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A Review of Ventilation and the Quality of Ventilation Air

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Abstract Ventilation is pivotal in terms of securing optimum indoor air quality. In addition, it also has a major impact on energy use in buildings. It is important, therefore, that the role and impact of ventilation is fully understood and that ventilation is employed efficiently. The purpose of this paper is to review these aspects with particular reference to recent research and developments. Key aspects are concerned with identifying the role of ventilation and reviewing this role in the context of the other measures that must be taken to secure a healthy indoor environment. References are particularly made to the development of standards and recent related research. Although good progress is being made, areas that still need to be addressed include maintaining good outdoor air quality and preventing contaminated outdoor air from entering buildings. The outcome of recent research must also be disseminated in practical ways to policy makers, building occupiers and practitioners. Good indoor climate can be achieved, not so much by introducing expensive concepts, but by developing a rationale approach to identifying needs and applying the necessary tools to deal with each need.

Key words Ventilation; Filtration; Outdoor air quality; Indoor air quality; Standards.

Practical Implications
This paper reviews ventilation and its impact on indoor air quality. It looks, first, at outdoor air quality and develops a hierarchy of procedures to ensure that clean air is delivered to the building. The treatment of indoor pollutant sources is then considered and the role of ventilation is described in the context of other mitigation methods. Recent standards are referenced covering ventilation requirements and filtration. A step-by-step approach to achieve good indoor air quality is stressed and described.

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Introduction

Ventilation plays a fundamental role in maintaining good indoor air quality and thermal comfort in buildings. In fulfilling this need it touches on a wide range of topics associated with building design and services. Added to this, it is estimated that more than 40% of primary energy in OECD (and European) countries is consumed in buildings and that half of this is dissipated through ventilation and air infiltration. In investigating the impact of ventilation, it is important to consider various aspects including the role of ventilation, minimum ventilation need, ventilation mechanisms, climate, location, cooling need and the quality of ventilation air. The purpose of this paper is to provide a brief review to recent work associated with the elements that contribute to securing effective ventilation.

The Role of Ventilation

Ventilation is the process by which 'clean' air is intentionally provided to a space and 'stale' air is removed. It may either be blended with the existing room air (mixing ventilation) to uniformly dilute pollutants or it may be introduced without mixing (displacement ventilation) so that the breathing zone for occupants becomes separated from polluting sources. Modern strategies frequently aspire to the displacement approach but this requires careful design and, very often, separate measures to provide thermal conditioning (both heating and cooling) to a space. For effective and energy efficient ventilation, the primary role of ventilation should be to dilute and remove pollutants that are unavoidably emitted into a space. In essence this is the metabolic pollution generated by occupants and the pollution generated by the essential activities of occupants. Very often, however, ventilation is called upon to remove gaseous and particulate pollutants that have been imported into a space without sufficient regard to the impact on indoor air quality. This area has been of particular concern within the Indoor Air research community.

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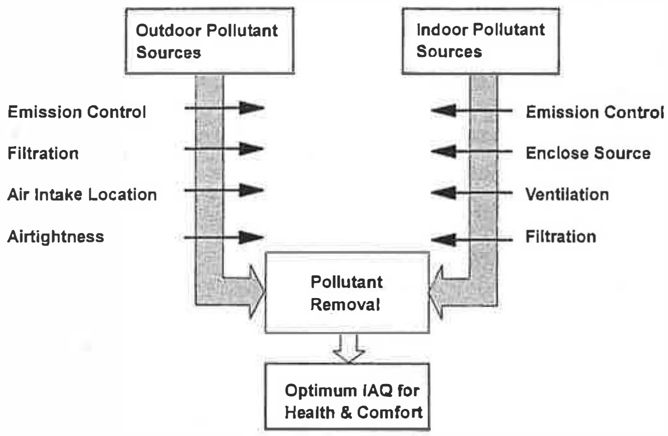

Fig. 1 Achieving optimum indoor air quality

Although ventilation performs such a major part of building service design and installation, it needs to be viewed in the context of the total air quality equation. In this way, it is possible to develop more effective approaches to ventilation and identify important new research needs. The various steps for achieving optimum indoor air quality are illustrated in Figure 1.

From this figure, it can be seen that ventilation represents a small component of a much larger chain. In part the operations listed are hierarchical and it is important that the details to the left and directly above the ventilation component are assessed first. Developments in each of these areas are summarised below.

Outdoor Air Quality

Good outdoor air quality is an essential prerequisite for effective ventilation, yet increasing urbanisation and contaminant emissions into the atmosphere is presenting difficulty. Significant sources of local pollution include regional industrial pollution, pollution from vehicles and pollution emissions from adjacent buildings. In agricultural regions, pollen and chemical sprays can also be a problem. The importance of achieving good outdoor air quality cannot be overstated. Stevenson (1999) at the London School of Hygiene, for example, reports on an epidemiological study linking respiratory related deaths to traffic fumes in urban areas. Respiratory problems related to urban pollution are also reported by Anderson et al. (1997), and by the North American Six cities study (Lauerman, 1999).

The resultant pollution entry into buildings is widely documented (Limb, 1999). Kukadia et al. (1996) have undertaken extensive measurements and studies on the impact of urban pollution inside buildings. These studies note that the concentration of external pollutants found in monitored buildings followed the daily external variation although at a lower concentration. Also, Green et al. (1998) describe two separate experiments in which carbon monoxide (CO) from traffic is monitored inside buildings.

Solutions to Outdoor Air Quality Problems

The structure for dealing with outdoor air pollution should be based on the following.

Emission Controls

Depending on the type of pollution, outdoor air quality can be a national or even an international problem. For this reason emission controls must be covered by legislation. In the United States, for example, emissions are covered by the Clean Air Act, while, in Europe, it fits within the European Air Framework Directive (1999). Approaches within the legislation include emission caps, permits, offsets and target dates for reduced emissions. Because of the proven impact of adverse outdoor air quality on people, it is essential that governments continue to monitor and restrict the emission of pollutants into the atmosphere.

The Siting of Air Intakes

Some outdoor pollutants are localised. These include exhaust outlets from other buildings and roadside pollutants. While regional monitoring, therefore, might indicate acceptable pollutant concentrations, the concentration close to individual buildings may be unacceptably high. To overcome this, a survey of local sources must be made and then the air intakes for the building must be located away from the proximity of such sources. New guidance on the siting of air intakes has recently been published by Rock and Moylan (1999), as part of an ASHRAE sponsored research project and by Irving and Palmer (1997), as part of a UK (CIBSE) research project. In The Netherlands, a Code of Practice and regulations (1998) have been introduced covering the location of air inlets. This is based on an acceptable dilution factor depending on the type of pollutant emitted from nearby exhaust stacks. Frequently, local urban air quality exhibits diurnal behaviour with peaks being associated with rush hour traffic. Where this is the case, the automatic control of air intake dampers has been attempted. Fletcher (1997), for example, illustrates this daily variation, with peaks occurring at rush hours. His paper presents potential control techniques for periods when outdoor air quality is poor based on pollutant monitoring combined with intake damper control.

Filtration

Filtration is commonly practised and is an obvious solution to dealing with external pollutants. It is almost universally used in conjunction with mechanical ventilation systems associated with fully air-conditioned buildings. In the European Union, filtration performance is governed by a Standard 'EU' rating which categorises filtration performance by means of the efficiency with which it can trap particles of varying size. The classification system is presented in Figure 2. More detail is presented by Macdonald (1999).

Typically, an EU3 filter would be used for prefiltering, coupled to an EU6 or EU7 main filter. This gives approximately 97% efficiency down to 2.5 μm and between 44% (EU6) and 55% (EU7) at 0.1 μm. Subject to good design and building airtightness, this filtration approach is therefore potentially effective at reducing the higher end of respirable particle concentration. To reduce fine particle concentration (e.g. below 2.5 μm) by a greater amount, however, high efficiency (HEPA) filters in the EU10–14 range must be considered. Also gaseous components must be controlled using gas adsorption filters. In comparison to conventional filtration, gaseous and HEPA filtration is expensive. This is because of the cost of achieving the necessary performance specification of the filters themselves, their relatively limited holding capacity and because of the additional pressure drop across such filters. Additionally, such filters must be placed after conventional filtering, hence adding to the overall energy needed to overcome the total filtration pressure drop. All filter assemblies also suffer from increased pressure drop (from a few 10s of Pascals up to, possibly, several hundred Pascals), as they are loaded with contaminants. This effect has to be incorporated into the design and means that fan ratings may need to be much higher than for basic dust filtration.

In the United States, filtration is covered by ASHRAE Standard 52.2–1999. This classifies performance by particle removal efficiency using a standard Minimum Efficiency Reporting Value (MERV). There are a total of 16 performance ranges covering efficiency in three particle size ranges (i.e. range 1: 0.3–1.0 μm, range 2: 1.0–3.0 μm and range 3: 3.0–10.0 μm). A MERV value of 1 covers the lowest performance filters with an efficiency of <20% for range 3 particles. A MERV value of 10 equates to a filter with a 50 – 65% efficiency for range 2 (>85% for range 3). A MERV value of 16 equates to a filter with >95% performance in all three ranges.

Despite the benefit of filters, therefore, they should not be seen as an excuse to accept poor outdoor air quality. Filtration solutions are expensive and cannot be applied to the many buildings that are naturally ventilated (since there is insufficient driving pressure through natural air inlets) or excessively leaky (since filtration systems will be bypassed through air infiltration).

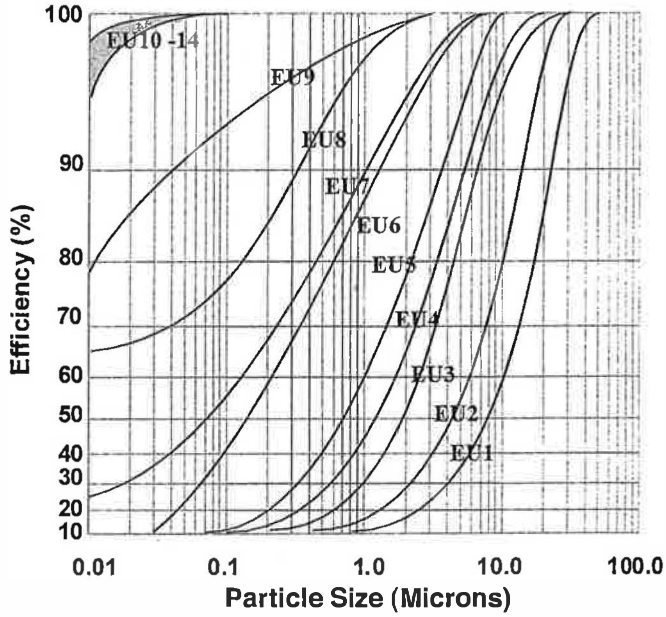

Fig. 2 Typical EU characteristics for filter efficiency

Airtightness

The tightness of the building shell is critical to the energy performance of the ventilation system. A tight shell also provides a barrier to transient outdoor pollution. Some ventilation systems, especially those incorporating air to air heat recovery systems, cannot function correctly unless the building is virtually completely airtight. This means air change rates of below 1 air change per hour (ach) at 50 Pa pressurisation. In terms of surface area of envelope, airtightness should be less than approximately 3 $m^3/m^2 \cdot h$ at 50 Pa pressurisation. On the other hand 'adventitiously' ventilated buildings rely on the natural porosity of the building. Many countries have introduced standards for airtightness. These cover not only the performance of individual components but also the construction as a whole and site practice. Before the level of airtightness is specified, it is paramount that the ventilation approach is understood. Where mechanical systems are used, the sealing of duct joints is critical, since many studies show these to be poor. Regulations and proposals for future developments are covered in the final report of the European 'SAVE Duct' programme (Carrié et al. 1999).

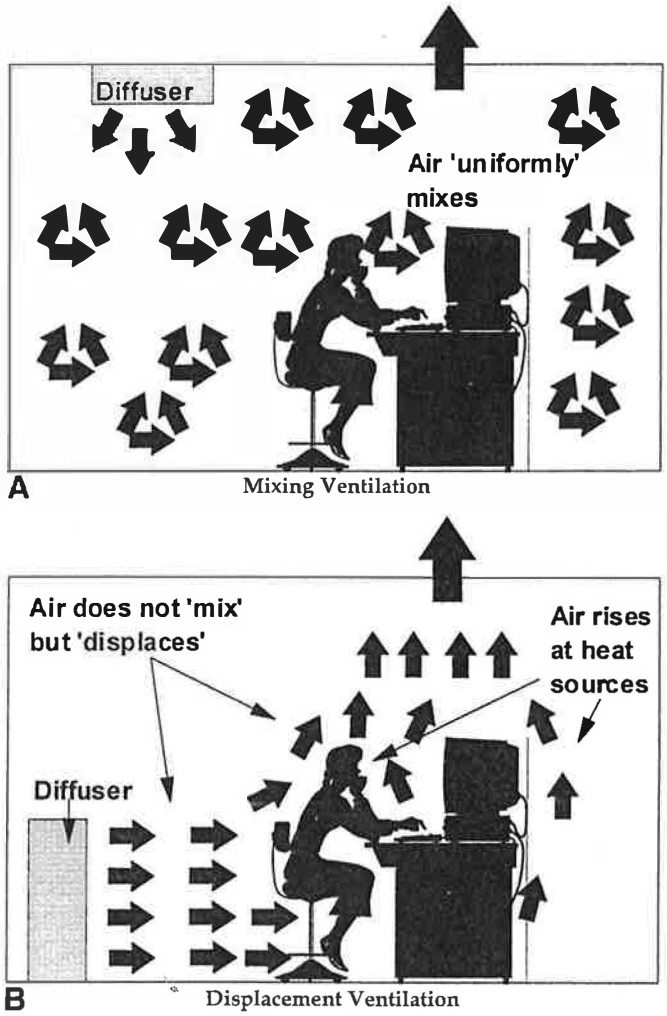

Fig. 3 Mixing and displacement ventilation (see text for description)

Solutions to Indoor Air Quality Problems

Only after the outdoor air quality is addressed should attention be directed towards dealing with indoor air quality issues. Pollutants emitted inside buildings include the products of metabolism and emissions from materials used in construction and furnishing. Important indoor pollutants are odour, particles (organic and inorganic), moisture, tobacco smoke, formaldehyde, volatile organic compounds (VOCs), bacteria and products of combustion. The order of mitigation should be as follows:

Source/Emission Control

Various standards exist or are being developed aimed at limiting emissions from materials used inside buildings. Many world standards follow or have adapted the Guidelines of ASHRAE Standard 62–1999. This Standard is currently in the course of revision. One of the major difficulties being experienced within ASHRAE and elsewhere is the liability and uncertainty associated with any prescription of 'safe' pollutant concentrations. As a consequence, ASHRAE has published a position paper on indoor air quality (1998). This outlines ASHRAE's past, current, and future interests in and responsibilities for Indoor Air Quality. It also covers the reasons for increased indoor air quality concerns and summarises problems involving the effects of indoor air quality on short and long-term occupant health and comfort. Several pollutants are examined for their perceived and real effects in indoor environments. In addition, research needs are addressed and recommendations are listed aimed at continued improvement and maintenance of acceptable indoor air quality.

Containing a Process

All polluting activities should be contained. A containment zone is normally held at a negative pressure with respect to adjacent rooms (and the outside) by the use of a mechanical extract system. Sometimes the room itself may be occupied (e.g. a hospital operating theatre) otherwise it may be unoccupied (e.g. a nuclear process). This under-pressure, combined with airtight construction, prevents air leakage from the containment zone to the surrounding area. In the laboratory, a chemical or microbiological process will be contained in a fume cupboard. In less toxic situations (e.g. domestic cooking) the containment might be achieved by placing a canopy, with extractor, over the cooking appliance. In this case there will be leakage (of moisture, odour etc.) into the occupied space but much of the pollutant will be entrapped and removed. If pollutants produced inside a containment area are highly toxic or exceed regulatory discharge criteria, then they must be removed out of the extract air stream (e.g. by filtration and/or incineration).

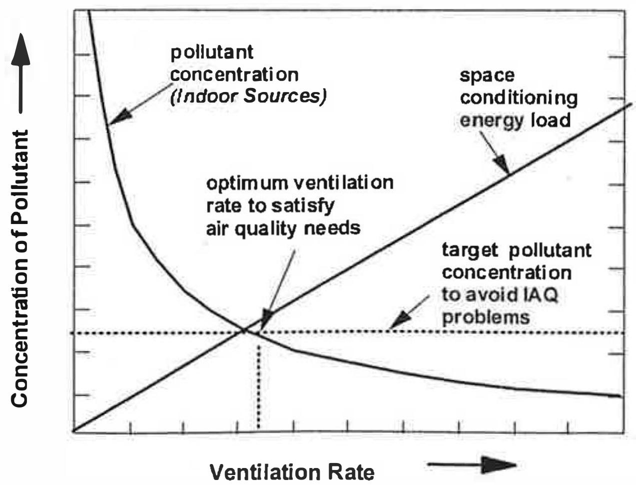

Fig. 4 Characteristics of dilution ventilation

Ventilation

In recent times, the role of ventilation in securing a good indoor climate has undergone a radical re-assessment. Classically, ventilation is used to maintain air quality by dilution (mixing ventilation) and, wherever possible, by displacement (see Figure 3A, B).

Mixing ventilation is aimed at uniformly mixing clean air into a space, thus diluting the indoor pollutant concentration. This dilution process is summarised in Figure 4. For a given pollutant emission rate, the steady concentration of pollutant within a space depends on the rate of ventilation. As the ventilation rate is increased, the ultimate steady-state pollutant concentration is reduced. This, however, incurs an energy penalty, both in terms of the loss of 'thermally' conditioned air and in terms of electrical fan energy. It is usual, therefore, to identify the 'dominant' pollutant in a space, i.e. the pollutant needing the most ventilation to reduce the steady-state concentration to, at or below an acceptable 'comfort' and 'safe' concentration. Once this is determined, the ventilation needs of the lesser pollutants will also be satisfied. This dilution approach is described in more detail in the AIVC Guide to Energy Efficient Ventilation (Liddament, 1996).

Displacement ventilation is aimed at displacing air already present in a space, rather than mixing with it. The advantage is that occupants can receive fresh air directly while thermal pollutant sources are enveloped by ventilation air, thus isolating the occupant from the pollutant. Successful displacement ventilation requires precision design and operation. Supply air should be between 2–3 K below the ambient room air temperature and emitted at low level at a horizontal velocity of, typically, 0.1–0.3 m/s. This ensures the gentle ponding of fresh air within the occupant breathing zone, followed by a vertical, thermally driven, rise of air to ceiling mounted extract points.

In theory, for a given value of indoor pollutant concentration, a displacement system can operate at a lower rate of air change than an equivalent mixing system. For added safety, however, the ventilation rate for displacement systems should preferably be based on the overall rate needed for the dilution approach. While displacement systems are capable of delivering much cleaner air to occupants than equivalent capacity mixing systems, they demand very careful design and operation. Also, they are less able to carry the heating and cooling loads of mixing systems, since mixing systems can deliver high, (thermally conditioned) air flow rates by intentional recirculation. Instead, heating and cooling must often be supplied independently by means of radiant panels and chilled ceilings.

In the United States, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in conjunction with the American National Standards Institute (ANSI) has been responsible for developing requirements for minimum ventilation, especially in relation to the current Standard, ASHRAE 62 (1999). While generally now being regarded as in need of revision, such is the public concern over defining minimum ventilation rates, that attempts to update this Standard have, so far, largely failed. In an attempt to overcome this difficulty, the ASHRAE Standards Committee approved in 1998 separating the proposed revision of Standard 62 into two separate Standards, these being: Standard 62.1: Ventilation and Acceptable Indoor Air Quality in Commercial, Institutional, and High-Rise Residential Buildings; and Standard 62.2:Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings (ASHRAE 1998).

In both cases, the scopes are aimed at defining the roles of, and the minimum requirements for, ventilation to provide acceptable indoor air quality. Also, while acceptable indoor air quality is the goal of these standards, these standards recognise that such goals may not be achieved, even if all requirements are met. This is largely because it is impossible to anticipate how the occupier will eventually operate the building and what pollutants will be imported into the space. In addition, many thousands of pollutants can be present of which the toxicological effects and threshold limit values of many are unknown. Hence these Standards can only provide guidelines for typical building use, based on the best data currently available.

In Europe, ventilation standards are being developed through CEN Technical Committee 156 "Ventilation for Buildings". Up to date accounts of current progress of both of these Standards have been published by Taylor (1999) for ASHRAE, and Green (1999) for CEN.

Filtration

While it is possible to control internally generated particles by ventilation, if the generation rate is high and unavoidable, the amount of ventilation needed may become excessive. In these circumstances, particulate pollutants may be controlled with recirculatory air filters. Assuming 100% filter efficiency, a filtration rate equivalent to the ventilation rate halves the pollution concentration. This is further reduced to 25% of the level achievable by ventilation alone by increasing the filtration rate to three times the fresh air ventilation rate. To be successful, therefore, the air handling capacity of the filtration system and the filtration efficiency must be high to accomplish a worthwhile pollutant reduction. For this reason, desktop 'air purifiers' must be regarded as totally ineffective. In The Netherlands, mixing ventilation systems incorporating recirculation must be fitted with filters to EU8 specification. To be effective, a recirculatory filtration system must fulfil the following requirements:

- It must not be used as a substitute for ventilation air needed for occupant generated pollutant or for combustion appliances;
- It must be designed to remove the particular problem pollutant;
- It must have a flow rate of at least two to three times the fresh air change rate;
- It must be well sited to intercept the polluted air;
- It must be easy to maintain and have a filter replacement indicator;
- It should be energy efficient;
- It should be free of operational noise;
- It should not cause excessive draughts;
- It should be designed to ensure that filtered air is not short-circuited back into the air intake;
- Filters should be well fitted into the assembly frame to ensure that there is no bypass leakage;
- There should be provision for cleaning;
- Air distribution across the filter should be uniform.

Maintenance

Ventilation systems must also be kept clean and be maintained, especially in the air supply network. Accumulation of dust within ductwork systems can provide a site for microbiological growth. This can result in bacterial and fungal spores being released into the occupied space as well as the emission of odour and other compounds. The control of dust contamination is improved by good filtration but provision in the system for cleaning is essential. A review of this topic is covered by Lloyd (1996). For some years, Sweden has been operating a compulsory inspection system for almost all mechanically ventilated buildings (Anon, 1992/3).

Conclusions

The impact of ventilation on energy, IAQ and thermal comfort is considerable. In addition there is a diverse range of options, guidelines and standards covering all aspects of ventilation. The purpose of this review has been to focus on recent publications covering ventilation related IAQ issues. In undertaking ventilation design it is essential that the implications and consequences of each ventilation choice is clearly understood and analysed. Too often it falls upon ventilation to accomplish tasks for which it is not appropriate. The prime role of ventilation is to meet metabolic needs of occupants and remove pollutants from unavoidable sources, i.e. pollutants generated by occupants themselves and their essential activities. All other pollutants should first be controlled by elimination or source containment.

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