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An Engineering Approach to Ventilation System Design

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Abstract
Many ventilation systems fail to meet the expectations of the occupants, despite the level of knowledge available to aid their construction, including best practice and good design criteria. This paper looks at how a ventilation system should be designed, installed and maintained in order to maximise occupant satisfaction and minimise operating costs. Contemporary design solutions are discussed, and a case study of the new parliamentary building in Westminster, London, is presented.

Introduction

Many ventilation systems fail to meet the expectations of the occupants, despite the level of knowledge available to aid their construction including best practice and good design criteria. After many decades of research, it is generally accepted that to provide a high degree of occupant satisfaction, the internal environment should: (1) have an internal temperature of 21–24 °C; (2) maintain a humidity level of around 40%; (3) provide sufficient fresh air to dilute any contaminants (8.0 litres$\cdot$s^{-1} per person minimum); (4) introduce supply air such that the air velocity is around 0.2 m$\cdot$s^{-1}.

These figures provide the basis of a comfort envelope. They are not recent findings; many of the basic parameters were established over a century ago. It would therefore seem a relatively simple task to provide a fresh and comfortable environment for the occupants of any building.

Between 1950 and 1970, the building services industries focussed attention on improving the hardware available to construct air-conditioning systems within reasonable costs. It is apparent with hindsight that not all of these systems worked [1]. Many thousands of systems were installed that performed inadequately due to inappropriate selection of hardware, poor design and defective maintenance. Regrettably, this has left a legacy of mistrust between the clients and the engineers whose ability to design an effective mechanical ventilation or air-conditioning system is held in doubt.

The 1970s saw the emergence of the energy crisis and the need for energy-efficient ventilation systems. This trend has continued to the present day, but the emphasis has swung more in the direction of installations that have a low environmental impact. Again, the development of systems that were not fully tested has led to some indifferent solutions. In any event, it is an unfortunate statistical

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Table 1. Ventilation rates required for degrees of expectation of air quality (derived from data in Fanger [2])

Category	Required ventilation rate in litres·s^{-1} per occupant			
	no smoking	20% smoking	40% smoking	100% smoking
A	10	20	30	30
B	7	14	21	21
C	4	8	12	12

Assumes an outdoor CO_2 level of 370 ppm.

fact that the ventilation engineer is unlikely to satisfy all the occupants of a building all of the time. If engineers achieve satisfaction ratings greater than 90%, they may consider this a success.

Given this history, it is not surprising that the general consensus among clients today appears to be against mechanical ventilation and in favour of natural ventilation.

Consider the criteria noted above. There seems little doubt that temperatures within the range 21–23°C provide a reasonable level of satisfaction. In the UK, the minimum statutory temperature for a place of work is set at 16°C. Unfortunately, there is no upper temperature level which is applicable to office environments. It is generally considered that this should not exceed 27°C on more than 2–3% of occasions throughout the year, but there is no reference basis for this figure.

Considerably more controversy surrounds the question of what constitutes an appropriate allowance for ventilation air. In the UK the simple answer is 8 litres·s^{-1} of fresh air per person minimum for a non-smoking office. This figure has remained unchanged for many decades and is based upon a value that is likely to dilute the pollution created by the occupants to an acceptable level. What the pollutants are is difficult to quantify as they relate principally to body odour. One pollutant often used as a measure of acceptability is carbon dioxide (CO_2) for which various criteria and legislation do exist: (1) to prevent the build-up of CO_2 to hazardous levels, a ventilation rate of 0.3 litres·s^{-1} is required; (2) to satisfy UK Health & Safety legislation, an 8-hour exposure limit for CO_2 has been set at 5,000 ppm, requiring a ventilation rate of around 1.0 litres·s^{-1}; (3) if the recommendation that CO_2 levels should not exceed 2,500 ppm is accepted, then this requires a ventilation rate of 2.5 litres·s^{-1}; (4) to maintain CO_2 levels below 1,000 ppm and control body odour levels requires a ventilation rate of 8.0 litres·s^{-1}.

Prof. Ole Fanger has proposed a method of determining the appropriate ventilation rate that went beyond an allowance based upon occupancy levels. This was embodied in a pre-standard called *prENV 1752: Ventilation for buildings* [2]. This draft proposed adding an allowance for any pollutant emitters within the building, including such things as carpets, photocopiers and wall coverings. This does seem eminently sensible.

However, engineers identify with standards that may be clearly applied. The methods proposed for calculating the ventilation rate in *prENV 1752* were considered not to be sufficiently robust, and therefore the advisory committee refused to adopt the pre-standard.

In many ways, the rejection of the pre-standard was unfortunate. It contained much more detailed information than any of the existing standards. One interesting aspect was the proposal to categorise the quality of the indoor environment at three levels: category A corresponds to a high level of expectation; category B corresponds to a medium level of expectation; category C corresponds to a moderate level of expectation. The ventilation rates corresponding to these categories are shown in table 1.

There is some debate over whether the adoption of *prENV 1752* would have increased the ventilation allowance above the normally accepted minimum standards for office spaces (8 litres·s^{-1} per person). It is not easy to determine whether this would be the case, as *prENV 1752* allowed the designer to take a number of other factors into account. However, for office spaces, it is very probable that if followed, it would increase the ventilation rate, thereby increasing the energy consumed by the ventilation systems. On the other hand, the current guidance level of providing a minimum of 8 litres·s^{-1} per person, regardless of other factors, could also lead to an over-provision of ventilation air.

An example of where this might happen could be in a large space such as a sports or leisure arena. Guidance in *prENV 1752* would allow the ventilation rate to be reduced to 4 litres·s^{-1} per person. Due to factors such as the 'reservoir effect' for a sedentary audience, a category C environment is exceeded only after 150 min (fig. 1). Even with an audience with a high metabolic rate, the HSE 8-hour exposure limit would not be reached. This level of ventilation could be considered quite acceptable for such an arena space and would result in a 50% reduction in the air supply rate which would significantly reduce both capital and running costs.

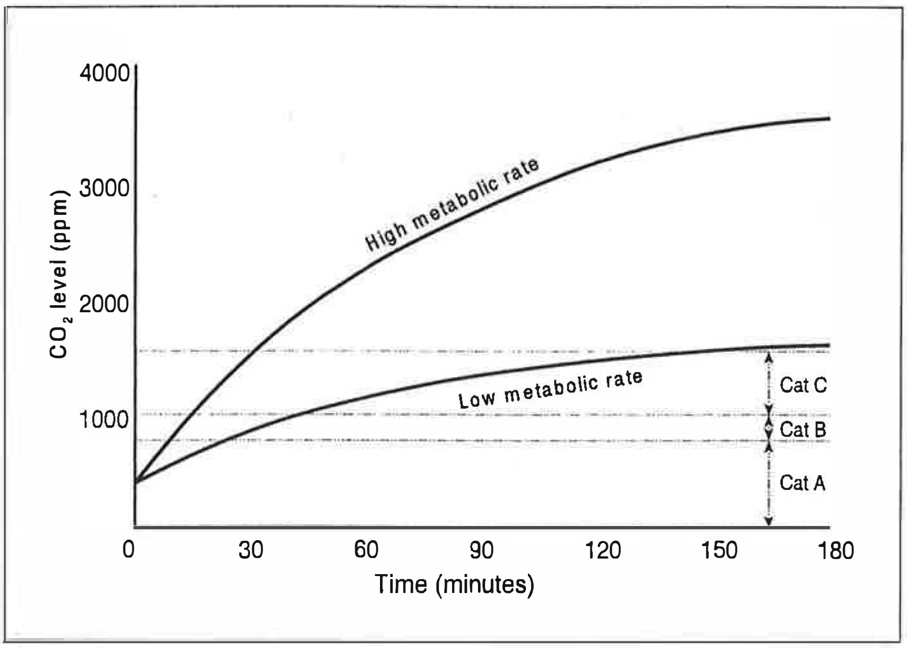

Fig. 1. Predicted CO_2 levels in a fully occupied 12,000-seat arena ventilated at a rate of 4 litres$\cdot s^{-1}$.

This paper looks at how a ventilation system for a building should be designed, installed and maintained in order to maximise occupant satisfaction and minimise operating costs. Contemporary design solutions are discussed and a case study presented.

Natural Ventilation: The Simple Solution?

Anecdotal evidence suggests that most people would prefer to work in a naturally ventilated space. Perhaps this stems from the belief that the workplace should replicate the domestic environment [3, 4]. Other reasons for preferring naturally ventilated spaces may include a psychological preference for being able to open windows. This maintains contact with the outside and makes the space feel less like a prison. The ability to open or close the window and control your own environment is understandably attractive [5, 6]. Unfortunately, other factors are likely to be present in the office environment which do not all arise in the domestic situation such as: (1) noise intrusion from busy urban environments; (2) office size; (3) restricted ability to move to another location to avoid solar gain; (4) in shared spaces – who has control of the window? (5) thermal gain from equipment and the particular environment required for the use of VDUs.

The task of the engineers becomes more exacting when they attempt to achieve the target criteria for comfort, temperature, air velocity and air quantity in a naturally ventilated space.

There are a number of methods that can be applied to evaluate to what extent these criteria may be met. But it is clear that in the UK climate, well-designed naturally ventilated buildings will still break out of the comfort envelope on a number of occasions. Although the engineer can apply a number of sophisticated tools to predict to what extent this is likely to happen, the accuracy of the predictions depends upon a number of assumptions, not all of which are readily quantifiable. Also, the design must acknowledge the effect of global warming which predicts that hot summer temperatures (last experienced in 1997, one of the hottest summers on record) will be experienced three times a decade by 2020 [7].

The client – and it must be the client, not the engineer – is faced with a difficult decision. To what extent will business efficiency be compromised when the conditions in the building extend beyond the comfort envelope? Discussions with property agents indicate that this can have a great influence on the market. Following the summer of 1997, tenants who endured overheated office spaces were determined not to accept anything less than air-conditioned spaces.

It is also a mistake to focus only on the summer conditions when deciding whether a building can be successfully naturally ventilated. This has led to problems in a number of recently completed naturally ventilated buildings

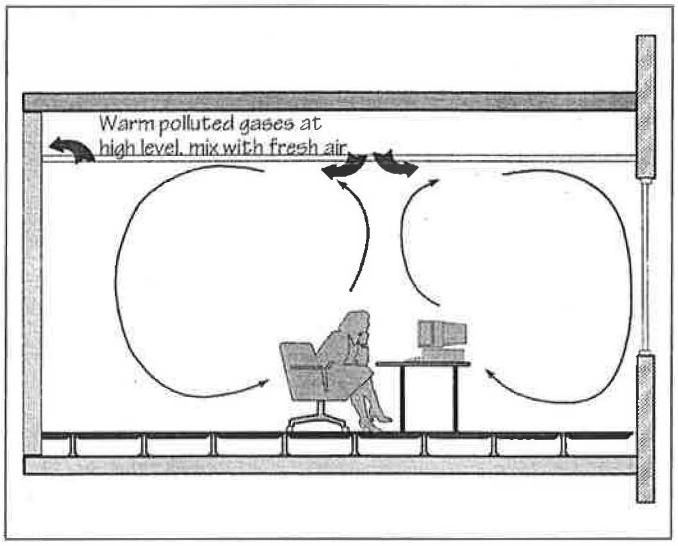

Fig. 2. In traditional mixing systems, air enters the space at high velocity in excess of 2 $m \cdot s^{-1}$. The energy in the air jet then induces movement in a significant volume of room air. If the inlet diffusers are properly spaced and rated, this will provide a general air velocity that does not exceed 0.25 $m \cdot s^{-1}$. Supply air temperature differentials may be as high as 12 °C.

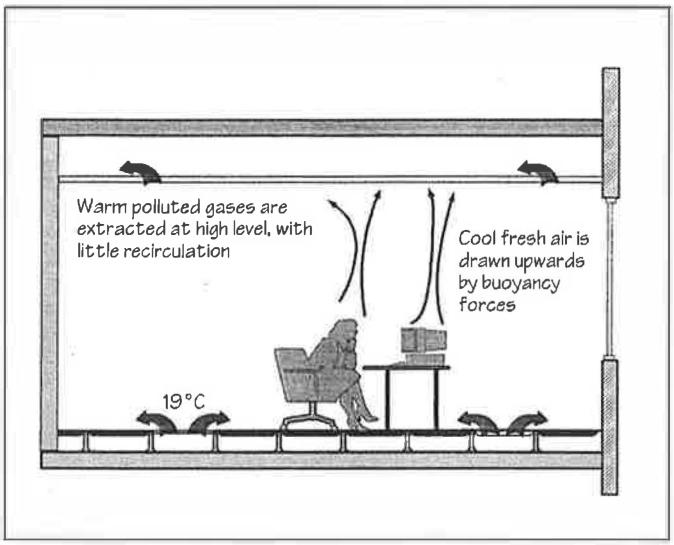

Fig. 3. Displacement systems introduce air at low level, very low velocities and temperatures of around 19 °C. When the thermal loads match the displacement air cooling load, displacement airflow patterns are established. A stratification boundary occurs when the net upward airflow equals the incoming airflow which should be kept above the occupied zone.

where minimum ventilation rates have not been maintained during the winter. Clearly, relying upon fixed openings (trickle ventilators) to maintain a minimum fresh air rate over a range of wind strengths and speeds is unlikely to succeed. Current thinking suggests that guaranteed winter ventilation rates are best achieved by mechanical ventilation.

Mechanical Ventilation Systems

The last 5 years have seen a considerable change in the types of mechanical ventilation systems installed in the UK. This has been driven by a number of factors, some more commendable than others. Installations are now required to accommodate: (1) a reduced environmental impact; (2) an increase in occupant satisfaction rating; (3) a reduction in energy costs; (4) a reduction of the installation costs; (5) marketability; (6) 'fashion' engineering.

With regard to reducing energy costs, the ultimate aim would be a building which is effectively cost-neutral. Such a building would on balance generate all the energy it requires. There would be times when it could export surplus generated energy which would be re-imported at a later time, thus it would be a net zero user of imported refined fuel.

The previously popular specification of large all air central plants connected to terminal installations, such as variable air volume (VAV) units (fig. 2), has changed in favour of fan coil installations and displacement or underfloor based systems. Displacement ventilation systems (fig. 3) have enjoyed particularly good press. Persuasive arguments have been proferred that displacement systems: (1) provide high levels of occupant satisfaction; (2) eliminate draughts; (3) minimise the recirculation of pollutants; (4) reduce energy costs. Several of these claims have some foundation.

This comparison provides a powerful argument for displacement ventilation systems. On the debit side, the displacement systems alone will rarely satisfy the needs of institutional organisations, due to their inability to cater for anything other than moderate cooling loads (25 $W \cdot m^{-2}$) in traditional buildings [8]. This has led to the marriage of displacement systems with 'complimentary' cooling systems such as chilled beams and/or chilled ceilings (fig. 4, 5) [9, 10]. Initially, it was claimed that these add-on cooling systems did not compromise the attractive concept that displacement systems do not recirculate room pollutants. This claim did not stand up to common

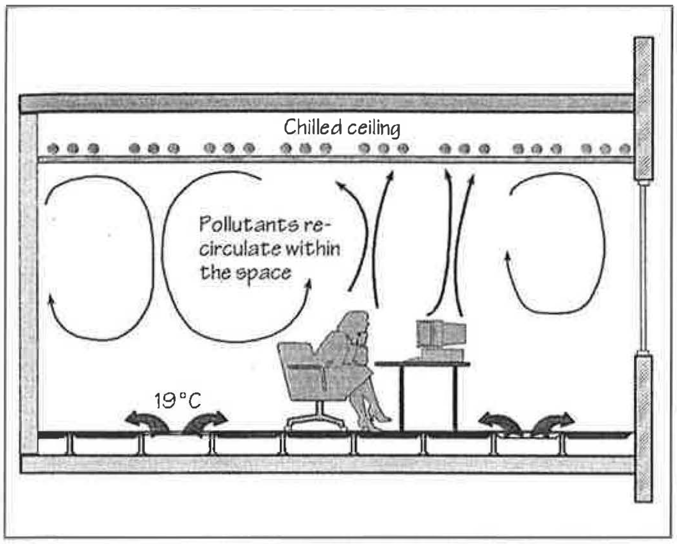

Fig. 4. Chilled ceilings transfer around 50% of the heat by radiation. They work by cooling the ceiling surface via chilled water pipework arranged in a serpentine coil fixed to the back of the panel.

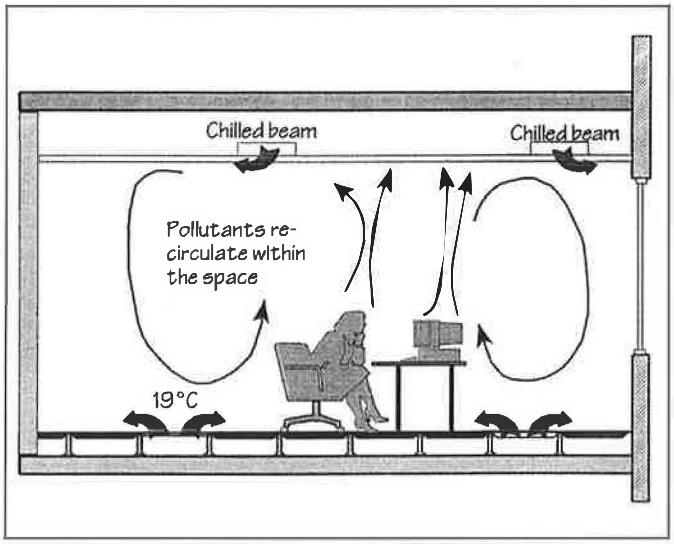

Fig. 5. Chilled beams are essentially finned tubes through which chilled water is circulated. They come in two main forms: active, where ventilation air is forced over the finned coils and passive where there is no forced ventilation.

sense scrutiny, particularly when advocates claimed that the cooling output of the relatively small chilled beams was primarily by radiation. Recent research indicates that, as suspected, this is not the case.

The results of the research show that chilled ceilings do produce re-circulatory air paths within the space. With chilled beams, the extent of the mixing will introduce pollutants from the mixed air region well into the occupied zone. This can extend to the point where the system has similar characteristics to that of a conventional mixed flow system. In addition, the primary airflow rate is likely to be significantly above the minimum required in order to ensure that the stratification level is above the occupancy level.

Care also needs to be taken in the design of chilled ceiling systems to ensure that the so-called 'office rain' effect does not arise. This problem occurs when condensation forms on the ceiling to the extent that it drips off the ceiling panels, or chilled beams. It is likely that this problem may be overstated, but if it does occur the consequences may be significant. This leaves the control regimes necessary to prevent occurrence at the mercy of poor maintenance, or malfunction.

Even so, the evidence is that properly designed displacement ventilation systems give rise to high levels of occupant satisfaction, even when they generate air movement in the space comparable with conventional mixing systems. This may be due to the higher fresh air rates, or the inherent low air velocities and noise levels generated by displacement systems. In addition, many ceiling discharge systems suffer from poorly selected diffusers, which create excessive air movement in the occupied zone.

Assuming that displacement systems do provide improved comfort conditions, there are situations where their adoption is difficult. As stated, displacement systems are unable to deal effectively with heat loads greater than 25 $W \cdot m^{-2}$. Ignoring solar gains, this would effectively only deal with the heat gains from occupants and lighting. Achieving a cooling rate of 25 $W \cdot m^{-2}$ would require a minimum of 5 $litres \cdot s^{-1} \cdot m^{-2}$ of fresh air, or 50 litres per person based upon 1 person per 10 m^2. Therefore, displacement ventilation systems require air volumes in the order of 5 times that of a fan coil installation and probably more, to operate in true displacement mode.

In many buildings, such as high-rise office spaces, this is not practical due to the increased size of the distribution ducts. Ceiling-mounted systems are therefore the only practical solution and can take many forms. One such system (fig. 6) claims to produce a 'displacement effect'.

Currently the most popular system in the UK is the fan coil system. This has a number of important advantages. Such installations may usually be installed for the lowest capital cost and will provide a high degree of flexibility, both in terms of the loads that they are able to handle and

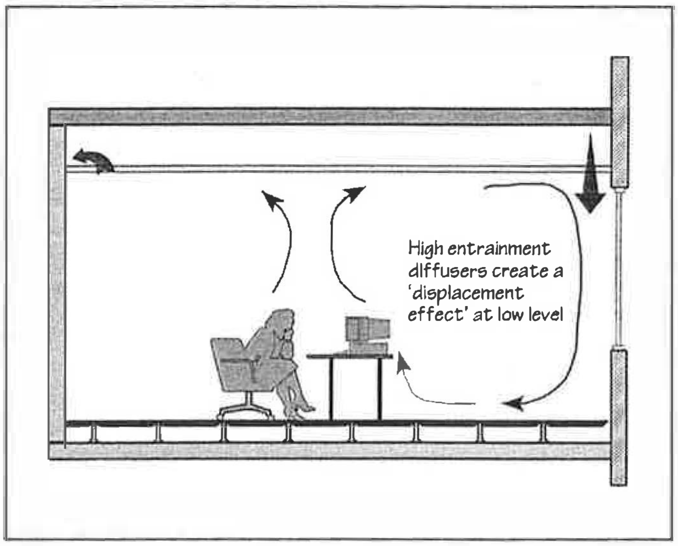

Fig. 6. An alternative ceiling supply system claims to achieve a 'displacement effect' by introducing cool air via high induction diffusers. This system has the advantage of being able to satisfy higher cooling loads as the air is introduced to the room at temperature differentials of up to 14 °C. Due to the high room air entrainment rate, this differential is rapidly reduced to around 0.5 °C some 1 m below the diffuser. The air jet continues to fall to floor level where it is claimed to establish a displacement effect.

the degree of controllability. In addition, the technology is readily understood by designers, and fault diagnosis is well within the grasp of competent maintenance staff.

On the down side, the systems are not as energy efficient as other systems due to their inability to maximise the benefit of free cooling. This may be graphically demonstrated by the need for chillers to cool fan coils even on days when there is snow on the ground. In addition, fan coil units contain small inefficient fans and need regular maintenance and cleaning, which often requires regular access to the ceiling void within the occupied zone.

Even so, fan coil units remain as one of the most popular forms of HVAC system, particularly on speculatively designed buildings or where individual control is required to a number of small spaces [11, 12].

Mixed-Mode Systems

For many decades there have been a large number of buildings that are neither fully mechanically ventilated, nor fully naturally ventilated. Until recently, this strategy did not carry a label, but recent work by the Building Research Establishment has developed a set of useful definitions that describe the approaches that may be taken in developing a mixed-mode solution [13].

(1) *Contingency* designs make the provision for future addition or removal of mechanical systems. For example, a naturally ventilated building may be planned to give appropriate space provision for the later addition of mechanical ventilation or comfort cooling. This may arise due to a change in use, or change in climatic conditions. Conversely, a mechanically ventilated, or comfort cooled building may revert to natural ventilation if comfort cooling were no longer required.

(2) *Complimentary* designs utilise a combination of natural ventilation and mechanical systems. These designs can be further subdivided into: (a) *Concurrent* systems that use mechanical cooling and ventilation when required but rely upon opening windows for a majority of the time. The ability to open the windows increases the tolerance of the occupants to a wider operating range of conditions. (b) *Changeover* systems may call for the use of mechanical ventilation or air conditioning as required by the season or even the time of day. The changeover strategy needs careful design so that it is readily understood. It is very easy for this system to default to a situation where relience is placed on the mechanical system for a majority of the time.

(3) *Zoned* designs utilise different systems in different parts of the building, depending upon occupancy, usage or location.

Cost, Energy and Environmental Considerations

In the UK, buildings are responsible for 40% of the total energy consumption [14]. These are therefore a proper target for control, given the current pressure to reduce energy consumption and CO_2 emissions.

Considerable effort has been put into improving the levels of thermal insulation in our buildings. Now the energy needed to heat the ventilation air has become the greater component of total building heat loss. Regardless of whether the space is mechanically or naturally ventilated in winter, ventilation air has to be heated to an appropriate temperature. To demonstrate the energy consumption and cost consequences of heating outside air, it is worth examining some simple facts.

If we look at the power required to heat 8 $\text{litre}\cdot\text{s}^{-1}$ of ventilation air, using a typical UK winter design temperature of −3 °C, the load equates to approximately 230 W (table 2). If the same volume of air is heated via a mechan-

Table 2. Heating energy and CO_2 emission (8 litres$\cdot s^{-1}$ ventilation air per person)

	Energy, W·h	£/person/h[1]	CO_2, kg$\cdot h^{-1}$
Natural ventilation	230	0.0023	0.05
Simple mechanical ventilation	240	0.0030	0.06
Mechanical ventilation with heat recovery	90	0.0013	0.03

[1] Based on an energy cost of £0.05 per kWh for electricity of £0.01 per kWh gas and 1 person per 10 m^2.

Table 3. Energy costs per office occupant (based on 1 person per 10 m^2 earning an average salary of £20,000)

Building type	Delivered energy/annum kWh$\cdot m^{-2}$ [15]	Cost per person/annum £	% of annual salary
Typical air-conditioned office	420	140	0.7
Good-practice air-conditioned office	235	80	0.4
Good-practice naturally ventilated office	120	40	0.2

ical ventilation system, the fan power has to be added. Using a typical ventilation plant this would add a further 3 W$\cdot$litre$^{-1}\cdot s^{-1}$ of air moved, equating to an additional 24 W, remembering that at least 16 W of this will be converted into useful heat gain. If a heat recovery system is added to the mechanical system with an efficiency of 75%, this could reduce the power consumed by the system to around 90 W.

This clearly demonstrates the improved efficiency achieved by using mechanical ventilation with heat recovery in terms of cost energy and the reduction of CO_2 emissions. Clearly, when the annual cost of running fan-powered systems is addressed, the balance is different unless a mixed-mode system is adopted. Whilst the cost saving may equate to some £5,000 per annum for an office building with 500 occupants, this is a relatively small sum compared with the payroll cost. The cost of employing the person benefiting from these 8 litres$\cdot s^{-1}$ of heated fresh air is on average some £10.00 per hour. The energy cost of providing the air is less than £0.01 per hour. Furthermore, most heat recovery installations often produce savings that have a payback period in excess of 15 years. This rarely provides sufficient incentive to invest in heat recovery on purely financial grounds. A more altruistic reason such as a genuine desire to reduce environmental impact is required, or differently, the introduction by government of an energy tax.

The cost of reduced occupant production is also worthy of examination. The effect that excursions beyond the comfort envelope have on human performance is not well documented. If precise data were available that demonstrated that a given increase in temperature reduced human performance by a quantifiable degree, the engineer would have a powerful analysis tool. For example, if we look at the energy costs per office occupant, assuming 1 person per 10 m^2 and an average salary of £20,000 (table 3) it can be seen that it would only take a 0.2% decrease in occupant efficiency, due to lower comfort levels, to counteract any saving in energy costs. Clearly, there are other issues to take into account, such as the environmental impact. However, the difference between the energy consumption of a good-practice air-conditioned office and that of a good-practice naturally ventilated office is relatively small in financial terms.

When designing a heating system for a naturally ventilated building, the engineer is justifiably concerned that energy will be wasted by the occupant opening the windows during the winter. A number of systems have been designed that shut down the heating system if the windows are opened. It is understood that this is a standard requirement in France. Experience has shown that unless the windows are opened, there is a strong possibility that reliance upon the trickle vents alone is likely to lead to a ventilation rate below 8 litres$\cdot s^{-1}$ per person for an appreciable proportion of the time. Again, this will lead to a greater reduction in energy than predicted by calculation, but at the risk of lowering the quality of the indoor environment.

Other usage factors suggest that in practice, buildings with natural ventilation use less energy than those served by mechanical systems. Outside the heating season (October–May) many buildings, such as schools, turn the heating system off. This may give rise to the problems early in the morning of the occasional cold day, but this policy generates considerable savings as there are zero standing losses.

Operation and Maintenance

Mechanical ventilation systems will only guarantee a regular supply of fresh air if they are properly installed, commissioned and maintained. Following the completion of numerous investigations into systems that were performing poorly, a number of problems consistently arise: (1) poor commissioning; (2) maintenance staff who do not understand how the system is supposed to work; (3) clogged filters, and (4) poorly set up control systems.

It is not surprising that many ventilation systems fail to perform satisfactorily given the extent to which they are neglected. The commonest fault (occurring in 80% of installations inspected) is with dampers that do not operate correctly. These are often found to be fixed in the full recirculation position. On most occasions, this does not arise from any drive to reduce energy, but from a failure of the maintenance staff to recognise the fault. When questioned, maintenance operatives frequently fail to understand the control system set up, particularly when enthalpy, CO_2, or air quality sensors are installed [16].

In many buildings, the occupancy level may vary considerably (auditoria, museums, sports arenas, lecture theatres). It is therefore understandable for the design engineer to attempt to modulate the fresh air rate to suit the occupancy level. This requires a sensing device that will effectively monitor return air conditions and control the fresh air dampers. These usually take the form of indoor air quality or CO_2 sensors. Experience has shown that indoor air quality sensors have a very limited response to all but heavy pollutants such as cigarette smoke. This renders them ineffective in the standard office environment. Better performance will be provided by CO_2 sensors, but there are two reasons to question whether they are sufficiently robust for general use. Firstly, the sensor needs to be accurate over a relatively small concentration range (300–1,200 ppm). Secondly, the sensors need to be regularly inspected and re-calibrated. It might be reasonable to expect this high level of maintenance in the aircraft industry, but it is unrealistic to expect such care to be expended on an office ventilation system.

It is clear that proper maintenance procedures are essential to maintain good operational performance from ventilation systems. To assist in this, the designer must keep system operation as simple as possible, avoiding any complex control algorithms that defy interpretation.

Case Study: The New Parliamentary Building, Westminster (Portcullis House)

The New Parliamentary building in Westminster, London, is an example of how all of the above principles can be embraced, when the right opportunity comes along.

Background

The New Parliamentary Building is located opposite Big Ben, one of London's most familiar landmarks. It is designed to provide office accommodation for the UK's 650 MPs who are currently housed in inadequate accommodation within the existing Houses of Parliament. The brief for the building demanded the highest quality of internal room conditions in terms of air quality, temperature and acoustics for MP offices, Select Committee and ancillary accommodation.

The central urban site where the building is constructed suffers from considerable traffic pollution. It was necessary, therefore, for the building to have a sealed facade to the site boundary. Key aspects of the brief were that there should be mostly cellular accommodation, but also Select Committee and ancillary accommodation. There would be: 10 m^2 per person office occupancy; 2.5 m^2 per person in meeting rooms; 10 $W \cdot m^{-2}$ office machines cooling; office background noise level to NR35; meeting room background noise level to NR30; a background lighting level of 350 lux; room temperatures of 22 ± 2 °C; room relative humidities of 30–70%; smoking permitted; meeting rooms designed to broadcasting standards; a 120-year building design life, and low building energy consumption.

With regard to the environment in the building, the aim of the design was to use fully the ability of the passive structure of the building, through design of form and choice of materials, to maintain the indoor climate. Thus, at the earliest stage in the design, a strategy was established with the architect so that: (1) the facade as a 'living wall' provided the means for modifying and using external influences; (2) room conditions would be controlled by the thermal performance of the fabric; (3) window solar performance would be based on the passive cooling capacity of the rooms, which in turn would be based on the extent of exposed thermal mass and night ventilation abilities; (4) the facade and the roof would be part of an integrated ducted ventilation and heat recovery system, and (5) groundwater would be used as a means of cooling warm summer fresh air.

The aim was to produce an inherently stabler room environment than the norm that addressed a full range of physical and perception comfort aspects, and which 'failed safe' if any parameter moved out of the range assumed by the design.

In global environmental terms, the result is a design that has an energy consumption target of 90 $kWh \cdot m^{-2} \cdot a^{-1}$ (based on a 50-hour week including ventilation, heating, cooling, lighting, office small power and miscellaneous electrical power allowance). This contrasts with a typical (type 3 [17]) air-conditioned building with comparable use which would be expected to use 402 $kWh \cdot m^{-2} \cdot a^{-1}$. As a comparison, a good-practice naturally ventilated building would be expected to consume between 124 and 140 $kWh \cdot m^{-2} \cdot a^{-1}$. In CO_2 emission terms [18] the building reduction equates to more than 2,600 tonnes per year.

The Building Facade

The cladding system had to provide a solution to the apparently conflicting requirements of an outdoor view, room daylight control, passive and active solar energy collection, excess solar heat protection, the minimisation of room heat loss, ventilation supply and extract and room heat recovery (fig. 7).

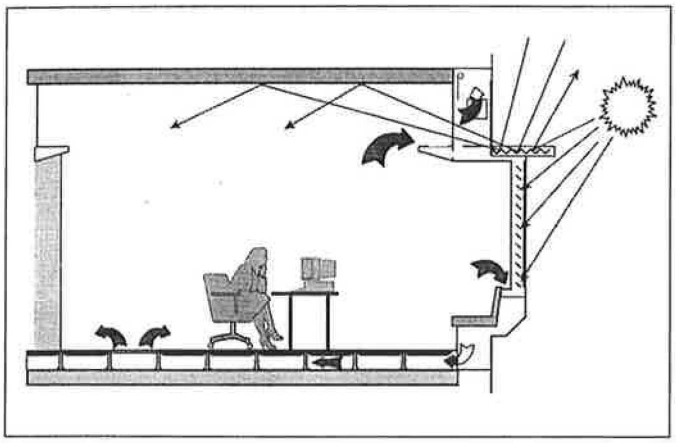

Fig. 7. The facade.

The fenestration super-glazing consists of triple panes with cavity-ventilated blinds. The outer double glazed unit is argon filled with a low emissivity coating to retain winter heat. The inner cavity contains retractable dark louvre blinds designed to maximise the absorbed solar heat. This cavity is ventilated with a proportion of room extract air and acts as a solar collector. The blind material and finish were chosen specifically to maximise short-wave solar absorption and minimise long-wave heat loss in association with low emissivity coatings on the glazed surfaces either side of the ventilated cavity. This arrangement results in less than 25 $W \cdot m^{-2}$ summer solar heat gain across the floor area of a 4.5-metre-deep perimeter room. In shading performance terms, the glazing system is comparable with external shading, but in energy efficiency terms exceeds it because of its solar heat recovery ability.

The window arrangement uses a light shelf to preserve room day lighting when solar shading is in use to avoid the 'blinds down, lights on' scenario. This permits a larger glazed area because without luminaire heat gain, the room can cope with more solar gain. Although a typical light shelf does not increase the total daylight introduced into the room, it significantly reduces internal to perimeter contrast and increases daylight usability and with it reduces luminaire electrical consumption. The particular light shelf form has a corrugated reflective surface designed to maximise high-altitude diffuse skylight reflections, but to reject the lower altitude direct short-wave sun radiation. This arrangement has the added benefit of almost doubling the daylight levels in north facade rooms facing other buildings little more than 8 m away.

In many senses, the facade is a highly active system. It has many elements serving a wide variety of functions at differing levels and for differing orientations. Yet it is predominantly a passive system with the occupant-operated blinds as the only moving component across which the ventilation air is drawn.

Cooling

To satisfy the brief requirement for an occupied room temperature range of 22 ± 2 °C, but using passive cooling, required an in-depth understanding of the constantly changing heat flows into, within and then out of the room. All of this is non-steady state, with heat flows in and out occurring at differing times and related to the room's thermal capacity and a variety of time constants. The facade of high overall thermal resistance means that most of the room daytime heat gain is retained, so for a large proportion of the year, there is a heat excess to be managed. This heat is stored, first to deal with the night heat loss and to avoid boost heating prior to morning occupancy and then to allow night ventilation to remove surplus heat from the building.

The exposed room surfaces are used for the heat storage and heat load shifting purpose because of their ability to function with small temperature difference changes and to take full advantage of both radiated and convective heat transfer. The thermal inertia of the floor void is also used although predominately this has a supply air temperature stabilisation effect. Each room has a barrel-vaulted white concrete ceiling together with dense raised floor tiles and architect-designed 50-mm precast wall panels. The high thermal capacity room surfaces have a density range between 50 and 200 $kg \cdot m^{-2}$ provided at the area of approximately 2.5 $m^2 \cdot m^{-2}$ of room floor area.

The use of such room surfaces has demonstrated the remarkable robustness of thermal mass passive cooling. Typically, the effect of doubling the machine heat gains for part of a day is so small as to be virtually unmeasurable in terms of room dry resultant temperature. Doubling it all day and every day, for example, affects the temperature by less than 1 °C. This shows the inherent overload capacity of passive thermal mass cooling. Likewise, 2 days of peak summer heat-wave hardly registers an effect, simply because any slight increase in room temperature swing from day to night significantly increases the mass heat storage capacity. This overload capacity is greater than that provided by a conventionally sized room air-conditioning unit.

The room thermal capacity handles the internal room heat gains. However, for fresh air ventilation, when the outside air is above 19 °C, groundwater at about 14 °C is drawn from two on site boreholes to cool the air down to room temperature (fig. 8).

To make further use of this natural resource after it is used for cooling, the groundwater feeds a greywater system serving toilet cisterns, to reduce the building's demand for refined mains water.

Ventilation System

The mechanical ventilation system (fig. 9) provides 100% outside air to each room by way of a network of linked floor plenums on each floor and vertical ductwork in the facade (fig. 7). Not only does the system allow year-round ventilation with generous quantities of outside air together with satisfying the higher heating needs of displacement ventilation, but it also permits the recovery of solar heat from

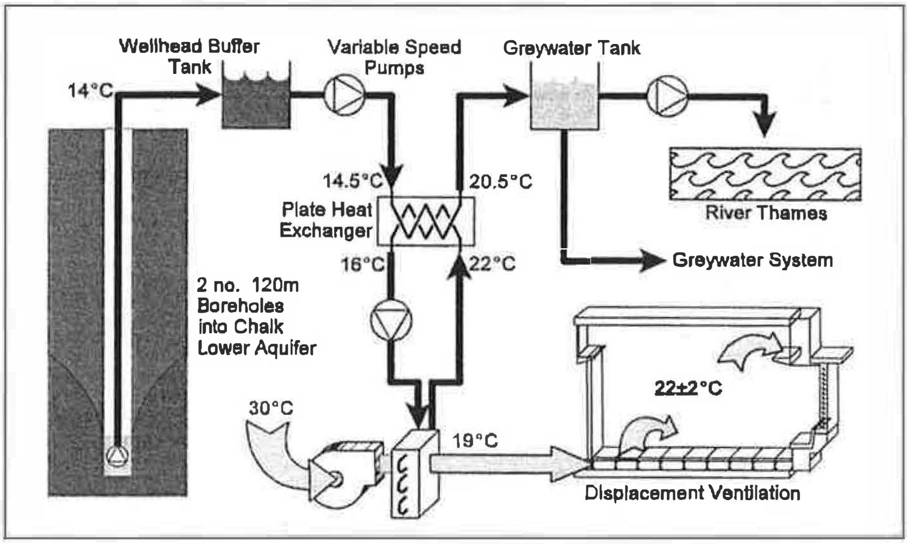

Fig. 8. Groundwater cooling.

the window system, the occupants, their electrical equipment and the room radiators.

The heat recovery devices are rotary heat exchangers located in each of the rooftop turrets, operating at an efficiency of 85%. They are of the hygroscopic type to recover moisture from the exhaust air and reduce winter supply air humidification requirements. Concerns about exhaust air to supply air contamination were discounted after a review of their successful use in Scandinavian hospitals.

Very low pressure loss air handling and duct system components have been selected to achieve a ventilation energy use target of 1 W·litre^{-1} of air supplied. This compares with typical fan energy use of between 2 and 3 W·litre^{-1}. To achieve this means avoiding long duct runs and, in particular, minimising bends, duct expansions and control dampers. This led to the low-pressure plenums arrangement and duct linking of all roof air plant.

The fan total pressure generated by supply and extract fans added together is only 640 Pa with a fan efficiency (fan, drive, motor and inverter combined) of 65%. Typically, the air-handling plant component face velocities are 1.2 m·s^{-1}, with 0.65 m·s^{-1} across the filters.

The fans have variable speed inverter drives so that they can be commissioned to match the actual duty and avoid the sizing and selection margins which can become a lifelong energy penalty. This specification gave both the maximum allowable fan total pressures together with the lower commissioning set points alongside the normal sizing duties. The normal night time ventilation rate is set at half that of daytime flows to provide adequate night cooling. Instead of switching off half the roof turret air plant, all are run at half speed because this greatly reduces the fan pressure required and hence power requirements, as well as increasing coil and heat recovery efficiencies. Flexibility of the ventilation system was of prime importance. Too often, heating and ventilation systems are stripped out long before most of the components need replacing due to proposed

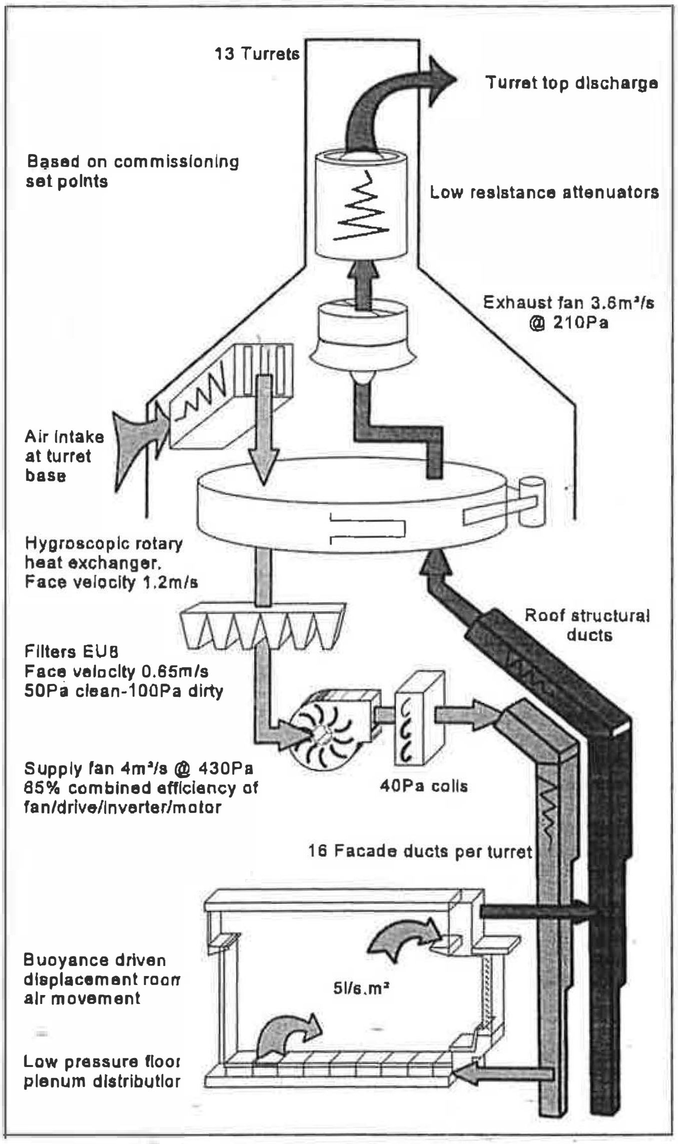

Fig. 9. The ventilation system.

changes in room use and arrangement. The objective in this case was to find a single system that could serve most different room types, thus avoiding a services refit prompted by each change of room use. To achieve this, the distribution ductwork and extract was integrated into the window surrounds, and hence the building and partition grids, while the floor plenums with the associated raised floor tiles were intended to allow flexibility in siting supply diffusers.

To complement this, the system supplies only 100% fresh air with no recirculation of extracted air. So whatever a room contains now or in the future, be it for meeting rooms, print/copy equipment, heavy smoking, general office use or simply a need to remove volatile materials off-gassed from furniture and furnishings, the system is appropriate. Not only does this make the services more compatible with the long life of the building fabric, but it also reduces the embodied energy content of the normal engineering services cyclical replacement throughout the lifetime of the building.

The system operates at constant volume and constant temperature. Room temperature control is provided by the room thermal inertia supplemented by radiators in winter, so that modulation of supply temperatures or air volumes to each room is avoided. Operating the ventilation as a variable air volume was considered, particularly as most of the hardware is provided. However, this was discounted because ductwork pressures are so low that it is doubtful that pressure sensors would register a meaningful and predictable proportional band. Besides this, the energy benefits of VAV over the very low pressure constant volume system are small. To cap it all, the added complexity of VAV controls was viewed as a definite disadvantage.

Room air distribution is by low-velocity displacement, chosen because of its low fan pressure needs and the direct compatibility of its supply temperature with the groundwater cooling source. With a supply air temperature of 19 °C, the groundwater can provide adequate cooling, whereas it would be inadequate for the lower supply temperatures of alternative air-conditioning solutions. The room air supply diffusers can be manually throttled down to 50% airflow by the occupant. The throttled air is redistributed through the plenums to the rest of the system with the aid of flat performance-curved backward-curved centrifugal fans without any need for complex automatic controls.

Prefabrication

The site constraints, together with matters of site possession and the need to minimise the site construction period, set an early design objective of maximising off-site pre-fabrication. All structural stone columns, concrete floors, cores, cladding and roof were prefabricated and assembled on-site. This philosophy was also applied to the building services.

The roof air plant, roof primary services distribution, vertical cores, on-floor secondary services run-outs were all prefabricated multi-service modules. Many were pre-installed into structural and cladding elements for delivery to site as integrated units. Most were to be lowered in through the roof before it was finally topped-out and made watertight. Pre-insulated and tested pipework was mounted alongside electrical busbars on common racking installed into all the floor voids. To achieve this degree of pre-fabrication of the services, it was necessary to consider and specify it as a construction option in the original design. It required an early understanding of the influence of pre-fabrication assembly size, shape, repetition, cage clearance, installation methods and programming. This approach ideally needs accessible, well laid out and regular serviced ducts and spaces without intruding structure. If extensive pre-fabrication can be achieved, the benefits are many, including better and more consistent quality, less material and man-hour waste, and more control over programme aspects.

Conclusion

Over the last 5 years, research has provided excellent base information from which the practising engineer has had the opportunity to develop effective and efficient designs. These designs should provide high comfort levels whilst significantly reducing the production of greenhouse gases.

However, for a variety of reasons, the engineer will often not be able to realise solutions such as those developed for the New Parliamentary building. It is therefore important that the engineer understands the limitations that any chosen ventilation strategy might impose on the use, or operation, of the building. The engineer should clearly explain the choices available, and if compromises have to be made, their effect must be fully explained to the building's procurers.

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References

1 Sick building syndrome, productivity and control. Property J 1993.
2 Fanger O: Pre standard – prENV 1752: Ventilation for buildings.
3 Natural ventilation in non-domestic buildings. CIBSE Applications Manual AM 10, 1997.
4 Building Research Establishment: Natural ventilation in non-domestic buildings. BRE Digest 399.
5 Are You in Control?, Building Services. CIBSE J 1993.
6 Raw G, Roys M, Leaman A: User and occupant controls in office buildings; in Sterlings E, Bieva C, Collet C (eds): Proceedings of the International Conference on Building Design, Technology and Occupant Well-Being in Temperate Climates, Brussels, Feb 17–19, 1993. Atlanta, ASHRAE, 1993; pp 12–15.
7 DETR: Climate Change Scenarios for the United Kingdom, UKCIP Technical report No 1, October 1998.
8 Berry J: Passive Cooling Put to the Test. Architects J 1995.
9 Building Services Research and Information Association: Displacement ventilation and chilled ceilings. BSRIA TN 2/96.
10 Alamdari F, Butler D: Chilled ceilings and displacement ventilation – Do they work? Building Services Research and Information Association.
11 Bordass A, Bromley A, Leaman A: Control Strategies for Building Services, Advanced Systems of Passive and Active Climatisation. Barcelona, Institut Catala d'Energia (ICAEN) as part of Thermie Programme, Jun 3, 1993.
12 Bordass A, Leaman A, Willis S: Comfort, Control and Energy Efficiency in Offices. BRE Information Paper, IP3/95, February 1995.
13 Mixed mode ventilation. CIBSE Applications Manual 2000.
14 DETR: Energy Efficiency Best Practice Programme – Energy Consumption Guide 19, HMSO, London (1998).
15 Building Services Research and Information Association: CO_2 controlled mechanical ventilation systems BSRIA TN 12/94.1.
16 BRE: Building Research Establishment, Best Practice Programme, Energy Consumption Guide 19.
17 BRE: Building Research Establishment Environmental Assessment Method (BREEAM), Natural gas carbon dioxide emission is 0.21kg/kWh.
18 Electricity Council: Electricity Council assessment of average electricity carbon dioxide emission for the year 2000 is 0.56 kg/kWh.