dwellings, while central mechanical extract systems are more common in multi-family than single-family dwellings.

Table 2.1: Distribution of Ventilation Systems in the Existing Dwelling Stock

	Single Family Houses					**Multi Family Houses**				
	Natural			**Mechanical**		**Natural**		**Mechanical**		
	Adv.	**Stack**	**S+Fan**	**Ext.**	**Bal**	**Adv.**	**Stack**	**S+Fan**	**Ext.**	**Bal**
Belgium	100					95	5			
Canada		15	85							
Denmark		50*		48	2		50*		50	
Finland										
France	40	15	20	22	3	40	20	10	30	
Germany										
Italy	80		10	10		75			25	
Japan										
Netherlands		62*		38			37*		63	
Norway			80	15	5		60		30	10
Sweden		12	63	14	11		40		44	16
Switzerland	70		30			40		60		
UK		95*	5				100*			
USA	60			40						

Note:

Based on AIVC – workshop, 1994

** = includes all natural supply & extract ventilation system*

Adv. = adventitious ventilation

Stack = passive stack ventilation

S+fan = purpose provided openings plus extract fans

Ext = mechanical extract

Bal = whole house balance mechanical ventilation

Table 2.2 indicates the proportion of different ventilation systems used in different countries for new dwellings. There is generally a move towards systems with improved control over ventilation rates.

Table 2.2: Distribution of Ventilation Systems in Newly Constructed Dwellings

	Single Family Houses				**Multi Family Houses**			
	Natural		**Mechanical**		**Natural**		**Mechanical**	
	S+ fan	**Stack**	**Ext.**	**Bal**	**S+fan**	**Stack**	**Ext.**	**Bal.**
Belgium								
Canada				100				
Denmark								
Finland								
France		20	75	5	1		99	
Germany								
Italy	80		20		90		10	
Japan								
Netherlands		20	80			20	80	
Norway								
Sweden			80	20			20	80
Switzerland								
UK	100				100			
USA	90	10			90	10		

Based on AIVC – workshop, 1994

For countries with cold climates mechanical ventilation systems dominate the new build market. While most systems are mechanical extract, Canada and Sweden are moving towards significant numbers of balanced systems.

Some European countries with moderate climates are following suite. However, natural ventilation still dominates countries with mild or moderate climates such as Italy, the UK and USA. Better control for these natural ventilation systems is being provided by use of local extract fans in wet rooms and the use of purpose provided inlets.

2.5 Building Air Tightness

Air infiltration is the uncontrolled flow of air into a space through adventitious or unintentional gaps and cracks in the building fabric. The rate of infiltration is dependent on the air tightness of the building and on the driving forces applied across the building envelope. Air infiltration not only adds to the quantity of air entering a building but it may also distort the intended airflow pattern to the detriment of indoor air quality and comfort.

2.5.1 Air Leakage Paths

The common construction methods used for residential buildings are all porous to some extent. In addition, wherever there are joints between building components or between building and service components, then possible air leakage paths exist. Figure 2.7 illustrates the major air leakage paths in dwellings.

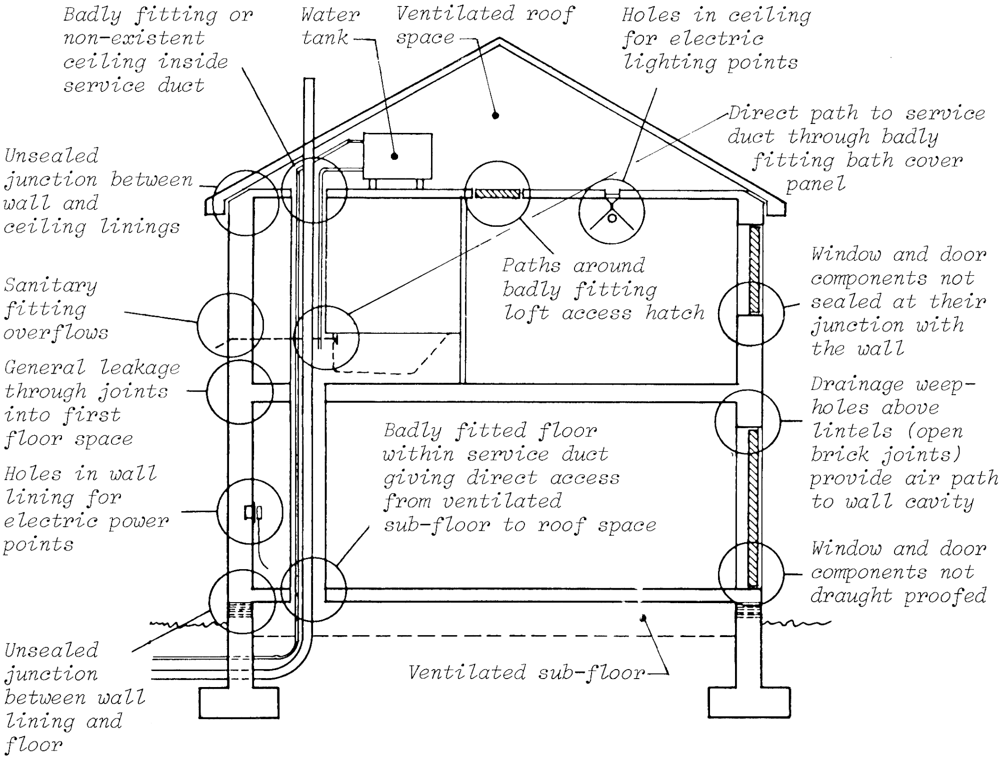

Figure 2.7: Major Air Leakage Paths in Dwellings

Elmroth & Levin [1983] have produced extensive guidance on air leakage and how to control infiltration in housing. Timber frame buildings make use of a physical vapour barrier together with careful sealing around service penetrations, windows and doors to reduce infiltration. Masonry structures can be sealed by either rendering the external surface or, more commonly, plastering the internal surface. Sealing around service penetrations, windows and door openings must also be carried out.

More recent forms of construction such as concrete tunnel form and steel frame require similar measures to be taken to those applied to these two construction types to avoid excessive infiltration.

2.5.2 Influence of Air Leakage

As previously mentioned infiltration can have a detrimental effect on ventilation effectiveness and hence indoor air quality and comfort.

Excessively leaky buildings will lead to high infiltration rates during the heating season when inside-outside temperature differences and wind speeds tend to be high. This will increase the space heating energy lost through ventilation and may well lead to a feeling of cold draughts.

Where mechanical extract ventilation is used in conjunction with an excessively leaky building then infiltration rates will be high with similar results to the naturally ventilated building.

On the other hand, for buildings with mechanical extract systems that are too air tight, high suction pressures may be developed. This can lead to excessive fan power requirements, back-draughts from open flue combustion devices and soil stacks, and under-ventilation. Thus this situation can lead to poor indoor air quality.

Balanced ventilation systems may suffer a reduction in performance when installed in leaky buildings as infiltration will occur when natural driving forces are high, thus overcoming the control offered by balanced systems. The performance of heat recovery devices included in balanced systems is very sensitive to infiltration. High infiltration rates effectively by-pass the heat recovery unit leading to high heat losses while imposing the additional fan power requirement to overcome the resistance of the heat exchanger in the ventilation system.

2.5.3 Air Tightness Appropriate to Ventilation Systems

Each method of ventilation operates most effectively if the building envelope is constructed to the appropriate air tightness standards. However, as previously mentioned, different standards are appropriate to the different ventilation methods.

Figure 2.8 illustrates suggested air tightness values put forward by Liddament & Wilson [1991] for various ventilation systems. There is no advantage in having a very leaky building as this will nearly always lead to cold draughts and uncontrolled ventilation.

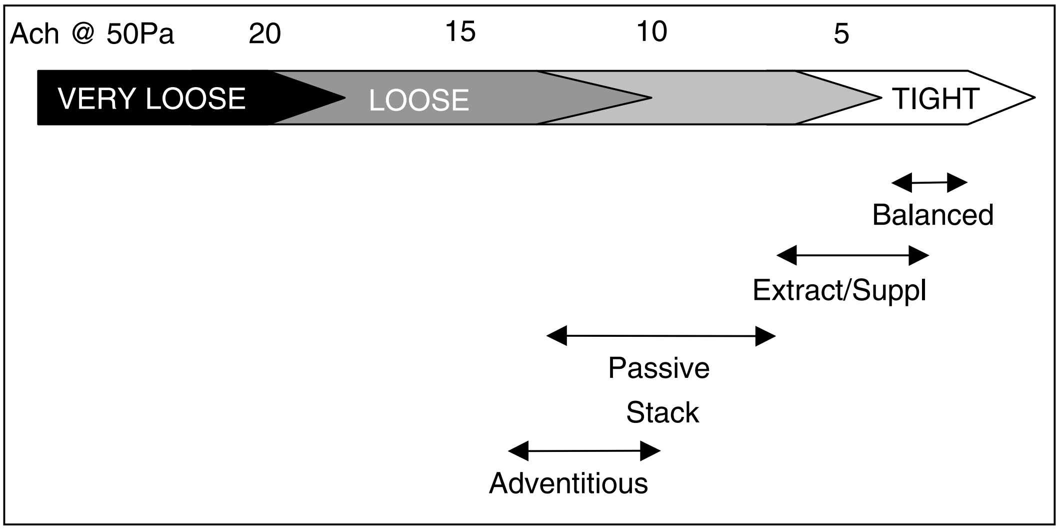

Figure 2.8: Suggested Suitable Air Tightness Levels

2.6 Ventilation Standards

The presentation of ventilation standards varies from country to country. However, ventilation for basic needs form the basis for most requirements. Table 2.3 (pp 13-14), taken from Limb [2001], summarises the current ventilation requirements for dwellings. Some standards are provided as whole house ventilation rates while others specify ventilation rates for specific rooms.

An approximate calculation has been carried out by Limb [1994] to compare the various whole house standards. This shows that minimum whole house ventilation rates vary from 0.3 ach to 1.0 ach.

No comparable calculation has been carried out for individual room ventilation rates. However, common features occur relating to pollutant control at source. The higher extract rates are usually specified for kitchens and bathrooms to ensure removal of moisture. Supply ventilation is usually provided to living rooms and bedrooms for the provision of metabolic oxygen for occupants and for the dilution of occupant produced pollutants such as odour.

2.7 Influence of Climate

Climate has an influence on the choice of ventilation system, as can be seen from the prevalence of different ventilation systems in different countries.

High heating requirements and the potential for severe cold draughts in countries with cold climates have led to a more rigorous approach to building air tightness and ventilation systems that offer good control.

Milder climates favour ventilation systems with less control, usually natural ventilation systems. Heating energy and cold draughts are seldom a problem and summer overheating may present more of a problem. Natural ventilation offers a lower cost solution to mechanical ventilation and the higher ventilation rates may even be an advantage in removing high summer heat gains from dwellings without the need for air-conditioning.

Moderate climates have traditionally also favoured natural ventilation with relatively leaky buildings. However, there is now a move towards reducing energy consumption with improved ventilation control, obtained by tighter buildings and purpose provided ventilation.

Table 2.3: Ventilation Standards in Dwellings

Country & Standard Reference	**Whole Building Ventilation Rates**	**Living Room**	**Bedroom**	**Kitchen**	**Bathroom + WC**	**WC only**
Belgium (NBN D50-001 1991)	1 l/s/m^2 of floor area with specific values for kitchens, wcs & bathrooms	Supply 1 l/s/m^2 Min 75 m^3/h May be limited to 150 m^3/h	Supply 1 l/s/m^2 Min 25 m^3/h May be limited to 36 m^3/h	Exhaust 1 l/s per m^2 Min 50 m^3/h May be limited to 75 m^3/h	Exhaust 1 l/s per m^2 Min 50 m^3/h May be limited to 75 m^3/h	Exhaust 25 m^3/h
Canada (F326, 1-M1989)	>0.3 ach 5.0 l/s/p			Exhaust 50 l/s (inter) 30 l/s (cont.)	Exhaust 25 l/s (inter) 15 l/s (cont.)	
Denmark	0.5 ach	Supply fresh air: Hinged window, hatch or door, together with one or more fresh air valves with a total clear opening of at least 30 cm^2 per 25m^2 floor area		Supply: Hinged window, hatch or door, or fresh air valve. Extraction: volume flow 20 l/s. The air shall be extracted through an extractor hood.	Supply: Hinged window, hatch or door, or fresh air valve. And / or opening to the access. Extraction: Volume flow 15 l/s.	Supply: Hinged window, hatch or door, or fresh air valve. And / or opening to the access. Extraction: Volume flow 10 l/s.
Finland	Exhaust figures air flows can be reduced when the spaces are not in use provided that the air change rate in the whole building is greater than 0.4 ach and min air flow rates in bedrooms and living rooms are fulfilled.	0.5 l/s/m^2	Min 4.0 l/s/person or 0.7 l/s/m^2 floor area	Exhaust air flow 20 l/s	Exhaust 15 l/s	
France				Continuous: 20-45 m^3/h Intermittent: 75-135 m^3/h	15 - 30 m^3/h	15 - 30 m^3/h
Germany	<50m^2 up to 2 occupants Min 60m^3/h Total 60m^3/h <80m^2 up to 4 occupants Min 90m^3/h Total 120m^3/h >800m^2 up to 2 occupants Min 120m^3/h Total 180m^3/h	1.0 – 1.5 ach		Normal 40m^3/h (>12 hr occupation / day) 60m^3/h (overall air flow) Purge 200m^3/h (>12 hr occupation / day) 200m^3/h (overall air flow) Kitchenet 40m^3/h (>12 hr occupation / day) 60m^3/h (overall	40m^3/h (>12 hr occupation / day) 60m^3/h (overall air flow)	20m^3/h (>12 hr occupation / day) 30m^3/h (overall air flow)

Country & Standard Reference	**Whole Building Ventilation Rates**	**Living Room**	**Bedroom**	**Kitchen**	**Bathroom + WC**	**WC only**
				air flow)		
Greece	Dwellings Est 5 persons per 100m^2 of floor area Flats Est 7 persons per 100m^2 of floor area	Dwellings & Flats Min 8.5m^3/h/p Max 12-17.5 m^3/h		Dwellings & Flats Min 8.5m^3/h/p Max 50-85 m^3/h	Dwellings & Flats Min 34 m^3/h/p Max 50-85 m^3/h	
Italy (MD 05.07.75) (Standard UNI 10339)	Naturally ventilated dwelling 0.35 to 5.0 ach	15 m^3/h/p 40m^3/h/p	40m^3/h/p	1 ach 4 ach exhaust	2 ach 4 ach exhaust	1 ach
Netherlands Building Decree		0.9 dm^3/s/m^2 floor area	0.9 dm^3/s/m^2 floor area	21 dm^3/s	14 dm^3/s	7 dm^3/s
New Zealand (ASRAE 62-1999)	0.35 ach but no less than 7 l/s/person Nat. vent min are of openable window as 5% of floor area in each room			50 l/s (inter.) or 12 l/s (cont.) or Operatable windows	25 l/s (inter.) or 10 l/s(cont.) or Operatable windows	
Norway (Norwegian Bldg Code)	Not less than 0.5 ach	Supply: Openable window or inlet bigger than 100cm^2 in external wall	Supply: Openable window or inlet bigger than 100cm^2 in external wall	Mech extract 60m3/h or by natural extract at least 150cm^2 duct above roof	Mech extract 60m3/h or by natural extract at least 150cm^2 duct above roof	Mech extract 40m3/h or by natural extract at least 100cm^2 duct above roof
Sweden (BFS 1988: 38)	Requirements: Rooms shall have continual 0.35 l/s/m^2 floor area when in use		Recommendations: Not less than 4.0 l/s/bed place	Recommendations: Extract: 10 l/s	10 l/s with openable window or 10 l/s with high speed rate up to 30 l/s or 15 l/s without openable window	
Switzerland (SIA 180:00)	15 m3/h/p (Non-smoking)					
UK (Building Regulations Approved Document F)		Rapid vent: 1/20th of floor area Background vent: 8000mm^2	Rapid vent: 1/20th of floor area Background vent: 8000mm^2	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates of: 30 l/s adjacent to hob or	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates of: 15 l/s or PSV	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates of: 15 l/s or

Country & Standard Reference	Whole Building Ventilation Rates	Living Room	Bedroom	Kitchen	Bathroom + WC	WC only
				60 l/s else where or PSV		PSV
USA (ASHRAE 62-99)	0.35 ach but no less than 7.5 l/s/p Nat. vent Min area of openable window as 5% of floor area in each room			50 l/s (inter.) or 12 l/s (cont.) or openable windows	25 l/s per room (inter.) or 10l/s (cont.) or openable windows	

2.8 Innovative Systems

2.8.1 Heat Recovery With Balanced Mechanical Systems

Heat recovery is common with balanced mechanical ventilation systems. Conventional plate heat exchangers offer a relatively simple solution and can have heat recovery efficiencies of up to 70%.

Work to improve the efficiency and reduce friction loss and fan power is constantly on-going, some of the latest improvements being reported by Op't Veld [2000]. These results suggest that a new generation of heat recovery devices with low energy DC fans are likely to operate with efficiencies greater than 80%.

An alternative approach to enhance the energy recovery from balanced ventilation systems is the use of a heat pump in addition to a conventional heat exchanger. These heat pumps can reclaim and upgrade the remaining energy from the exhaust ventilation air and transfer it to the supply air. While such systems have been shown to provide benefit in terms of reduced space heating requirements, they usually require some additional heating for part of the year to maintain comfort.

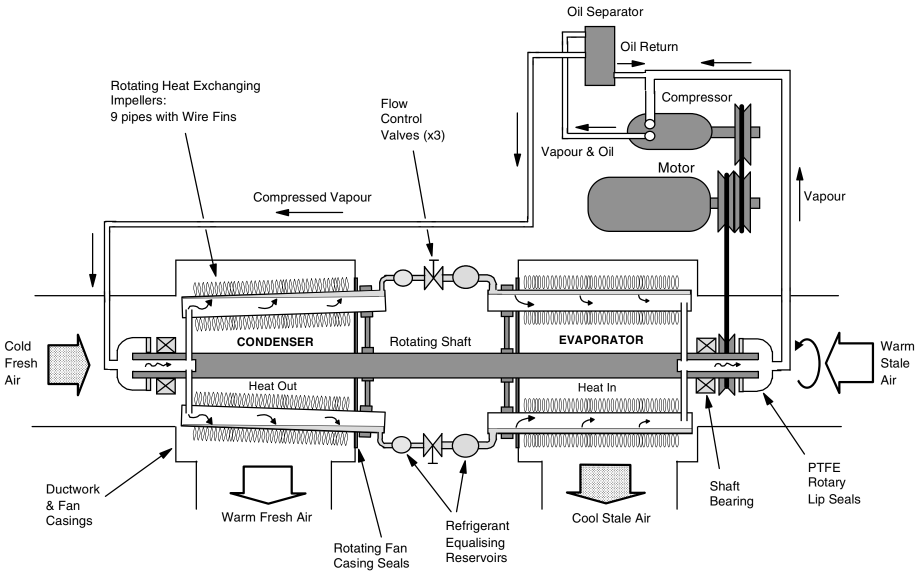

Figure 2.9: Novel Heat Pump Heat Recovery Unit

In an attempt to improve the performance of such systems, novel approaches have been adopted. Riffat and Gillott [2000] have presented results for a novel heat pump system using heat pipes to combine the functions of heat recovery and heat pump into one unit. Initial results show that the unit can achieve system COPs in the order of 2.1, and by reversing ventilation flows across the unit could provide summer cooling at COPs of around 1.1. Further work is continuing into reducing friction losses and improvements in fan and motor performance.

2.8.2 Pressure Controlled Natural Inlets

Driving forces for natural ventilation are very variable. Often driving forces are highest when the lowest ventilation rates are required and lowest when higher ventilation rates could offer benefits from free cooling.

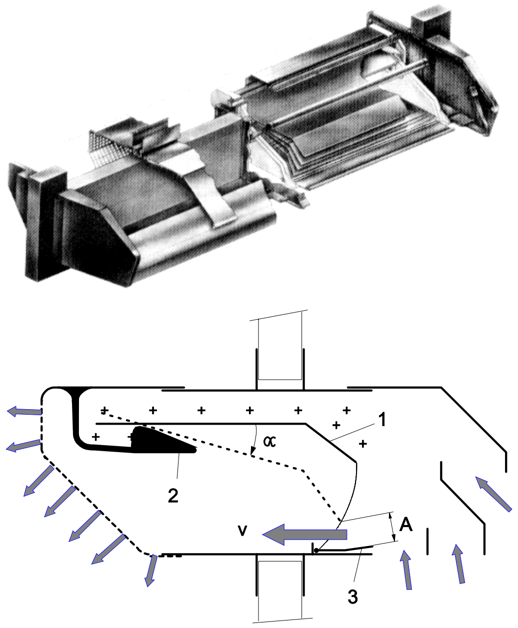

Figure 2.10: Constant Flow Rate Natural Ventilator

Attempts have been made to produce pressure sensitive purpose provided ventilators that can provide a constant ventilation rate for a range of pressures provided by variations in external conditions.

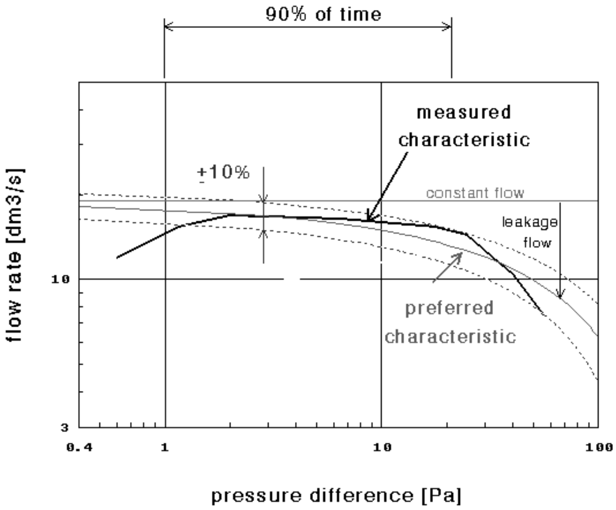

Figure 2.11: Ventilation Rate vs Pressure

While suitable ventilators have been produced, their installation remains relatively uncommon, with the cheaper uncontrolled ventilators or humidity controlled ventilators dominating the market.

2.8.3 Demand Control

Ventilation standards for air flow rates have been developed over a number of years and are predominantly based on empirical evidence. While these standards are capable of providing reasonable indoor air quality and avoiding problems with condensation, they can lead to over-ventilation. Demand control ventilation (DCV) offers a method of matching ventilation rates more closely to actual requirements, thus reducing energy losses and fan power consumption.

Relative humidity is currently used to control both mechanical and passive stack ventilation systems. However, relative humidity sensors are notoriously unreliable in performance and do not recognise changes in ventilation needs for all situations.

Carbon dioxide offers a better measure of occupant activity, and hence ventilation requirement. Concentrations will rise with occupation and activity level, thus allowing for high activity rates, sedentary occupation and the unoccupied condition. Research suggests that reductions in ventilation of 20 to 30% could be achieved using DCV without compromising indoor air quality. Particular advantages will occur in dwellings with variable occupancy.

2.8.4 Passive Stack Heat Recovery

One of the disadvantages of passive stack ventilation systems is the current inability to recover heat from exhaust air.

Driving pressures for passive stack ventilation are very low and therefore cannot overcome the additional resistance to flow created by the introduction of a conventional heat exchanger. In addition, the transfer of heat from the exhaust to supply air streams reduces the temperature difference, thus reducing the available driving forces further.

Work has been carried out [Shao 1998] [Blom, Brunsell 1999] [Sasaki et al 1999] into providing low-pressure loss heat recovery for passive stack and hybrid ventilation systems. Conventional plate heat exchangers have relatively high resistances and are therefore unlikely to be suitable for pure passive stack systems. Better results have been achieved using heat pipes, which can be configured to have lower pressure losses. Shao et al [1998] suggest that heat recovery efficiencies of up to 50% could be achieved using heat pipes, while pressure losses can be kept in the order of 1 Pa at flow velocities of 1 m/s.

Other alterations would be necessary to the overall system in order to implement heat recovery in residential situations. Currently supply air is provided to a number of rooms by purpose provided openings in the building façade. This part of the system would need to be altered to enable a more central supply air arrangement and to enable heat recovered from the exhaust air to be provided to the supply air.

2.8.5 Induction Assisted Natural Ventilation

Natural ventilation driving forces are very variable, making the design of robust natural ventilation systems that minimise energy loss difficult. One approach being investigated is the use a hybrid induction system to provide better reliability for natural ventilation without the running costs associated with full mechanical ventilation.

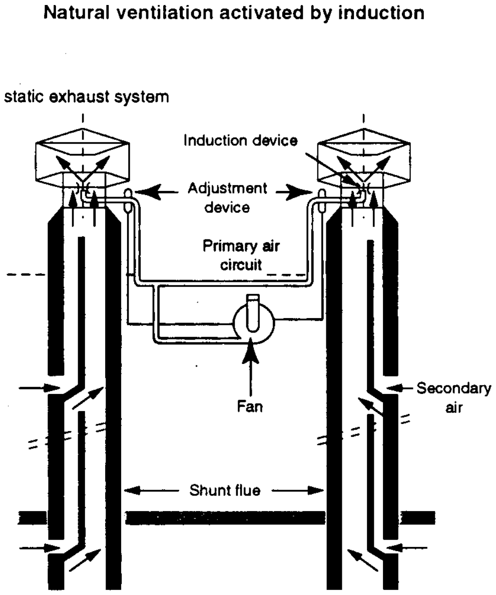

Figure 2.12: Natural Ventilation Activated by Induction

Primary air is mechanically supplied at high speed into extract ducts, inducing stale extract air. The system ensures the required driving force is always available even when natural diving forces are low. Varying the primary airflow can provide additional control over exhaust flow rates.

Noel et al [2000] have reported preliminary results for an induction assisted natural ventilation system in a test house. These results indicate that it is possible to design safe and controllable systems for dwellings.

3 Energy Impact of Ventilation

3.1 Ventilation Energy Consumption

Energy consumption associated with residential buildings represents a significant proportion of the total energy consumption within OECD countries. Figures for 1998 [IEA, 2000] indicate that, of some 145 EJ of primary energy consumption, around 28 EJ was associated with residential buildings. Of this, ventilation and infiltration energy losses account for an important proportion.

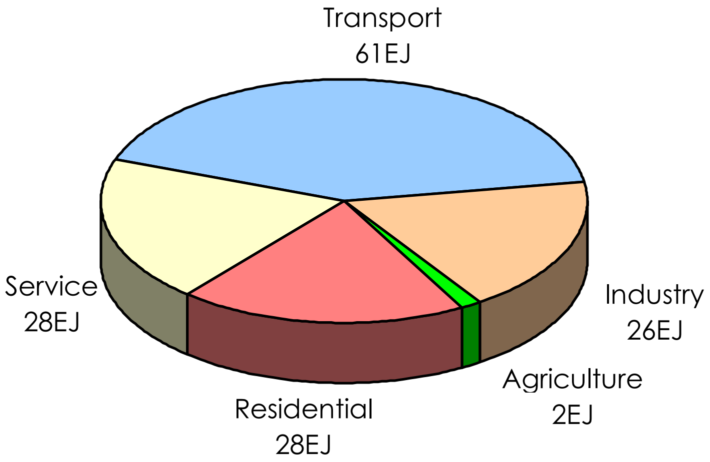

Figure 3.1: Primary Energy Consumption By Sector

The delivered energy associated with ventilation can be split into three areas: air change losses due to conditioning (heating & cooling) ventilation and infiltration air; losses from equipment used to condition the air; energy used to transport air into and out of the buildings. Orme [1998] has estimated the breakdown of delivered space conditioning energy for the combined residential and service sector, as illustrated in Figure 3.2. These figures suggest that around 12 EJ of delivered energy consumption are associated with ventilation.

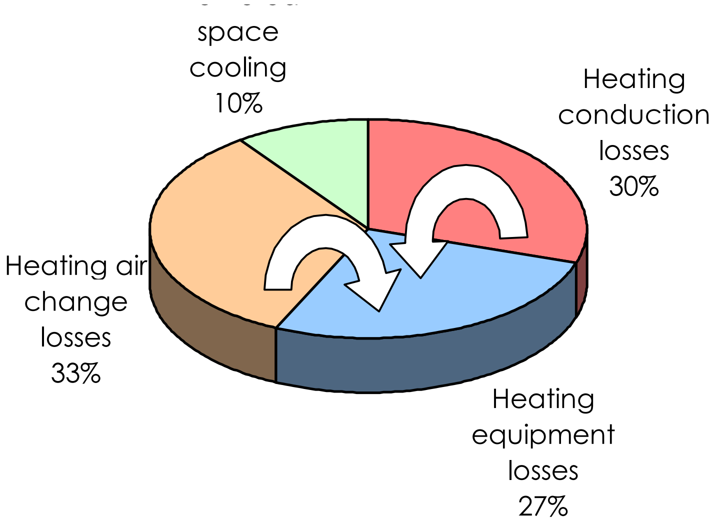

Figure 3.2: Delivered Energy by End use in Residential & Service Sectors

Excessive ventilation over and above the minimum necessary will lead to unnecessary energy consumption. Some estimate of the potential energy savings can be obtained by assuming that ventilation rates can be reduced to a minimum of 10 l/s per person. This standard is commonly used in service buildings, but can be equated to the range of minimum ventilation rates given in ventilation standards previously quoted. If the estimate quoted in Orme [1998] for residential and service sector buildings, illustrated in Figure 3.3, is applied to the current residential sector figures, then energy savings of up to 9 EJ are possible by reducing ventilation rates.

Where heat recovery is possible even higher reductions are possible. If all ventilation were to be provided by balance mechanical ventilation with heat recovery at 70% efficiency then a further reduction in space heating energy of 2.8 EJ could be made.

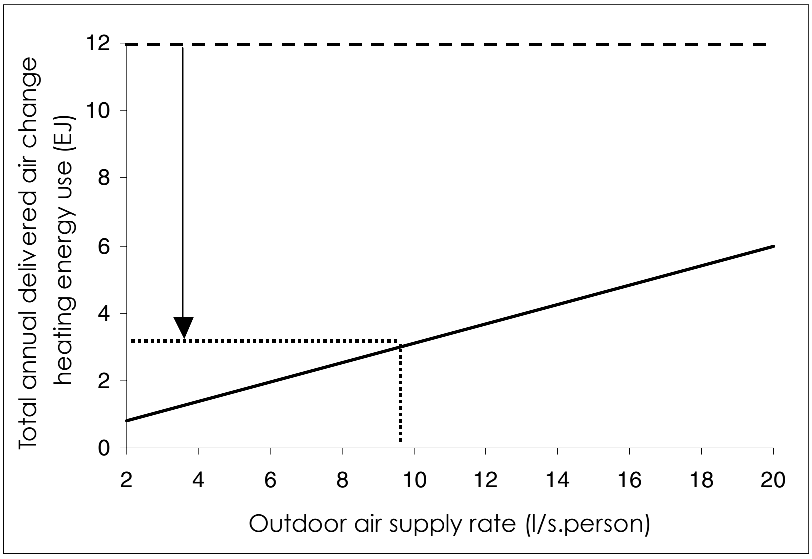

Figure 3.3: Potential Delivered Energy Savings for the Residential & Services Sector

3.2 Influence of Air Tightness

The actual air change energy losses and their attendant conditioning plant losses result from both deliberate ventilation and from infiltration. While most natural ventilation systems rely to some extent on infiltration to provide part of the necessary background ventilation, lack of control can often lead to unnecessarily high air change rates and hence energy consumption.

It is not possible to recover heating energy from infiltration air due to its uncontrolled and dissipated nature. High infiltration rates therefore severely reduce the effectiveness and efficiency of heat recovery devices.

Suggested air tightness standards suitable for different ventilation systems are given in Figure 2.8 in section 2.5.

3.3 Influence of Climate

Climate can have a significant impact on the energy consumption associated with ventilation. Considerably more heating energy will be required for a given ventilation rate in a cold climate than in a mild climate. Similarly dwellings in cold or moderate climates may not require any space cooling while mild or hot climates will. Humidity will also have an influence where dehumidification is required (humidification is rarely installed in dwellings).

One method of assessing climate is the degree day method. Usually this method is applied to heating, but cooling degree-days also exist. Heating degree-days are essentially the number of degrees of temperature difference, averaged over a one-day period, that the mean outdoor temperature is below a given base temperature. Similarly cooling degree days are used to quantify the enthalpy of the air above a given base temperature and moisture content. This concept is useful as it combines temperature with time and figures for degree-days are widely available. One disadvantage however is the use of different base temperatures in different countries.

Liddament [1996] defines climatic zones in terms of degree-days as follows:

Mild climate:	neither heating nor cooling is significant with an annual degree-day value of perhaps 2000 or less.
Moderate climate:	heating or cooling requirements may be seasonally significant with a possible annual degree-day range of between 2000 and 3000.
Severe climate:	heating or cooling energy requirements are high with a possible annual degree-day value of greater than 3000.

Figure 3.4 illustrates the effect of climate, as measured by degree-days, on heating energy loss through ventilation. The range of typical whole house ventilation rates is also marked.

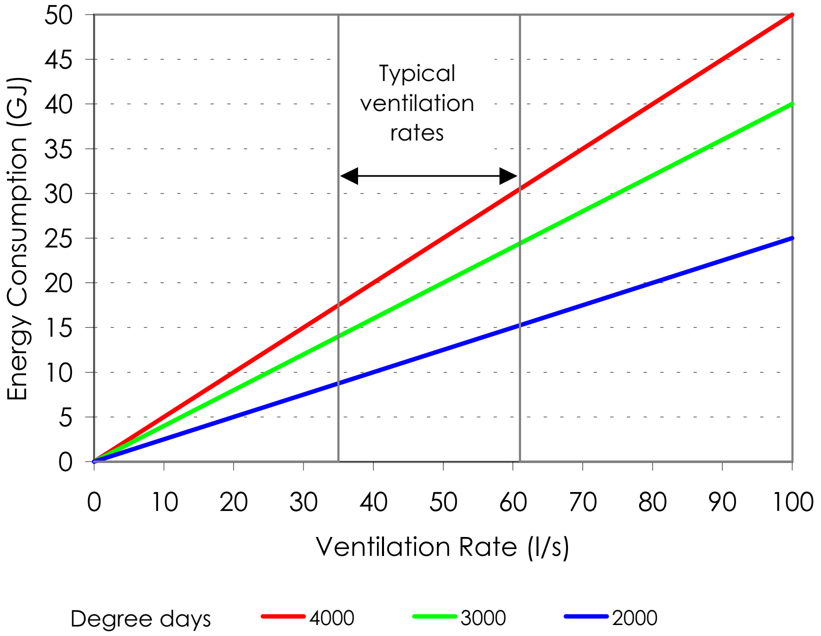

Figure 3.4: Impact of Climate on Annual Heating Energy Requirement

An alternative approach has been used by Colliver [1995] to estimate energy consumption to condition each kg/h of incoming air to a heating set point of 18°C and a cooling set point of 25.6°C at 40% relative humidity for 43 sites throughout Europe and the United States. Figure 3.5 illustrates the results for a selection of sites. Clearly in cold and moderate climates heating of ventilation air dominates, while in humid climates dehumidification is the main energy requirement.

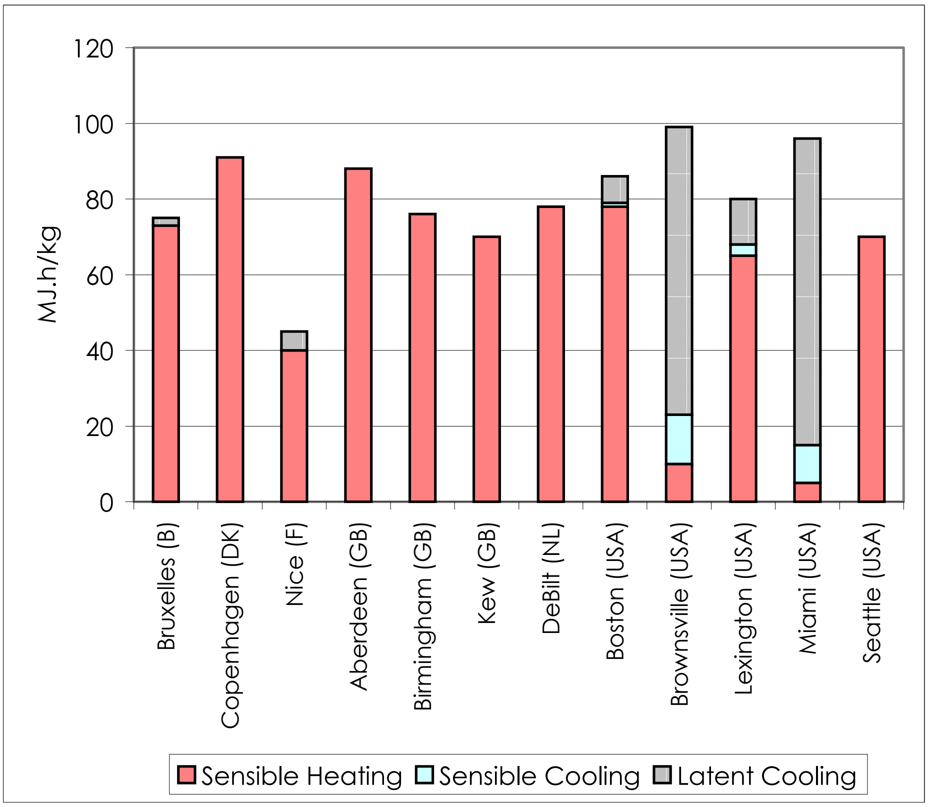

Figure 3.5: Energy Demands for Various Locations

3.4 Standards

3.4.1 Energy Standards

Information on energy standards has been taken from Limb [2001] and is summarised in Table 3.1 below. More detailed information on these standards can be found in the AIVC Report.

Three main routes are used to ensure that energy consumption in buildings is controlled, these are the “elemental method”, the “calculation method” and the “energy method”. Some countries allow one method to be followed, while others allow all three.

The elemental method requires each building construction to meet or better a specific maximum thermal transmission value (usually expressed as a U-value in W/m^2K).

The calculation method either sets an average U-value for buildings or a target heat loss based on a standard building that meets the elemental method. Within certain limits this method allows more flexibility than the elemental method, in selecting areas of windows, personnel doors and rooflights and/or the insulation levels of individual elements in the building envelope.

The energy method sets a target energy consumption for a building that must be equalled or bettered. It takes account of the performance of energy consuming plant within buildings as well as the building envelope performance. This is the most flexible method as reduced building fabric performance can be offset by improved plant performance.

Table 3.1: Energy Standards

Country	**Standard(s)**	**Elemental Method**	**Calculation Method**	**Energy Method**
Belgium	Decree of Flemish Government of 18 September 1991 concerning thermal requirements of buildings (application from 1 September 1992). Decree of Walloon Government of 15 February 1996 concerning thermal requirements of buildings (application from 1 December 1996). Decree of Brussels Government of 3 June 1999 concerning thermal requirements of buildings (application from 1 January 2000).	✓	✓	✓
Denmark	The Building Regulations - Chapter 8 Thermal Insulation.	✓	✓	✓
France	Réglementation thermique 2000 (so called RT2000).			✓
Greece	Presidential Decree 1-6/4-7/1979, "Thermal Insulation Regulation".		✓	
Netherlands	NEN 5128 – Energy Performance Standard.	✓		✓
New Zealand	Insulation standards; NZS 4218 for small buildings, NZS 4305 for hot water systems. New Zealand Building Code clause H1 which sets a building performance index.			
Norway	Technical Regulations Under the Planning & Buildings Act 1997; Chapter 8-21 Energy & Power.	✓	✓	✓
Sweden	BFS 1993:57, with amendments. BFS 1995:17, BFS 1995:65. Building Regulations BBR 94 Section 9 Energy Economy and Heat Retention.		✓	
UK	Building Regulations 2000 –Approved Document L1 "Conservation of Fuel & Power".	✓	✓	✓
USA	ASHRAE 90.2 1993 Energy Efficient Design of New Low Rise Residential Buildings . ANSI/ASHRAE/IES 100.2-1991 Energy Conservation in Existing Buildings – High Rise Residential.			

3.4.2 Insulation Standards

Insulation standards are covered under energy regulations and information, taken from Limb [2001], and are summarised in Table 3.2 below.

Table 3.2: Insulation Standards – Figures are U-values in W/m^2K

	Ground Floors	**Walls**	**Windows**	**Roofs**
Belgium	0.60 above space, 0.90 above frost free space, 1.20 in contact with ground	External walls 0.60 unless adjacent to frost free space of ground when 0.90 Walls common between buildings 1.00	Brussels 2.50 Flanders 3.50 Wallonia 3.50	Brussels 0.40 Flanders 0.60 Wallonia 0.40
Denmark (For rooms heated to minimum of 18°C)	0.20	External <100kg/m^2 0.20 External >100kg/m^2 0.30 Internal to rooms at lower temp 0.40	1.80	0.15 Sloping 0.20 Flat
Norway (For spaces heated to between 15 & 20°C – figures in brackets where >20°C)	0.20 (0.15)	External walls 0.28 (0.22) Walls to unheated space 0.80	2.00 (1.60)	0.20 (0.15)
Sweden	-	-	-	-
UK (Gas or oil fired boiler with target SEDBUK)	0.25	0.35	2.00 Timber & UPVC 2.20 Metal	0.25 Flat 0.16 Pitched
USA	-	-	-	-

3.4.3 Air Tightness Standards

Information on air tightness standards has been taken from Limb [2001] and is summarised in Table 3.3 below. Standards come in two forms, those that specify a standard for the whole building, and those that specify standards for building components. More detailed information and analysis of these standards can be found in Limb [2001].

Table 3.3: Air Tightness Standards

Country	**Whole Building**	**Components**	
		Windows	Doors
Belgium	Recommendations: >3ach at 50Pa for balanced mechanical ventilation >1ach at 50Pa with balance mechanical ventilation with heat recovery		0.50 dm^3.s/m at 50Pa
Denmark			0.50 dm^3.s/m at 50Pa
Finland		Class 1 <0.5 m^3/h.m^2 at 50 Pa Class 2 0.5-2.5 m^3/h.m^2 at 50 Pa Class 3 >2.5 m^3/h.m^2 at 50 Pa	
France	The reference value in the air flow under 4 Pa, divided by the area of the envelope (and so	Class A1 20-60 m^3/h.m^2 at 100Pa ClassA2 7-20	Class A1 20-60 m^3/h.m^2 at 100Pa ClassA2 7-20 m^3/h.m^2

Country	Whole Building	Components	
		Windows	Doors
	expressed in m^3/(h.m^2)). The reference values vary from 0.8 to 2.5 depending on the type of construction. If no engagement is taken on a given value, a default value can be applied by adding 0.5 to the reference one.	m^3/h.m^2 at 100Pa Class A3 <7 m^3/h.m^2 at 100Pa	at 100Pa Class A3 <7 m^3/h.m^2 at 100Pa
Germany		The standard classifies windows by exposure level and gives acceptable air permeability values for each group under pressure over the range 10 to 1000Pa pressure difference 1-20 m^3/h.m length of crack over pressure diff 10 to 1000 Pa	
Italy		1.4 – 4.0 m^3/h.m at 50 Pa air flow rate per unit length of opening. 4.8 – 31 m^3/h.m^2 at 50 Pa air flow rate per unit area of window.	
Netherlands	Class 1 Max 200 dm^3/s at 10Pa (2.24 ach at 10Pa) Class 1 Min 30-50dm^3/s (0.4 - 0.72 ach at 10Pa) Class 2 Max up to 80 dm^3/s (0.72 - 1.15 ach at 10 Pa)	2.5 dm^3/s per m length of crack at 75Pa 0.5 dm^3/s per 100 mm of frame section.	
New Zealand		0.6-4.0 dm^3/s per m length of joint at 150 Pa 2.0-17 dm^3/s.m^2 windows area at 150Pa.	
Norway	Detached and undetached houses 4 ach at 50 Pa Other buildings two storeys high or less 3 ach at 50 Pa Other buildings >2 storeys high 1.5 ach at 50 Pa		
Sweden	The building envelope shall be so airtight that the average air leakage rate at a pressure difference of 50 Pa does not exceed 0.8 l/s per m^2		
Switzerland	New Buildings upper limit 0.75 m^3/h.m^2 Recommended limit 0.5 m^3/h.m^2 Refurbished or modified buildings upper limit 1.5 m^3/h.m^2 Recommended limit 1 m^3/h.m^2	0.2 m^3/h at 1 Pa (when n=0.66) (a) 5.65 m^3/h.m at 150 Pa (b) 8.95 m^3/h.m at 300 Pa (c) 14.25 m^3/h.m at 600 Pa	
United Kingdom	Recommended in CIBSE TM23	1.22-6.2 m^3/h.m of	

Country	Whole Building	Components	
		Windows	Doors
	2000 Air Leakage index for Dwellings 15.0 m3.h.m2 at 50Pa (Good practice) 8 m3.h.m2 at 50Pa (best practice) Dwellings (with whole house balanced mech. Vent) 8.0 (GP) – 4.0 (BP) m3.h.m2 at 50Pa	joint opening at 50Pa	
United States of America	Normalised leakage range taken from measurements at 4Pa ELA for whole of USA. From <0.1-1.60 (from ASHRAE 119-1988 (RA)Apped.B ACH≈LN. therefore <0.1-1.6ach) Note: Standard requires no part of the US to be tighter than 0.28 (only a small part of upper Midwest) Mostly the tightness requirement is 0.4.	Windows are .3 cfm per m^2 of window area, when tested by ASTM E28 ASHRAE Standard 90.1-99 gives recommendations for the leakage rate of windows and doors in accordance with NFRC 400. Air leakage shall not exceed 5 l/s.m^2 for glazed swinging entrance doors and for revolving doors 2.0 l/s m^2 for all other products. *ASHRAE 90.2-1999.* The requirement for manufactured housing windows shall be 0.50 cfm/ft^2 of window area. The air infiltration rate requirement for windows not covered by the specific listed references shall be 0.34 cfm/ft of sash crack. The requirement for fixed windows shall be0.34 cfm/ft^2 of window area.	ASHRAE Standard 90.1-99 gives recommendations for the leakage rate of windows and doors in accordance with NFRC 400. Air leakage shall not exceed 5 l/s.m^2 for glazed swinging entrance doors and for revolving doors 2.0 l/s m^2 for all other products. Sliding Doors The infiltration rate shall not exceed 0.5 cfm/ft^2 of door area for manufactured housing sliding doors. Swinging Doors The infiltration rate shall not exceed 1.0 cfm/ft^2 of door area for manufactured housing swinging doors.

3.5 Interaction with Heating & Cooling Systems

Buildings are not closed systems but open systems subjected to airflows induced by purpose-provided ventilation, infiltration / exfiltration, heating, air conditioning, local exhaust and open combustion devices. As each of these airflows can act to pressurise or depressurise rooms in the house, they necessarily interact with each other.

In moderate and cold climates, natural ventilation systems may be expected to depressurise the dwellings they serve. Similarly mechanical extract and balanced mechanical systems are designed to depressurise the dwelling. Under these circumstances the ventilation system may act in competition with open flue combustion devices by decreasing smoke stack pressures and thereby increasing the chances of back-draughting and spillage of combustion gases. Careful design of the ventilation system or the use of closed combustion systems can overcome this potential problem. Further interaction between the ventilation system and other systems can occur when the ventilation system induces airflows in non-operating exhaust fans, heating or air conditioning subsystems, resulting in increased infiltration. Conversely, the operation of the dwelling heating or air conditioning system may induce unintended airflows in inlets or outlets of the ventilation systems.

Mechanical supply systems and natural ventilation systems in warmer climates, or during windy conditions, will pressurise the dwelling. For natural ventilation systems this occurs when the indoor air temperatures are maintained lower than outdoor temperatures. Again, as a result, unintended airflows may be induced in non-operating exhaust fans, heating or air-conditioning systems. Furthermore, the migration of indoor moisture outward through the wall construction may be increased and moisture damage may result.

Careful design of the ventilation system and its components, together with the appropriate level of building air tightness can overcome these pressure difference problems.

3.6 Economic Influences

The relative costs of heating energy and electrical energy for the transport of air will influence the choice of ventilation systems preferred. In countries with high heating fuel costs but low electrical costs there is a positive economic argument for installing mechanical balanced ventilation with heat recovery. In countries where heating fuel is relatively cheap compared to electricity prices the economic argument is less compelling as there may not be a suitable payback in energy cost savings.

At the present time it can be calculated that for the UK the cost savings in heating energy derived from the installation of balanced mechanical ventilation with heat recovery are about the same as the additional electrical fan energy costs.

Under these circumstances benefits other than economics have to be used to justify installation and maintenance costs of mechanical systems.

4 Indoor Air Quality

Indoor air quality has been described by the World Health Organisation (WHO) as acceptable if:

- not more than 50% of the occupants can detect any odour, and
- not more than 20% experience discomfort, and
- not more than 10% suffer from mucosal irritation, and
- not more than 5% experience annoyance,
- for less than 2% of the time.

There are a wide range of pollutants which can lead to discomfort, and others, such as radon, that while not affecting comfort may still have health implications. These pollutants are commonly differentiated by whether they are produced externally or within buildings.

4.1 Internally Generated Pollutants

Internal pollutants are generated from the building fabric and furnishings, building occupants and their activities and from the use of combustion devices and equipment within the home.

Carbon Dioxide (CO_2) is a product of human metabolism and of the combustion of fuels in heat sources or for cooking. The level of CO_2 within the dwelling will therefore be a function of the level of occupation and activities being carried out. While CO_2 is a non-toxic gas it contributes to a feeling of stuffiness.

Moisture is also produced by building occupants and from a range of activities. Clothes washing, bathing or showering and cooking all produce significant amounts of water vapour. Combustion of fossil fuels for heating or cooking will also produce water vapour, which may be released into the dwelling.

Excessive moisture can lead to condensation on cold surfaces, mould growth and damage to the building fabric. Fungal spores and dust mites, which will proliferate under high levels of moisture, have been identified as aggravating conditions such as asthma and other bronchial problems.

Odour can come from human metabolism, from furnishings and from cooking. This causes discomfort to building occupants.

Carbon Monoxide is a product of incomplete combustion of fuels for heating or cooking. A poison, which replaces oxygen in the human blood stream, thus starving the body of oxygen, carbon monoxide can have an adverse effect on humans even in moderate concentrations. Legislation exists in some countries to limit emissions from combustion devices. However, dangerous levels can be produced where there is insufficient combustion air available to the device.

Tobacco Smoke produces both chemical and particulate pollutants. In dwellings where smoking takes place, this can be the major source of pollution within the home. While generally considered an irritant there is growing evidence that airborne pollutants from tobacco smoking can affect health.

Volatile Organic Compounds (VOCs) are a range of chemicals with low boiling points that are given off from furnishings and building products. They can have a strong odour and some are known to have harmful effects on health. New furnishings can give off substantial amounts of these pollutants.

Formaldehyde is used in boarding and building products. It can be an irritant and have harmful effects on the health of building occupants. Levels of formaldehyde are often significant in new dwellings, unless specific measures have been taken to exclude products containing it.

4.2 External Pollutants

Outside air is generally thought of as clean “fresh” air. In reality it can contain a significant level of pollutants, depending on location and level of external human activity.

Rural pollutants can come from natural and man-made sources. They are often associated with man’s farming activities but the natural pollutants will occur in all rural areas.

Natural pollutants are highly seasonal and can induce allergic reactions such as asthma and hay fever. Unfavourable weather conditions can increase the effect of such pollutants on suffers of these conditions. Typical pollutants include:

- fugal spores,
- pollen,
- dust.

Legislation exists to reduce the impact of man-made pollutants, which typically include:

- fertilizers,
- weedkillers,
- insecticides.
- Seasonal, like natural pollutants, they can have far wider impacts on human health and on wildlife.

Industrial pollutants can include a wide range of chemicals, particulates and fibres. The worst contaminated areas are usually localised within a few kilometres of industrial sources. Typical pollutants can include:

- oxides of nitrogen and sulphur,
- ozone,
- heavy metals,
- volatile organic components,
- hydrocarbons,
- smoke, particulates and fibres.

Many of these can be harmful to man and a considerable wealth of regulations exist, such as the EU Air Quality Framework Directive [1996] in Europe and the Clean Air Act [1990] in the United States, to control and reduce their release into the atmosphere.

Pollution generation from industrial sources usually occurs evenly throughout the year. However, weather conditions can alter the effects of pollution by reducing or increasing the rate of pollutant dispersal.

Traffic pollution is a major source of transient pollution within large built up areas. Typical pollutants include:

- carbon monoxide,
- carbon dust,

- lead,
- oxides of nitrogen,
- fuel additives and unburnt fuel.

In some cities pollution from traffic is so acute that severe restrictions can be placed on the use of private vehicles during times of high pollution concentration.

Major roads, railways and areas where vehicles are parked are all major sources of these pollutants. As with other airborne pollutants, weather conditions can increase the effect of these pollutants by reducing the rate of dispersal.

Both industrial and traffic pollution has been identified as having an adverse effect on those suffering from asthma and other bronchial problems.

Ground-borne pollutants can have an impact on dwellings where their occurrence coincides with buildings. These pollutants include:

- Radon: a naturally occurring radioactive gas that originates in specific geological formations and so is regionalised. Exposure to high concentrations of radon has been shown to increase the risk of lung cancer.
- Methane: naturally occurring in some soils but is more usually a product of waste disposal in landfill sites and therefore localised in a similar manner to radon. While having no direct effect on dwelling occupants, explosive concentrations have been found to build up under certain conditions, leading to legislation to avoid the build-up of methane within dwellings.
- Moisture: can add to the moisture burden already within the building where no action is taken to prevent its ingress from the ground.

4.3 Pollutant Control

4.3.1 Dilution vs Source Control

The most effective method of avoiding the harmful effects of pollutants is to control the source of pollution. Legislation can be used to ensure those producing potential pollutants either limit or do not permit their entry into the environment. This mechanism is primarily used on industrial and traffic pollutants but can be applied to building and furnishing materials as well. There are, however, pollutants not covered by legislation that can still best be controlled at source. Within the dwelling moisture produced by clothes washing, bathing or cooking is best removed at source, while exhaust gases from heating appliances should be vented directly to the outside.

Within the residential environment the alternative pollutant control mechanism to source control is dilution. This aims to keep the concentration of any one pollutant below an acceptable threshold by replacing polluted air with fresh air. Ideally ventilation rates will therefore be adjusted to match the production rates of pollutants. Often the control mechanisms used to increase ventilation rates are crude, e.g. opening windows or step changes in fan speed. More sophisticated control techniques using demand control exist but are not commonly used.

In practice there will be a number of different pollutants within the dwelling at any one time. In order to keep all these pollutants within acceptable concentrations it is necessary to identify the ventilation rate needed to control the dominant pollutant. It can then be assumed that all lesser pollutants will remain below their acceptable thresholds. Moisture is often used within dwellings as the key pollutant for increased ventilation rates as it is connected with many activities within the home. For pollutants such as tobacco smoke increased ventilation rates are usually left to the discretion of occupants.

4.3.2 External Pollutants

Airborne pollutants from industrial, traffic and rural sources are difficult for designers and occupants of residential buildings to control. Legislation offers the major mechanism for control, as previously mentioned in the Air Quality Framework Directive in Europe and the Clean Air Act in the United States.

Careful siting of air inlets away from local external pollution sources, such as roads, can reduce the impact of the pollution generated. Building occupants can also choose to reduce ventilation during times of high pollution production, such as rush-hour traffic, where sufficient control is available. These measures are much easier to implement with mechanical than with natural ventilation systems. An additional control measure that can be implemented with mechanical supply or balanced ventilation systems is the use of filtration to reduce airborne particulates transferred from outside to inside. In the future active carbon filters may offer control of some gaseous pollutants as well.

Ground source pollutant control is often covered by regulations and guidance, usually included in building codes and standards. Carrying out measures to prevent gas ingress into the building generally reduces the risk to dwelling occupants from ground source gases such as radon. These measures generally consist of providing a ventilated void between the building and the ground and including a gas barrier in the building ground floor construction. Moisture ingress is also dealt with in a similar way by introducing a moisture barrier into the ground floor construction and keeping all vulnerable construction materials above this level.

4.3.3 Internal Pollutants

Building and furnishing materials can emit VOCs and formaldehyde, especially when new. Pollutants from building products can be removed at source by careful specification by designers to avoid products that contain high concentrations of VOCs and formaldehyde. Building users can also choose furnishings that have low or no emissions if product information is available. Where removal at source is not achieved then there may be some advantage in increasing ventilation rates early in the building's occupied life to dilute the higher concentrations of emissions from new products.

Metabolic carbon dioxide, odour and moisture are most commonly controlled by dilution, hence the specification of minimum background ventilation rates in regulations and standards.

Tighter control of minimum ventilation rates to overcome metabolic pollutants is being sought by investigations into demand control. This increases ventilation rates when higher levels of CO_2 are detected and reduces ventilation again when CO_2 levels fall. As well as reducing unnecessary ventilation, this form of control can also be used to increase ventilation rates in those rooms under occupation. Thus ventilation is matched to occupant needs.

Occupant activities such as cooking, bathing and clothes washing can produce water vapour, CO_2 and odour. Where possible these pollutants are removed close to source by increasing ventilation rates locally for a limited duration. This is reflected in regulations and standards requiring additional controllable natural or mechanical means of increasing ventilation to kitchens, bathrooms and toilets. In order to avoid the pollutants dispersing throughout the dwelling extract ventilation is preferred, with at least some of the make up air coming from other rooms within the dwelling.

Tobacco smoking is another major occupant based pollution source. Regulations and standards often require a method of increased ventilation to be provided within dwellings, such as openable windows or boost settings on fans. It has been suggested that in households with smokers this facility is often use by occupants to reduce the impact of smoking.

Combustion devices such as fires, boilers and cookers need an adequate air supply to ensure safe combustion of the fuel. Where possible devices should have a separate flue to outside so that they can draw the necessary combustion air without having to interact with the building. Combustion products should also be vented directly to outside. Where such devices are open to the inside of the building however it will be necessary to provide an additional air supply for combustion and to disperse combustion produces. For cookers the provisions made to remove pollutants from other activities may prove adequate, but boilers and fires often require further provision. This is often covered in standards and regulations such as the Building Regulations Part F in the UK.

4.4 Indoor Air Quality Standards

The WHO has produce recommendations for a wide range of airborne pollutants rather than regulations.

Table 4.1 summarises WHO Guidelines (1999a), (http://www.who.int/peh/air/Airqualitygd.htm) and Air Quality (England) Regulations 2000 (http://www.defra.gov.uk, environment, air quality) for a range of specific pollutants.

Information on standards for individual countries can be found in the Limb [2001] and ASHRAE Standard 62-1989: Ventilation for acceptable indoor air quality.

Table 4.1: Guideline Exposure Values for Individual Substances

Substance	**Average time**	**Guideline value concentration in air**		**Source/Notes**
		By mass	By volume	
Arsenic	Lifetime			Estimated 1500 deaths from cancer in population of 1 million through lifetime exposure 1 $\mu g.m^{-3}$ (1)
Benzene	1 Year (running) Lifetime	5 ppb	16.25 $\mu g.m^{-3}$	(2) Estimated 4.4 to 7.5 deaths from cancer in population of 1 million through lifetime exposure of 1 $\mu g.m^{-3}$ (1)
1,3-buta-diene	1 Year (running)	1 ppb	2.25 $\mu g.m^{-3}$	(2)
Carbon monoxide	15 min 30 min 1 hour 8 hour (running)	- - - -	100 $mg.m^{-3}$ 60 $mg.m^{-3}$ 30 $mg.m^{-3}$ 10 $mg.m^{-3}$	(1) (1) (1) (1)
Chromium	Lifetime	-	-	Estimated 11,000 to 13,000 deaths from cancer in population of 1 million through lifetime exposure 1 $\mu g.m^{-3}$ (1)
Dichloro-methane (methyl chloride)	24 hours	0.84 ppm	3 $mg.m^{-3}$	(1)
Formalde-hyde	30 min	80 ppb	100 $\mu g.m^{-3}$	(1)
Hydrogen sulphide	30 min 24 hour	- -	7 $\mu g.m^{-3}$ 150 $\mu g.m^{-3}$	(1) (1)
Lead	1 year	-	0.5 $\mu g.m^{-3}$	(1)
MMVF – RC (3)	Lifetime	-	-	Estimated 40,000 deaths from cancer in population of 1 million through lifetime exposure 1 $\mu g.m^{-3}$ (1)
Manganese	1 year	-	0.15 $\mu g.m^{-3}$	(1)
Mercury	1 year	-	1 $\mu g.m^{-3}$	(1)
Nickel	Lifetime	-	-	Estimated 380 deaths from cancer in population of 1 million through lifetime exposure 1 $\mu g.m^{-3}$ (1)
Nitrogen dioxide	1 hour 1 year	- -	200 $\mu g.m^{-3}$ 40 $\mu g.m^{-3}$	(1) (1)
Ozone	8 hour	-	120 $\mu g.m^{-3}$	(1)
PM_{10} (4)	24 hour 1 year	- -	50 $\mu g.m^{-3}$ 40 $\mu g.m^{-3}$	Not to be exceeded more than 35 times per year (2) (Mean) (2)
Radon	Lifetime	-	-	Estimated 36 deaths from cancer in population of 1 million through lifetime exposure 1 $Bq.m^{-3}$ (1)
Sulphur dioxide	10 min 24 hour 1 year	- - -	500 $\mu g.m^{-3}$ 125 $\mu g.m^{-3}$ 50 $\mu g.m^{-3}$	(1) (1) (1)
Tetrachloro-ethylene	30 min 24 hour	- -	8000 $\mu g.m^{-3}$ 250 $\mu g.m^{-3}$	(1) (1)
Toluene	30 min 1 week	- -	1000 $\mu g.m^{-3}$ 260 $\mu g.m^{-3}$	(1) (1)
Trichloro-ethylene	Lifetime	-	-	Estimated 1 death from cancer in population of 1 million through lifetime exposure 1 $\mu g.m^{-3}$ (1)

Notes: (1) WHO Guidelines (1999a) (2) Air Quality (England) Regulations (2000)
(3) MMVF – Man-made vitreous fibres, RC – Refractory ceramic fibres (4) Particulate matter < 10μm diameter

5 Occupant Interaction

The actual performance of ventilation systems will be influenced by the behaviour of building occupants as well as other design and operating factors.

A number of international and national studies have been undertaken into occupant interaction with ventilation systems. Liddament [2000] summarises the results of these, with residential ventilation being covered by:

- IEA ECBCS Annex 8 Inhabitant Behaviour with Respect to Ventilation [Dubrul, 1988]
- IEA ECBCS Annex 27 Evaluation and Demonstration of Residential Ventilation Systems [Månsson, 2000]
- 1992 Swedish Energy and Indoor Climate Survey (the ELIB) study
- French Study: "Ventilation in the home: survey of the attitudes and behaviour of Private Citizens" [Lemaire et al, 1998]

5.1 Observed Occupancy Interaction with Ventilation Systems and Controls

5.1.1 Reasons for Ventilating and Not Ventilating Given by Occupants

As part of the Annex 8 work participating countries enquired into the reasons why occupants ventilated and did not ventilate their homes. Reasons for ventilating included:

- To get fresh air into bedrooms and living rooms;
- To remove odour;
- To remove stale air and condensation;
- To 'air' the dwelling during residential activities;
- To remove tobacco smoke.

Reasons for not ventilating the home included:

- To prevent draughts;
- To maintain a preferred temperature;
- To protect against cold and rain;
- To maintain privacy and safety;
- To reduce external noise and pollution.

5.1.2 Use of Windows

Window opening is one of the most basic of occupant controls and the surveys of Annex 8 revealed the wide use of window opening to control the indoor environment. Observations of window opening trends are summarised in Table 5.1.

5.1.3 Use of Passive Stack Systems

Passive stack ventilation systems were included in the Oseland [1995] study. The results showed that of homes installed with a PSV system, only 7% of kitchen and 8% of bathroom stacks were reported as blocked up. Unlike the mechanical extract fans, most of the PSV systems were in constant use. Fewer occupants reported problems in homes installed with a PSV system than homes fitted with a mechanical extract fan.

5.1.4 Use of Mechanical Ventilation Systems

The French study indicated that simple (extract) ventilation was installed in about 17% of all homes. Almost a quarter of households fitted with mechanical systems reported that they often or fairly often switched them off, while a significant number (23%) could not be switched off by the occupants.

Almost all mechanical systems investigated by Annex 8 were found to have shortcomings to some degree. These included:

- Unacceptable noise level;
- Severe draught effects;
- High auxiliary energy consumption;
- Design air flow rates not established;
- Odour transmission;
- Deficient installation;
- Poor instructions;
- Restricted user access.

Table 5.1: Observations of Window Opening Trends

Factor	**Observed Trend**
Occupancy density:	Window opening increases with number of occupants present
Occupant's age:	The amount of window opening and ventilation reduces with the increasing age of the occupants
Outdoor air temperature:	Window opening decreases with decreasing outdoor air temperature, although a significant number are still opened at temperatures as low as –5°C.
Sunshine	More windows tend to be open on the sunny side of buildings than on the opposite side.
Wind speed:	Window opening decreases with increasing wind speed.
Day time opening	Windows are usually closed when the building is unoccupied during the day.
Night time opening:	A significant number of windows are kept opening in bedrooms at night, even in cold weather.
Weekend opening:	Windows are open more frequently at weekends than during the rest of the week.
Thermostat setting:	The higher a household sets its heating thermostat, the less often windows are opened.
Residential activities:	Reasons given for window opening include vacuum cleaning and airing of bed-clothes, cooking, odour and moisture problems.
Smoking:	Windows are opened twice as frequently in smoking households than in non-smoking households.
Energy use:	There is only a weak correlation between energy saving intentions and window opening. More window opening tends to take place in buildings in which heating energy is not separately metered to occupants.

5.1.5 Use of Balanced Mechanical Ventilation Systems

Hill [1998] outlines occupant surveys undertaken in Canada to evaluate the effectiveness of mechanical ventilation heat recovery in dwellings. In addition to the survey work tests were carried out on a sample of dwellings to determine actual performance.

The majority of the systems were operating and the occupants believed their use was beneficial. Potential, however, existed for far greater benefits and considerable improvements were possible in installation practice, system performance, occupant understanding and occupant interaction with their system.

5.1.6 Use of 'Automatic' Controls

Humidistats are often coupled to extract fans located in the 'wet' rooms of dwellings to provide automatic control in which a rise in humidity is detected resulting in fan operation thus reducing the need for occupant interaction.

A detailed analysis of the performance of sensors was undertaken as part of ECBCS Annex 18 [Månsson et al 1997]. Performance was found to be variable, with the most basic of sensor requiring frequent re-calibration and sometimes suffering from substantial hysterisis.

The commonly employed type of humidistat used for relative humidity control in dwellings was often grossly inaccurate, subject to drift over time and were lacking in any convenient means of calibration. However, humidity controlled systems showed considerable promise.

Boyd et al [1989] concluded from work carried out in the UK that low rate fans are unable to prevent condensation and that condensation is difficult to remove once present even with extended running from humidistat control.

In Canada, Buchan et al [1986] suggested that there was no clear link between the control of humidity and a reduction in moisture problems evident in the house investigated.

Presence Infra Red (PIR) Controls are relatively new for residential ventilation. This type of control operates a fan when someone is detected in the room in which the fan is installed, normally with an over-run time. There are advantages of low cost and good reliability. PIR control is used with demand control ventilation systems.

5.1.7 Other Observations

Water Use and Moisture Generation within the home can lead to a risk of mould growth. Annex 27 estimated typical water consumption in dwellings at between approximately 140 – 250 litres/day, used for a range of purposes:

- Clothes Washing and Drying - is undertaken several times a week in family dwellings, less frequently among older people. Moisture becomes a problem when clothes drying takes place indoors or when clothes dryers vent within the building
- Showering – can lead to the relative humidity reaching 100% within 5 minutes. Depending on age, Annex 27 indicated that between 70 – 85% of people take regular showers.
- Cooking – produces water vapour and, if gas is used, combustion adds to this. Mechanically extracted cooker hoods are estimated to capture and remove up to 70% of the moisture generated.

Smoking requires much additional ventilation to minimise the risks associated with tobacco smoke. Approximately 30% of the adult population are smokers.

Vent and Ventilation System Cleaning was reported as being carried out at least once a year by 2/3rds of occupants in the French study.

Overall System Satisfaction was reported as more than 73% of occupants in apartment buildings and 87% in single-family dwellings in the French study.

Poor Occupant Health was complained of by over 59% of those who reported dissatisfaction with their ventilation system in the French study.

5.2 Occupant Impact on the Total Ventilation and Air Change Rate

Annex 8 considered the additional seasonal ventilation rate due to the use of windows. This they defined as:

Low window use:	0.0 – 0.1 ach
Average window use:	0.1 – 0.5 ach
High window use:	0.5 – 0.8 ach

The average increase in air change rate due to occupancy was found to be 0.32 ach for naturally ventilated dwellings and 0.34 for mechanically ventilated dwellings.

The Swedish study showed that, on average, ventilation rates were lower than 0.5 ACH in more than 80% of all the single-family houses and more than 50% of all the multi-family houses. This equates to less than 50% of all houses having a ventilation rate higher than 10 l/s per inhabitant.

Iwashita et al [1997] conducted a residential survey in Japan, assessing indoor environment and residents' behaviour during the period of ventilation measurement. The main conclusion was that there is a large difference between the mean basic ventilation rate and the mean total ventilation rate. If the size of the basic ventilation rate and the user-influenced ventilation rate in the investigated dwellings are compared, it is found that 87% of the total air change rate is caused by the behaviour of the occupants.

5.3 Occupant Impact on Energy Consumption

A major component of the Annex 8 study was to evaluate the energy impact of ventilation in dwellings and to assess the benefit of avoiding excessive air change. The energy impact due to the estimated increase in ventilation from occupant behaviour for a moderate (heating) climate was estimated to increase energy consumption by up to 6,000 MJ/250m³ dwelling during the heating season.

Shorrock et al [1992], supported by subsequent analysis by Liddament [1996], estimated an approximate average air change rate of 0.92 ach. When compared with a minimum average (continuous) ventilation need of 0.5 – 0.6 ach, the order of potential energy saving by providing efficient ventilation with the minimum of occupant window opening is similar to that observed by the Annex 8 study.

5.4 Occupant Education

A key part of the Annex 8 study was to determine if ventilation habits could be improved by educating occupants to operate ventilation controls more efficiently, i.e. to 'modify' behaviour. To achieve this a specific set of ventilation instructions was developed for ventilation control in one of the monitored buildings. The use of these instructions showed some reduced use of unnecessary ventilation (window opening). Other conclusions common to many of the investigated studies were that:

- Designers and regulators should provide the occupant with the means to adjust indoor climate to meet their individual needs, more control is needed over ventilation openings (e.g. by using small windows and vents for winter ventilation);
- Information campaigns are needed to explain how to use ventilation openings and to avoid the contamination of indoor air. It is especially important to explain the operation of mechanical systems;
- Regulators must understand the background to ventilation, especially in relation to health.
- It is important, therefore, that ventilation guidance is specified.

5.5 Occupant Guidance

Key occupant guidance is given in Liddament [2000] covering indoor air quality, thermal comfort and the efficient operation of ventilation systems. The occupant actions for IAQ and thermal comfort relate to both residential and non-residential buildings and it may not be possible for occupants of residential buildings to carry out all these actions. The guidance on efficient operation of ventilation systems is drawn from lessons learnt for the behavioural studies carried out. The guidance is reproduced in the following three tables.

Table 5.2: Occupant Actions – Indoor Air Quality

If there is concern about indoor air quality, occupants should undertake the following actions
• Verify the quality of the outdoor air;
• Check the supply air through the ventilation system to identify the possible location of system related pollutants (e.g. dust, mould etc. in ventilation ductwork);
• Locate and eliminate or enclose all indoor pollutant sources;
• Check for odour and/or CO_2 concentration, if these peak with occupancy density, then the primary pollutant source is probably due to occupancy. Raise ventilation rates in all occupied zones to at least 8 – 10l/s of outdoor air for each occupant;
• Eliminate smoking;
• Discourage indoor clothes drying unless the area is vented;
• Ensure all 'wet' zones have effective extract ventilation.

Table 5.3: Occupant Actions – Thermal Comfort

If thermal comfort is inadequate, occupants should undertake the following actions:
Insufficient Warmth:
• Check heating system;
• Check and rectify sources of infiltration and cold draughts;
• Check for excess outdoor air from mechanical ventilation systems.
Overheating:
• Minimise indoor heat gains by shutting down all unnecessary electrical equipment;
• Apply external solar shading;
• Establish a night cooling strategy to cool the building fabric down at night;
• Implement window opening or maximum ventilation in the morning, before the indoor temperature becomes unacceptable;
• Reduce the ventilation rate once the outdoor air temperature exceeds the indoor temperature. Note, however, that closing windows might exacerbate solar gain hence the need for external solar shading on sun facing windows).

Table 5.4: Guidelines for Efficient Residential Ventilation

Whole House Mechanical Systems:
• Understand the system and its purpose;
• Do not seal or obstruct air grilles, or disconnect the system;
• Apply boost to meet high moisture loads etc.;
• Avoid excessive window opening during periods of heating (or mechanical cooling);
• Ensure the system is regularly cleaned and maintained.
Purpose Provided Natural Ventilation with Vents, Stacks and/or Local Extract etc.
• Maintain background ventilation in all rooms each day, ensuring vents etc. are kept open;
• Air bedrooms and living rooms daily by window opening for 10 – 20 minutes each day (e.g. while cleaning);
• Operate extract fans, set passive stacks to maximum or open a window while cooking. Maintain maximum airing for 10 - 20 minutes after cooking;
• Operate extract fans, windows etc. during and after showering. Vents should be left open for some hours.
• Do not allow indoor temperatures to fall below 16ºC since the capacity of the air to absorb moisture becomes drastically reduced thus increasing the risk of condensation.

6 Additional Design Issues

6.1 Safety

Back-draughting of combustion products from open flue combustion devices into the occupied spaces can occur where ventilation systems cause the internal pressure to be lower than external pressure. It is therefore necessary to ensure that supply air rates are equal to or exceed extract rates to provide a slight positive pressure within the occupied space. It is also important to ensure that the ventilation system provides sufficient fresh air to meet the combustion air needs of the device and the other fresh air needs within the space. Regulations often cover ventilation of open flue combustion devices separately from and in addition to ventilation for other purposes.

Radon gas emitted from the ground can pose health risks where natural concentrations are high. Control is usually achieved by taking measures to prevent gas ingress into the building. These measures generally consist of providing a ventilated void between the building and the ground and including a gas barrier in the building ground floor construction.

6.2 Siting of Inlet/Outlet

6.2.1 Re-entrainment

The location of ventilation inlets relative to outlets should be such that re-entrainment of exhaust air into the fresh air supply is minimised. This issue is of most relevance to balanced mechanical ventilation systems, although developments in passive stack systems may lead to similar considerations being applied.

Exhaust air is generally neutrally buoyant and dispersal is therefore dominated by prevailing winds and air-flow patterns around the building. General guidance can be given for the relative location of inlets and outlets as follows:

- Inlets should be located as far away from pollution sources as practicable;
- For locations with a prevailing wind direction, inlets should be located upwind of the outlets;
- For locations where several wind directions are prevalent, inlets should be located at a lower level than outlets.

Even following this simple guidance may not completely avoid re-entrainment where local air-flows set up areas of recirculation, such as on the leeward façade of buildings.

6.2.2 Pollution

External pollution can have a detrimental affect on indoor air quality. The effects of some pollutants can be reduced for supply or balanced mechanical ventilation systems by the careful siting of inlets.

Traffic pollution is generally localised and will therefore have a greater effect on those buildings close to the pollution source. Concentrations of pollution from traffic are highest where traffic is slow moving or vehicles run engines while stationary. Studies also suggest that traffic pollutant concentrations reduce with height. Ventilation inlets should therefore be located away from sources of static or slow moving traffic and at high level.

Local sources of pollution may exist, other than traffic, which should be taken into consideration when locating ventilation inlets. These include:

- Plumbing and oil vents;
- Boiler flues;

- Stagnant water;
- Roosting ledges for birds (potential biological contamination);
- Areas of vegetation (potential source of fungal spores and pollen);
- Areas where litter can accumulate.

6.3 Thermal Comfort

In order for the human body to maintain a consistent temperature it is necessary for the heat lost by the body to the surrounding atmosphere to equal the metabolic energy production of the body.

The sensation of thermal comfort is influenced by a range of parameters which constitute the thermal environment and upon the metabolic rate. These include:
- air temperature,
- mean radiant temperature,
- air velocity,
- air turbulence,
- moisture,
- clothing level,
- activity,
- radiant asymmetry.

One measure used to determine thermal comfort is the dry resultant temperature. This combines the air temperature, mean radiant temperature and air velocity as indicated by the following equation:

$$t_c = \frac{t_{ai}\,(10\nu)^{0.5} + t_r}{1 + (10\nu)^{0.5}}$$

t_c	dry resultant temperature (^{o}C)
t_{ai}	inside air temperature (^{o}C)
t_r	mean radiant temperature (^{o}C)
ν	air speed (m/s)

An alternative measure of comfort is the Predicted Mean Vote (PMV). This combines air temperature, mean radiant temperature, air movement and humidity with level of clothing and activity into a single equation derived by Fanger and dealt with in more detail in ISO 7730. The PMV figures can be related to the predicted percentage of occupants dissatisfied (PPD) using the equation below and illustrated in Figure 6.1.

$$PPD = 100 - 95 \exp[-(0.03353PMV^4 + 0.2179PMV^2)]$$

At low indoor air speeds the air temperatures at which building occupants will feel comfortable will depend to a great extent on their level of clothing and on the activity they are engaged in.

Air movement can have a significant impact on comfort. Excessive air movement during winter months (air speeds over 0.3m/s), particularly over the neck, will lead to discomfort. CIBSE Guide A indicates that increased air speeds can be offset by increasing the air temperature, as illustrated in Figure 6.2. During summer months increased air movement may actually be a benefit due to the additional cooling effect produced.

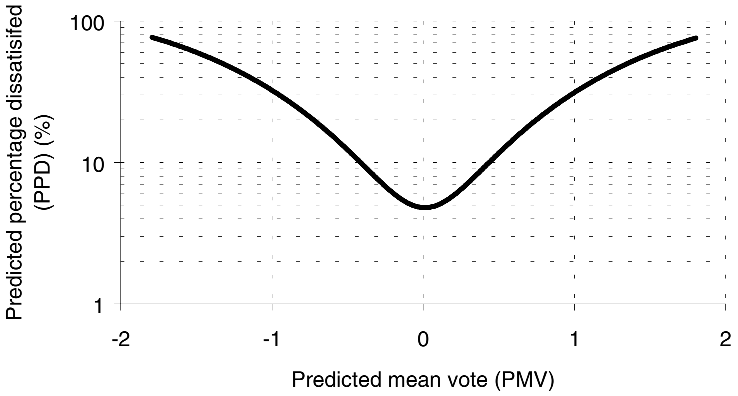

Figure 6.1: PPD vs PMV

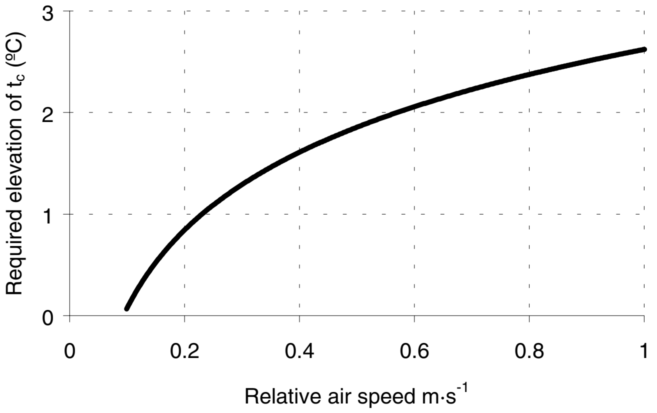

Figure 6.2: Increased Air Temperature vs Air Speed

Draughts can result not only from excessive ventilation rates but also due to the design and position of ventilation openings. Purpose provided vents or mechanical supply vents should be designed to ensure good mixing of cool fresh air with warmer room air before coming into contact with occupants.

6.4 Noise

Noise can be an important consideration when designing ventilation systems. There are three sources of noise that need to be considered:

- External noise from outside the building;
- Noise generated by the ventilation system itself (fan noise);
- Noise transmitted by ductwork or vents connecting rooms or dwellings.

Any of these sources can lead to dissatisfaction with the ventilation system if the system has not been designed to avoid creating excessive noise levels.

The importance of each source will depend on the ventilation system being designed as illustrated in Table 6.1.

Table 6.1: Importance of Noise

	Natural Ventilation	**Mechanical Extract**	**Balanced Mechanical**
External Noise	important	minor	minor
System Noise	irrelevant	important	important
Sound Transmission	minor	minor	important

6.4.1 External Noise

Noise generated by traffic, industrial processes and other external activities can become a nuisance within the dwelling if suitable barriers to sound transmission are not inherent in the building façade. Typical standards for sound levels resulting from external noise are 35dB(A), but some countries set tighter requirements of 30dB(A) (Sweden, Finland).

The sound level within a room resulting from externally generated noise will be a function of the noise reduction properties of the façade and the room absorbtance. Noise can travel through the façade via a number of routes, many of which are connected with the ventilation system. These routes include:

- Wall components;
- Window;
- Cracks and gaps within and between components;
- Purpose provided ventilation openings.

Cracks within and between components can be minimised by careful construction and the weatherstripping of windows and doors. These measures will also reduce infiltration thus requiring alternative purpose-provided ventilation openings.

Purpose-provided vents can be sound-proofed to improve their acoustic performance. After weather stripping this is the most effective measure of improving the acoustic performance of the façade.

The acoustic performance of windows can be improved by using higher standards of glazing. A typical double glazed unit may be 4mm glass – 12mm air gap – 6mm glass compared to a higher acoustic performance unit of 8mm glass – 20mm gas-filled gap – 10mm glass.

It may also be necessary to apply acoustic measures to any shunt ducts or passive stacks associated with natural ventilation systems where the building façade provides good noise reduction. If, however, the noise reduction performance of the building façade is poor, such ducts will have little influence on the noise level within rooms.

6.4.2 Ventilation System Noise

Noise generated by the ventilation system itself comes from fans and aerodynamic noise from fittings and outlets. Most countries have a limiting room noise level resulting from ventilation systems of 30dB(A).

Typically fans for single-family dwellings have A-weighted sound pressure levels of 60 to 65dB(A). The noise generated by the fan will be propagated through the ductwork system. With no sound reduction measures, noise levels of 30 to 45dB(A) can be experienced in rooms. To reduce the noise levels soundproofing materials should be placed immediately after the supply fan but before any branches.

Silencers for residential ventilation systems usually consist of a perforated inner duct, wrapped in mineral wool with an outer duct, and are often flexible. Performance is limited where duct sizes exceed 250mm, but below this these simple silencers are easy to integrate into ductwork systems.

Fans should also be mounted on suitable anti-vibration mats or fixings and connected to the ductwork system by flexible ductwork.

Aerodynamic noise can be minimised by careful duct design, specifically:

- Maximum velocities should be below 4m/s in main ducts and 2m/s in branches,
- Round ducts should be used where possible,
- Sharp bend and section changes should be avoided.

Manufacturers publish information regarding the acoustic performance of terminal devices. This should be used to choose suitable terminals to achieve the required room sound power levels.

6.4.3 Sound Transmission in or between Dwellings

Sound can be transmitted between dwellings or between rooms via ventilation ductwork or internal ventilation openings. Standards are typically expressed as the average sound reduction index in the range 125 to 2000 Hz, with standards between dwellings being higher (50 to 54dB) than those for internal noise transmission (34dB).

Common ductwork between dwellings for balance mechanical or natural ventilation systems will require some soundproofing measures, typically using soundproof terminals or silencers between terminals. Similar measures may also be required for ducts between rooms within a dwelling.

Where vents or doors from rooms are adjacent to each other, cross-talk can be a problem. The best solution is to avoid this situation by careful dwelling design. However, where this situation is unavoidable, improving the sound reduction of other wall components can ensure the overall performance of partitions remains acceptable.

6.5 Visual Appearance

Equipment and plant associated with ventilation will have an impact on both the internal and external appearance of the building.

Internally, grills associated with purpose provided openings or mechanical supply/extract systems will be the main visual elements. These will often be required to be sited to be as unobtrusive as possible, while maintaining good air distribution.

Externally, chimneys, passive stacks, extract and inlet grills can all have a visual impact. Choice of colours and location can be used to minimise this.

6.6 Construction

The ventilation system will impact on the building construction, both in terms of space required for the system and in terms of buildability.

Ventilation systems such as passive stack impose limitations on the building due to their design requirements. Vertical stacks must be provided with limited bends, termination locations are critical and space requirements can be high. Other systems such as mechanical ventilation are more flexible in terms of design but require careful planning to keep pressure drops within reasonable limits. Even purpose-provided openings require installation into either windows or through walls.

Most ventilation systems will require space allowances for containing the system, but in addition to this, space allowances for installation, maintenance and replacement must also be provided.

6.7 Reliability

Reliability in the context of residential ventilation relates to the ability of the ventilation system to provide the necessary minimum ventilation rates throughout the life of the building and under a range of external conditions.

Work carried out under Annex 27 identified three major factors which influence the reliability of a ventilation system:

- Outdoor weather conditions,
- Dust accumulation in ducts and other components,
- Malfunction of ventilation system equipment.

A fourth factor could be included as user interaction with the system.

6.7.1 Weather

Outdoor weather conditions will have a significant influence on the reliability of natural ventilation systems as they will determine the available driving forces. Passive stack ventilation systems are designed to try and avoid the worst of these effects but will still be influenced to some extent. Mechanical systems are less affected by outdoor conditions provided the dwelling is well sealed.

6.7.2 Dust Accumulation

Dust accumulation and malfunction of equipment obviously relate to mechanical systems. Measurements of the performance of real systems have shown the significant influence dust build up can have on system performance. Wallin [1978] showed that cleaning of ventilation systems can increase flow rates by around 25%.

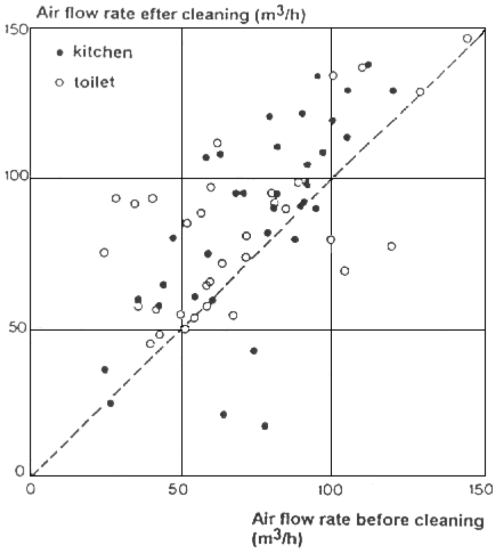

Figure 6.3: Comparison of Air Flow Rates through Exhaust Air Terminal Devices in a Multi-Family Building Before and After Cleaning

Further work in the early 80s suggested that air flow rates can drop by around 50% only one year after cleaning. It is therefore necessary to carry out regular cleaning each year to maintain ventilation performance.

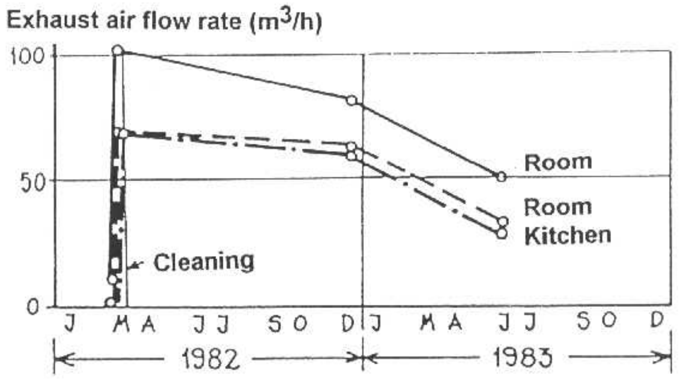

Figure 6.4: Air Flow Rate through Exhaust Terminal Before and After Cleaning

6.7.3 Component Failure

Malfunction of ventilation components mainly relates to mechanical systems. However, some consideration may be given to simplified analysis of natural systems such as passive stack.

Table 6.2: Expected Lifetime and Maintenance Costs as Proportion of Installation Costs

Component	**Life Span (Years)**	**Annual Maintenance Cost, % of Investment**
Air heaters, water	20	2
Air heaters, electric	15	2
Control equipment	15	4
Cooing compressor	15	4
Dampers	20	1
Dampers with control motor	15	4
Diffusers	20	4
Duct system	30	1
Exhaust grills	20	4
Fans	20	4
Fans with variable speed	15	6
Filter, cleaned	10	10
Filter, exchanged	1	10
Heat exchanger	15	4
Heat pump	15	4
Motor, electric	20	1
Pipes, copper	30	1
Pumps, open system	15	2
Pumps, closed system	20	2
Valves, manual control	30	4
Valves, automatic control	15	6
Valves, manual shut off	30	2
Valves, automatic shut off	15	4
Wiring	30	1

A number of studies have been carried out on component failure and reliability, notably IEA Annex 25 and work by Svennberg [1994], although there is no comprehensive data. Alternatively recommended maintenance intervals can be used to determine the likely reliability. Most “best” interval schemes recommend visual inspection of components every 3 months, cleaning every 6 months, check on pressure drop across filters every 3 months with replacement/cleaning once a critical pressure drop is reached.

Standard methods of analysing system failures due to component failure exist. These are either deductive (Fault Tree Analysis, Event Tree Analysis) or inductive (Failure Models and Effects Analysis). Deductive methods start with a top-event and work downwards through the system until the cause of the top-event is identified. Inductive methods start at a fault in a component and work up through the system to determine the likely end result on the system. Inductive methods are most commonly used for component design, while deductive methods can be used for very complex installed systems.

6.7.4 Human Influence

Human influence on ventilation system performance is discussed in more detail elsewhere in this document. However, when discussing system reliability the potential for the operator to misuse the system, leading to poor performance, must be considered. Where possible the ventilation system should be chosen and designed to minimise the potential for misuse.

6.8 Life Cycle Costing

Costs relating to buildings are usually considered in terms of initial or capital cost only. When dwellings are being built or refurbished for sale then there is little incentive to consider running costs. However, when the running costs are to be borne by the same organisation as the initial build costs then it is more appropriate to consider the overall life cycle costs.

Life cycle cost analysis is essentially the same as an investment appraisal. For residential ventilation systems this should take into account the initial capital cost of the system, component replacement costs during the life of the building, maintenance and operating costs.

The basis for life cycle costing is the concept of Discounted Cash Flow. This assumes that if we invest money today we will expect to increase its value over the duration of the investment. Thus for every Euro invested over a period of n years we will expect this to be worth $(1+r)^n$ at the end of the investment period where r is the interest rate over the investment period. Conversely we can determine that a Euro n years in the future is worth $1/(1+r)^n$ Euro today. This is known as the Net Present Value (NPV) and is a measure of the value of an investment. The value r is known as the discount rate, usually set to prevailing interest rates for public projects but higher for the private sector.

An alternative method of assessment is the Initial Rate of Return (IRR). Simply, this is the rate of interest r that reduces the NPV to zero.

In reality NPV calculations will have limitations.

Capital rationing results from there being a limited supply of capital available. It is therefore necessary to choose those projects which will be funded. NPV can be used to make these decisions. Alternatively the Benefit Cost Ratio can be used.

Financial risk in choosing a particular system will depend on the variable elements of the life cycle cost analysis. For ventilation systems this risk is most likely to be related to the cost of energy.

Opportunity cost relates to the fact that spending money on the ventilation system will take that money away from other potential areas of investment. A straight comparison between different ventilation systems will not take this into account. However, analyses that consider alternative investments become very complex. Attention is drawn to a paper by Gustafsson and Karlson [1987], which covers this subject in more depth.

7 Commissioning

In order to ensure that any system operates according to the design intent, it is necessary to carry out commissioning once the system has been installed.

Commissioning codes exist for mechanical ventilation systems such as the CIBSE Commissioning Codes A, however, time and cost pressures make these difficult to apply fully in residential buildings. Often such codes are not specifically aimed at residential buildings, although Sweden has introduced the Boverket procedure (Obligatorisk Ventilations-Kontroll, OKV), which presents a practical performance-orientated approach for system checking and is published by The Swedish National Board of Housing [1992].

Ongoing work by The Energy Performance of Buildings Group at Berkeley Laboratories in the USA (http://commissioning.lbl.gov) is developing comprehensive residential commissioning procedures, including the building envelope, ventilation systems and combustion devices. To date this work has reviewed existing literature with a view to identifying measurable performance indicators, methods of measurement and norms against which measured values can be compared. Areas where more work is need to develop matrices and norms have also been identified.

Work has also been carried out in Europe under the European Commission’s Joule programme “TIPVENT – Towards Improved Performance of mechanical VENTilation systems”. This work has investigated a performance-orientated approach to the design, commissioning and operation of ventilation systems. The advantages of such an approach are its encouragement of innovation and the improved component performance resulting from the need to meet commissionability and maintainability criteria.

Both pieces of work indicate that performance targets can be set at three levels, building level, system level and component level. Building level performance targets are indoor environmental performance or energy performance of the whole building. These will be influenced by the ventilation system but will also be related to other systems within the dwelling. System and component performance are much easier to directly use as part of the commissioning process. However, it is not sufficient to consider the ventilation system or its components in isolation as there will be interaction between different dwelling components.

Although performance indices can be identified and measured for ventilation systems, a number of areas have been identified where more work is required to determine techniques more readily applicable to the residential market. These include, duct leakage detection, measurement of ventilation system effectiveness/efficiency, measurement methods for IAQ, measurement of air velocity and testing for back-draughts.

7.1 Building Envelope

In order for a chosen ventilation system to operate effectively and energy efficiently the building envelope must be constructed to the appropriate level of air tightness. Buildings that are naturally ventilated do not need to be as air tight as those which are mechanically ventilated. There is, however, a practical minimum air tightness for all ventilation systems.

A number of parameters can be used to determine building envelope air tightness. These include airflow rates at differential pressure (ACH50, CFM50), air leakage areas and air barrier type.

Blower door pressurisation tests and tracer gas tests are the main measurement techniques used to determine building air tightness. Other techniques include combining pressurisation test with infra-red thermal imaging and draught sensation testing.

Norms against which the measured values can be compared are given in standards and codes of practice.

7.2 Air Distribution Systems

The air distribution system can be tested for both thermal performance and ventilation performance. Some parameters can be used for identifying both the thermal and ventilation performance, while some are unique to one or the other.

Thermal performance parameters include delivery effectiveness and efficiency, heat recovery effectiveness and efficiency or duct leakage flows and areas. Ventilation performance parameters include air flows or ventilation effectiveness and efficiency.

A range of diagnostic techniques are required to determine the above performance parameters. Flow measurements can be carried out using pilot-tube measurements, tracer gas techniques, static pressure measurements at specific points and the use of calibrated fans. Room air flows can be determined using flow hoods, anemometers or even timing the collection of known volumes of air from ventilation supply points. Duct leakage tests can be carried out using pressurisation tests or tracer gas tests, but are burdensome in residential situations.

Norms for duct systems are given in codes of practice and standards such as ASHRAE. Ventilation rates are also given in standards.

When the ventilation system is also used to provide heating and/or cooling to the dwelling then commissioning of additional equipment may be necessary as part of the ventilation system commissioning. Heating device performance is usually measured in terms of capacity and efficiency. Simple tests such as gas meter “clocking” can be used to determine steady-state capacity, while temperature and carbon dioxide measurements can be used to assess burner efficiency. Norms for these values are given in standards and building codes. Similarly cooling system performance is measured in terms of capacity and efficiency. An additional performance characteristic for cooling systems is refrigerant charge. Most diagnostic techniques described are based on laboratory tests, which may be too complex and time-consuming for commissioning. Norms for capacity and efficiency are available from standards and building codes, but there are no suitable norms for refrigerant charge.

7.3 Back-draughts

Combustion devices must be considered in terms of ventilation to ensure that adequate ventilation is provided for their correct and efficient operation and to ensure that back-draughts are not caused by interactions between the combustion ventilation system and the house ventilation system.

The assessment of back-draught risk is covered by ASTM, “Guide For Assessing Depressurisation-Induced Back-draughting and Spillage From Vented Combustion Appliances”, 1998, Philadelphia, PA; American Society for Testing and Materials and CGSB, “CAN/CGSB-51.71-95, Method To Determine The Potential For Pressure-Induced Spillage From Vented, Fuel-Fired, Space Heating Appliances, Water Heaters and

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Parameters used to determine the risk of back-draughts include house depressurisation, pressure difference created across the ventilation system, the maximum indoor to outdoor pressure difference against which a combustion gases can flow.

House depressurisation can be assessed by measuring the indoor/outdoor pressure difference created with the ventilation and combustion systems operating in combination. If the combustion device is off, then the same test can be used to determine downdraught. All the tests associated with back-draught are difficult to implement as they are all affected by wind and other variable natural driving forces. Further development work is necessary to provide a suitable test for residential buildings.

Norms are given in CGSB [1995] and ASTM [1998].

7.4 Controls

There is little documented information on the commissioning of residential controls. General commissioning codes for non-residential buildings indicate the methodologies that can be used, but may be too costly to carry out fully.

CIBSE Commissioning Code A 'Air Distribution Systems', indicates that checks need to be carried out on the building and air distribution system before the controls can be commissioned. It is necessary to ensure the building is sufficiently advanced to carry out pressure test, that the air distribution system has been leak tested, that the air distribution is clean and that all electrical systems have been checked.

CIBSE Guide H 'Building Control Systems' splits the commissioning of controls into two main areas, checking the control systems work and setting the parameters and switches to appropriate values. Suitable control settings may be found in design, environmental and good practice guides. These will vary with location.

7.5 Environmental Issues

The internal environment will be significantly affected by the ventilation system. As discussed above, measures such as IAQ and thermal comfort can be used to identify whole dwelling performance.

IAQ performance can be determined from parameters such as pollutant levels or indexes (pmm) relative to time, humidity or vapour partial pressure, or pollution generation and removal rates. However, measurements are not easy for a number of pollutants and pollution level will depend on occupant behaviour. Therefore measurement as part of the preoccupation commissioning process may not have any value.

Thermal Comfort performance can be determined from parameters such as air temperature, mean radiant temperature, air velocity and relative humidity. Measurement is relatively simple, however, occupant behaviour and perceptions can have an effect on the PMV and so such analysis may not be appropriate to preoccupation commissioning.

Both IAQ and thermal comfort are more appropriately assessed during occupation.

IAQ norms are available from standards and from legislation, see Section 4.

Environmental Audits

Environmental audits may be required on dwellings either by local legislation or by clients. Some of the requirements of such audits may provide guidance on the quality of installation.

Systems such as the Eco Homes award in the UK give credits for the calculated CO_2 emissions. These emissions are related to the overall energy consumption, the calculation for which takes account of the dwelling air tightness and ventilation design.

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