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'Blue Pages'

Articles on the state of the art of developments in building services engineering

Welcome to the 'Blue Pages'. This is where guest editors from the Editorial Advisory Panel for *Building Services Engineering Research and Technology* address current developments in building services engineering practice and research. The articles are very short, on one theme of current interest, and do not go through the longer refereeing process for conventional research papers. This is to encourage consultants and contractors to discuss their latest developments in a non-commercial manner. Academics will also be asked to outline current research areas in universities and colleges. Without the constraint of full refereeing there is scope in the articles to provoke interest and to raise issues for discussion of 'Blue Pages' articles. If you have a suggestion for an article or topic you would like to see included in the 'Blue Pages' please inform Robert Yarham, CIBSE. Comments on the 'Blue Pages' are also welcome. 'Blue Pages' will only succeed if readers of the journal wish the feature to succeed and contribute to its success.

Aspects of recent research on natural ventilation in non-domestic buildings

Editorial

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Statistical results suggest that naturally ventilated office buildings consume about half the energy of air-conditioned office buildings[1]. Because of this, the application of natural ventilation in newly built and/or refurbished buildings could contribute considerably to the reduction of CO_2 emissions due to energy consumption. In addition, surveys and anecdotal evidence suggest the buildings users prefer to work in well-managed naturally ventilated buildings. The renewed interest in natural ventilation is demonstrated by recent publications on the subject[2].

In particular in the UK several naturally ventilated buildings have been built and occupied during the last decade, indicating that the application of natural ventilation is gaining momentum as one of the 'low energy' design strategies. CIBSE has published an Application Manual on natural ventilation in which design methods and case studies are included[3]and BRECSU has published a complementary Good Practice Guide for designers, developers and owners[4] as well as several case studies. The CIBSE Natural Ventilation Group has been instrumental in disseminating current research findings and engineering practice, mainly through seminars and workshops[5,6].

This issue of Blue Pages focuses on the results of recently completed research projects that have investigated various aspects of natural ventilation. The articles concentrate on the following issues:

— Technical barriers for the application of natural ventilation and some solutions
— Natural ventilation for cooling
— Refurbishment for natural ventilation
— Models for natural ventilation
— Integration of natural ventilation into architectural design.

The first article is an overview of an important research project on natural ventilation that was completed in 1998. Organisations from seven European countries have been working for three years in identifying the technical barriers for the application of natural ventilation and proposing solutions to overcome them. Final results from the project are being prepared for publication as described in the article. Under the framework of the same project, the ventilation strategies of 19 buildings have been investigated in detail by monitoring during the summer and winter. One of the main parameters investigated in relation to a natural ventilation strategy for the summer months was thermal comfort. This was because it was found that the risk of overheating could be interpreted by engineers and users as one of the main barriers to the application of natural ventilation.

The second article discusses two Belgian case studies demonstrating the cooling effect of natural ventilation during the day or night and its coupling with the design of the building. The first case study is a new office building in which night natural ventilation is used as one of the strategies to reduce cooling requirements. The second case-study is the refurbishment of a 1970s building with overheating problems that night natural ventilation has effectively solved. Indeed, the application of natural ventilation during major refurbishment is a very important area and the subject of a number of ongoing research projects.

The third article summarises the results of a recently completed project on the refurbishment of air-conditioned buildings for natural ventilation. It discusses the advantages of applying natural ventilation to a building refurbishment and highlights the difficulties arising from the fact that the design solutions are often not as straightforward as those associated with new build because of the existing building restrictions and cost considerations.

The fourth article describes available models for predicting the performance of natural ventilation. Indeed, the development and appraisal of tools for natural ventilation has been the subject of many research projects. The paper discusses the latest trends based on the results of major research projects on natural ventilation carried out by the authors and their colleagues during the last decade.

The fifth article focuses on the integration of natural ventilation technology within the architectural context of the building. The transferability of natural ventilation concepts and the relationship to daylighting are discussed by Professor Jeffrey Cook, who has studied naturally ventilated buildings in the UK and elsewhere. He analyses their qualities in terms of their architectural impact.

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Naturally ventilating office buildings

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Natural ventilation is not just about operable and openable windows. It is rather a holistic design concept that, according to Cook and McEvoy[7], is now being used in the architectural design of large offices and other building types. Design is centred on using passive ventilation, based on the 'stack' (temperature) effect and wind pressure differentials, to supply fresh air to building interiors even when the windows are closed. As part of this process, designs incorporate atria or internal stairwells that, in some instances, use low-energy fans to provide 'assisted natural ventilation' (i.e. 'low energy ventilation').

For any ventilation strategy to succeed, it should be based on the principle that adequate ventilation is essential for the health, safety and comfort of the building's occupants, but that excessive ventilation leads to energy waste and sometimes to discomfort. The aim of good design is therefore to 'build tight—ventilate right'. That is, to minimise uncontrolled (and, usually, unwanted) infiltration by making the building envelope airtight while providing the required ventilation with 'fresh' air in a *controlled* manner. It should be emphasised that a building cannot be too tight but it can be underventilated. The issue of airtightness has been discussed in a previous issue of BSERT Blue-Pages[8].

There is a large body of generalised guidance available for the design of natural ventilation[9–11]. However, there is a perception in the commercial marketplace that certain specific technical barriers exist that prevent a wider uptake, in particular in urban areas and city centres. The European NatVent® project 'Overcoming technical barriers to low-energy natural ventilation in office type buildings'[12] identified the following as the five major issues:

- Combating summer overheating
- Air and noise pollution in urban areas and city centres
- Variability of weather around buildings and the dependence of natural ventilation on these variable driving forces
- Recovering heat from natural ventilation systems (an issue of concern to countries with very cold winters)
- Integrating and maintaining natural ventilation systems.

Over a 30-month period, the seven-nation (and nine-Partner) NatVent® consortium addressed these issues to develop 'smart' naturally ventilated technology systems and component solutions. On successful completion, the consortium has been able to provide the following solutions[13,14]:

- A low pressure drop inlet for attenuating external air and noise pollution in urban areas together with a design tools for the sizing and location of inlets
- A very low pressure drop vent with controlled incoming air flow to account for variable external weather conditions
- A low-energy fan-assisted system to recover heat for use in the colder climates
- Hardware window prototypes and control algorithms for controlled night cooling to minimise summer overheating
- A simple design tool integrating all the elements of NatVent®.

Currently a guidebook and a CD-ROM on the NatVent® work are being prepared and on completion can be obtained from BRE (contact: Earle Perera on 01923 664000). These will contain details about the project and its participants, reports on all the technical areas covered, including results from monitoring 19 low-energy office buildings in Europe, design tools, as well as information on hardware developed from the project

Acknowledgements

The NatVent® project has been funded partly by the European Commission under the Joule Programme 1994–98; and by the appropriate funding organisation within each participating country. Within the UK, we acknowledge with thanks the funding of the Department of the Environment, Transport and the Regions under the Partners in Technology (now Partners in Innovation) Programme.

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Natural ventilation for summer cooling

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Introduction

Overheating in summertime constitutes a major comfort problem in many office type buildings. Intensive night ventilation is one of the possible 'passive' strategies for reducing or avoiding the need for active cooling. This paper gives a short description of the strategy of intensive natural night ventilation and describes two buildings in Belgium where natural night ventilation is a key element in the concept for avoiding overheating under summer conditions.

Intensive night ventilation, one element in a global concept

High internal temperatures in office type buildings during summertime are usually the result of a combination of several factors, such as large glazing areas, high internal gains, etc. Therefore the overheating problem cannot be solved by a single passive technique but demands an overall approach. Only by controlling all the different factors that affect the indoor climate can one successfully control the indoor climate in a passive way. Intensive night ventilation can be a powerful element of such a global passive approach.

The first and most important step in any passive strategy against overheating is to reduce the heat gains. One can distinguish two types of heat gains: solar gains and internal gains. Solar gains are primarily related to transparent surfaces. The building designer can control direct solar gains by an appropriate choice of glazing areas, glazing orientation, type of glazing and shading devices. Lighting, equipment and people are the most important sources of internal gains. The heat gains from lighting can be reduced substantially by optimal use of daylighting, use of lights with electronic ballast and effective control systems. Reducing the internal gains has a double benefit: lower electricity consumption and lower cooling demand.

When internal and solar gains have been reduced as much as possible, the indoor climate can be further improved by applying intensive night ventilation. The idea is to cool the thermal mass of the building by means of high ventilation rates with cold external night air. Moderate European climates are very suitable for this strategy, as summer night temperatures in these climates are much lower than day temperatures.

Two elements are indispensable in night ventilation: thermal mass and large ventilation rates. During daytime the internal mass stores the heat and tempers the indoor temperature; during night-time the stored heat is released by bringing the thermal mass into contact with cold external air.

The following two Belgian case studies, a new building and a refurbishment project, show how the strategy of night ventilation can be put into practice as one element of a global strategy against overheating.

Two Belgian case studies

The IVEG *headquarters*

IVEG is a distribution company for gas and electricity near Antwerp, Belgium. Promotion of rational use of energy is one of the main objectives of the company. The new headquarters (1850 m^2) has to be a low-energy building based on simple and widely applicable techniques. The reduction of active cooling in summertime was a major objective of the building design.

Several 'passive' measures are adopted in the final design:

(*a*) Reduction of the indirect solar gains by a high insulation level of the roof and the external walls
(*b*) Reduction of the direct solar gains by:
- Selective glazing (*g*-value 0.25/visual transmittance 0.43)
- Automatically controlled vertical external screens on all facades, except north

(*c*) Application of intensive night ventilation and thermal storage

The night ventilation is based on the *stack effect* of two large chimneys on the roof of the building. Cold external air is supplied through large burglar-proof grilles with insect screen in the external facades. The internal doors are open at night. All supply and extraction openings are motorized and can be controlled automatically. Because of fire regulations the ground floor and the first floor are separated and each has its own chimney. The building has a lot of accessible thermal mass: the offices have open false ceilings (20%) and tiled floors (Figure 1).

The overall impact of the different measures was evaluated by thermal simulations using the program ESP-r of the University of Strathclyde. This program allows a coupling of the air flows and the temperatures, an essential element in simulating the thermal stack effect. Figure 2 shows the influence of night ventilation on the internal temperature during a warm period.

According to the simulations, night air changes were approximately 9 vol h^{-1} and the internal temperature was higher than 25°C for only 60 hours during working hours and was never higher than 28°C, assuming the Test Reference Year of Uccle. This result was acceptable to the owner. However, as there is some uncertainty in the simulation results, it was decided to retain the possibility of installing top-cooling on the mechanical ventilation system.

The study of the building was finished in 1997. Construction started in 1998 and will be completed in mid 1999. Further monitoring of the building is planned.

The PROBE *building*

The *PROBE* building was built in 1975 and renovated during 1996 and 1997. The building is situated on the BBRI's test site at Limelette. Before the renovation there were serious problems of overheating in summertime.

PROBE stands for Pragmatic Renovation of Office Buildings for a Better Environment. The renovation consists of a wide range of relatively small-scale improvements that can be applied to many similar office buildings (renovation

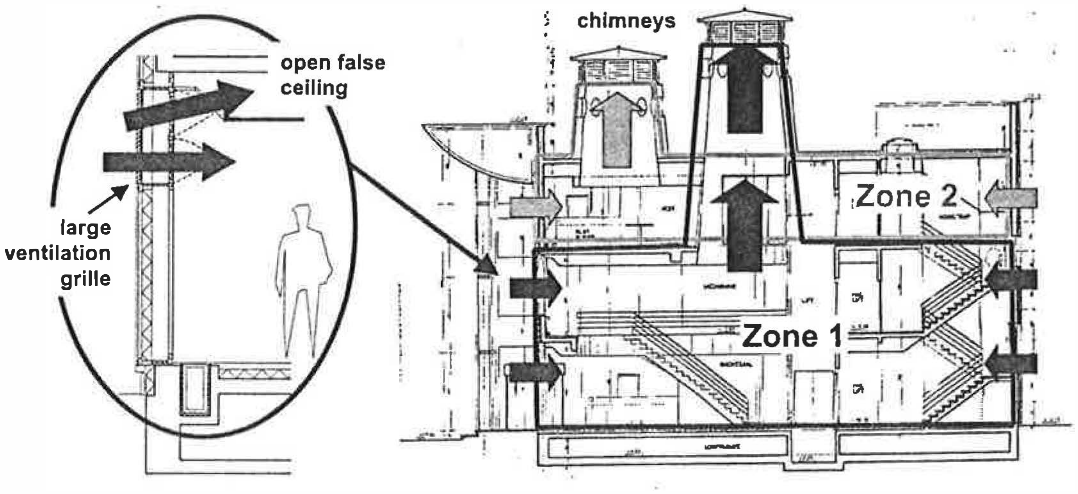

Figure 1 Ventilation concept: detail of air inlet and cross section of the building

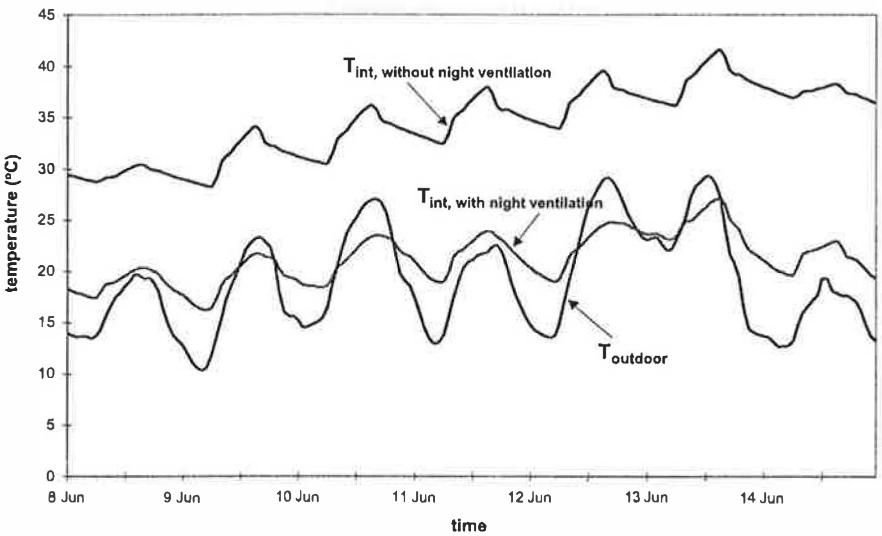

Figure 2 *IVEG* building: simulation of internal temperature and influence of night ventilation

that improves summer comfort are marked with an asterisk):

- Installation of a new fuel boiler, thermostatic radiator valves and improvement of the regulation system
- Replacement of the old roofing and placement of additional insulation on the roof*
- Installation of mechanical hygienic ventilation with infrared presence detection
- Replacement of single glazing with low-e argon-filled double glazing (central *U*-value = 1.1 W m^2 K^1)
- Installation of external solar shading with automatic control*
- Placement of large grilles for night ventilation*
- Replacement of the old artificial lighting with new lights with luminance control and electronic ballast*

The night ventilation is based on *cross ventilation.* At night large grilles in the east and west facades (see Figure 3) and the internal doors are opened manually. The building has a large internal mass; it has exposed ceilings and floors and heavy internal walls.

Measurements carried out in the framework of the NatVent® project show that the overall effect of the different measures provides acceptable summer comfort (see Figure 4b).

Several Belgian industrial partners and the Walloon Region funded this demonstration project.

Conclusions

The Belgian case studies show that intensive natural night ventilation can be an effective strategy against overheating, provided that the night ventilation is integrated in a global concept for summer comfort.

Putting intensive night ventilation into practice often has important consequences for the building design. Issues that must be considered include the following.

- *Security*: Natural night ventilation necessitates large supply openings in the facade. Security requirements can be met by the use of burglar-proof grilles.
- *Fire regulations*: The size of the ventilation zones is often restricted by local fire regulations.
- *Privacy*: When there are no strict requirements regarding privacy, internal flow paths can be achieved by opening the internal doors at night. Otherwise, large internal grilles can offer a solution.
- *Accessibility of thermal mass*: In many offices, false ceilings and false floors are used for reasons of cabling. These substantially decrease the accessibility of the thermal mass. Open false ceilings can combine both features.

As all the issues mentioned above have important influences on the design of the building, the integration of natural ven-

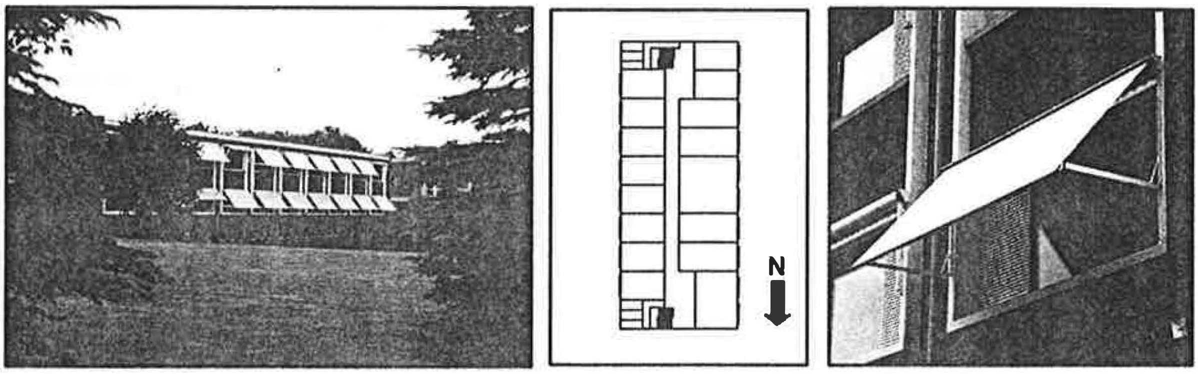

Figure 3 East facade, plan view and large ventilation grille and awnings for solar shading

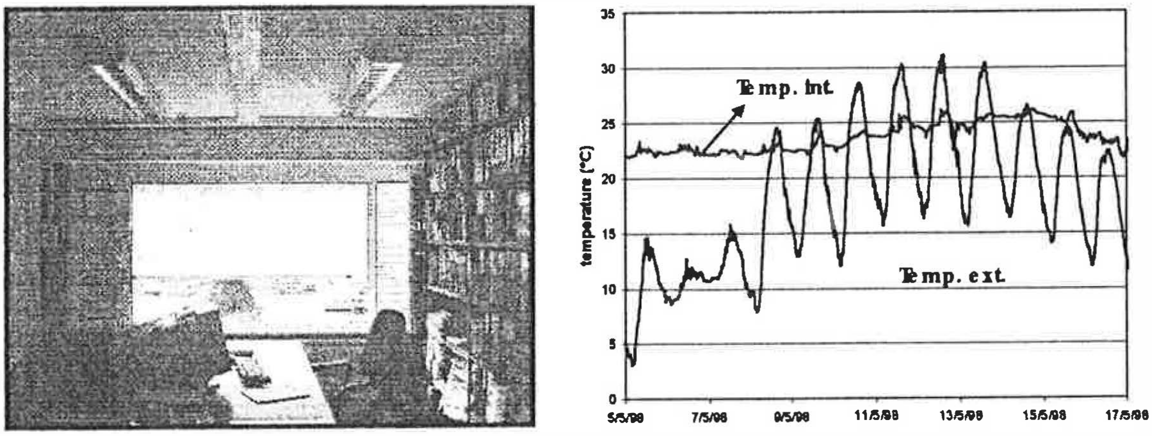

Figure 4 (a) Office at the west facade: large ventilation grilles and external screens. (b) Internal and external temperatures during a heat wave

tilation for summer comfort can only be successful when it is considered from the earliest design phase.

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Refurbishment of offices for natural ventilation

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Introduction

It is estimated that 10% of office space is refurbished in some form every year[17], representing approximately 8 million m^2 of office space. These office buildings have the potential to provide the standards of accommodation required in the 21st century if refurbished in the correct manner[18]. Conventional naturally ventilated offices may benefit from 'upgrading' of the natural ventilation strategy, together with the application of other passive measures to reduce summertime temperatures. Office buildings that were previously entirely actively ventilated (air conditioned) may benefit from the addition of natural ventilation, potentially providing occupants with greater control over their own environment. This may give a reduction in running costs as natural ventilation may satisfy cooling and ventilation requirements for much of the year. For some buildings, this may diminish mechanical cooling use to peak summer periods only, rendering its replacement as part of refurbishment unjustifiable.

The use of passive strategies applied to a building refurbishment requires careful design if the building is to be successful, especially as the design solutions are often not as straightforward as those associated with new build. Selection of the optimum passive measures will enable comfortable indoor conditions to be maintained or enhanced[19]. Where projects are speculative, the facility to provide air conditioning may be allowed for but not installed. This reduces the cost of refurbishment.

Ventilation strategy selection

The decision to refurbish a building for natural ventilation will not usually be taken in isolation, but will be part of a wider renovation scheme where perhaps the aim is to improve the building's functionality as well as to reduce overall running costs. The decision to implement or enhance natural ventilation is influenced by the following factors:

Table 1 Natural ventilation characteristics of different building types

Period/ description	Typical construction	Advantages for natural ventilation	Disadvantages for natural ventilation
Pre 1900	Masonry	High ceilings Tall windows Good natural light High thermal mass	May be listed building Structural partitions—inflexible space, poor circulation
1900–pre WWII	Masonry, concrete or steel frame	May have high ceiling Narrow floor plate	May be listed building Structural partitions—inflexible space, poor circulation
Late 1950s/1960s	Steel frame or reinforced concrete, curtain wall	Narrow floor plate Open plan layout	Low floor–ceiling height Large glazed area Low floor loading Relatively lightweight
1970s office	Steel frame or reinforced concrete	Larger floor–ceiling height than 1960s (for services) Open plan layout	Deep plan Lightweight construction

Table 2 Feasibility study considerations[23]

SITE	
Near a busy main road or railway line	Pollution and noise could be a problem with open windows on this side. The facade should ideally be at least 20 m from main roads. Separate ventilators can be used which incorporate noise attenuation.
Prevailing winds	Average wind speeds and prevailing direction should be determined from local meteorological records to assess the effect on the ventilation strategy. As a first approximation, handbooks such as *Climate in the United Kingdom*[24] can be used to find the data at the nearest site recorded.
Topography and surrounding buildings	Is the building on open ground, a suburban or an inner city site? Wind speed must be factored accordingly (*see Climate in the United Kingdom*[24]) and the likely impact of surrounding buildings and other obstacles assessed.
FORM	
Shape	Is the plan deep or shallow? The maximum depth for single-sided natural ventilation is currently accepted as 7–10 m. Cross-ventilation is suitable for spaces up to 15 m without an intervening corridor. If the plan is deeper, the use of a central stack or atrium may be a possibility. Otherwise, a mixed mode solution, using mechanical ventilation for the core areas may be advisable.
Orientation	The glazed wall surface should preferably be near perpendicular to the prevailing wind direction, to maximise wind-driven ventilation. The ventilation strategy will to some extent be dictated by this parameter. Orientation may affect the type of solar control device required. South-facing windows will require horizontal devices, whereas east- and west-facing windows may need vertical shading to cope with low sun angles.
Glazed area	The glazed area, expressed as a percentage of the total wall area, should be in the region of 30–50% for a good compromise between daylighting and solar gain reduction. Larger areas will need to be partially replaced with insulated cladding, whilst an underlit space may require light from a light well or atrium if excessive artificial lighting is to be avoided.
Method of construction	Construction methods may be heavy (masonry, concrete), medium or lightweight (structural frame, curtain walling). This influences the possibility of exposing thermal mass in the ceiling to help contain peak internal temperature by the use of night cooling and subsequent radiant temperature reduction.
INTERIOR	
Floor to ceiling height	This will influence the ability of the interior to cope with heat gains. A higher space will be beneficial, aiding high level cross-ventilation and the formation of a warmer air reservoir above the occupied zone.
Partitioning	This will affect the air flow rate into the space. Partitioning that can be removed should be dismantled in order to enhance the ventilation air flow path. Fixed structural or masonry partitions around the perimeter are likely to be restrictive to natural ventilation.
Existing ducts, risers and stairwells	It may be possible to use these as part of a natural ventilation strategy, with due regard to fire requirements. Core stairwells could be used as stacks to draw air through the building. Existing ductwork can be retained as part of a mixed mode approach to provide air to core areas or as mechanical backup on hot, still days.
OCCUPANCY	
Expected occupancy and equipment heat gains	The higher the heat gain, the more care must be taken in the design for natural ventilation, and the more measures have to be taken to maintain comfort. To assess potential heat gains, projected occupant density, lighting gains, and equipment usage must be estimated. Special areas can be allocated for high heat gain activities and local mechanical cooling installed if necessary.
Expected working patterns	Evening or night working will preclude the operation of a full night cooling regime as comfort conditions must be maintained 24 hours a day.

— Plant needs replacing, having reached the end of its economic lifespan (probably 20–25 years). Conversion to natural ventilation to reduce future running and maintenance costs, to improve occupant satisfaction, and to demonstrate environmental commitment. This is most likely instigated by an owner-occupier.
— Full building refurbishment is necessary due to the condition of the fabric and/or services. Passive features added as part of the overall work programme to improve the lettability. Probably carried out by a commercial developer.
— Radical change of use. For example, the rehabilitation of an older structure to make it suitable for office use, or refurbishment of offices to living accommodation. Passive measures added as part of the refurbishment of the whole building to avoid fitting more than minimum plant. Again, the motive may be to reduce running costs, improve the internal environment, and present a 'green' image.
— Unacceptable conditions in the building owing to increased heat gains. This could be from more intensive use of IT, increased occupation density, or a change of use, which would necessitate upgrading existing plant or installing new equipment.

The refurbishment may involve the entire building, or be restricted to a part where it is considered necessary, for example a top floor that suffers from overheating in summer. Different building types will have different characteristics when refurbished for natural ventilation, some of which are summarised in Table 1.

When it has been established that refurbishment is necessary, the potential for natural ventilation can be assessed as follows:

(1) Establish the likely heat gains from people, lighting and equipment: 40 W m^{-2} is generally seen as a limiting value for pure natural ventilation.
(2) Determine the noise level CIBSE Guide A recommends NP-40 for large offices but intrusion of high external values may, if continuous during occupation, permit relaxation of the standards at perimeter desk positions when windows are open.
(3) A subjective assessment of outdoor air quality may rule out natural ventilation, at least at some facades. Proposed definitive values for concentrations of various pollutants are given in 'The UK national air quality strategy: consultation draft'[20].
(4) If natural ventilation is still an option, a feasibility study should be undertaken to assess the viability of, or ease of conversion to, natural ventilation. The issues to be considered are presented in Table 2.

The cost of refurbishment for natural ventilation[18] (see Table 3) should also be considered against the alternative cost of replacing or providing mechanical ventilation and/or mechanical cooling. Mechanical ventilation ensures that recommended ventilation rates are provided throughout the year and mechanical cooling guarantees avoidance of building overheating and allows provision of relative humidity control, where necessary. In many marginal cases, the best solution may be to design a simple yet flexible mixed-mode system rather than to spend the budget on costly alterations such as complex controls and sophisticated solar shading. Nonetheless, many of the measures favouring natural ventilation, such as exposed thermal mass, effective solar control, improved use of natural light and lighting control, should still be implemented. This allows a reduction in plant capacity, saving money, space and energy.

Table 3 Cost and heat gains associated with different levels of refurbishment[23]

Heat gain (W m^{-2})	Level of refurbishment	Indicative cost (£/m^2)
15–20	*Level 1: Minor refurbishment* Opening windows, install modern blinds, repaint interior, redesign layout	200–350
20–25	*Level 2: Intermediate refurbishment* Opening windows, install modern blinds (possibly exterior louvres), renew lighting, repaint interior, remove false ceiling to expose thermal capacity and raise ceiling height	350–600
25–35	*Level 3: Major refurbishment* Opening windows, install modern blinds (possibly exterior louvres), renew lighting, repaint interior, remove false ceiling to expose thermal capacity and raise ceiling height, possible use of stair cores as stacks, BMS-controlled night cooling with motorised window/vent opening	600–800
35–45	*Level 4: Complete refurbishment* Opening windows, install modern blinds (possibly exterior louvres), renew lighting, repaint interior, remove false ceiling to expose thermal capacity and raise ceiling height, possible use of stair cores as stacks, BMS-controlled night cooling with motorised window/vent opening. Radical changes to air flow paths, for example by addition of a central atrium, or use of a double facade to drive stack ventilation	800–1000

Typical minimum costs for heating/mechanical ventilation and full air conditioning are £60/m^2 and £200/m^2, respectively[21], but their associated operating and maintenance costs throughout their lifetime should also be considered. The additional costs for air conditioning over those for a purely naturally ventilated building, adjusted for inflation, are estimated as £5.49/m^2 for energy costs and £5.27/m^2 for maintenance[22].

Computer modelling

BSRIA undertook computer modelling using TAS combined air movement /dynamic thermal simulation software to indicate the effect of carrying out different measures on a 1960s concrete-framed office building that was due for refurbishment[23]. Different ventilation and solar shading options were investigated and assessed for their affect on resultant temperature. Many of the measures are valid for both naturally and mechanically ventilated buildings.

Figure 1 shows resultant temperatures when a measure is adopted in place of the reference case (black bar) of no shading, exposed soffit, and 3 ac h^{-1} ventilation, with only the one stated change being made. This is a good indicator of the comparative effect of the different options for the modelled building and may be used as a general guide for other buildings to help minimise overheating.

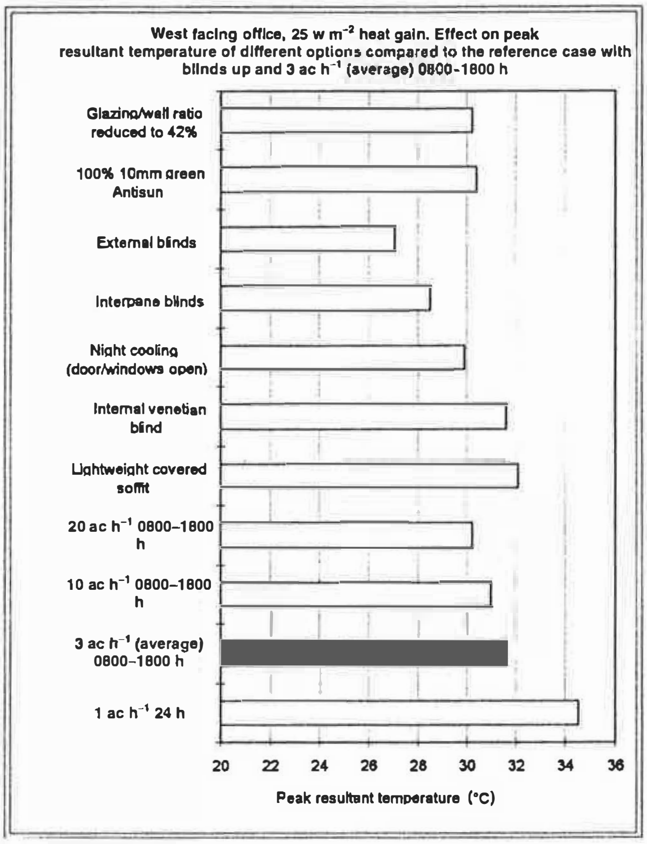

Figure 1 Effect on resultant temperature of different options compared with reference case. Key: ac h^{-1} = air changes per hour

The modelling showed that for a west-facing office in the case study building, the temperature increased by 0.5 °C for every 10 W m^{-2} rise in internal heat gain. Efficient lighting, use of occupancy and daylight sensors, and effective use of daylighting could reduce gains by 10 W m^{-2} or more in most cases. Further reductions can be obtained by application of solar shading and careful positioning of people and office equipment.

Solar shading had the greatest effect on peak resultant temperature as the main facades faced east and west. Internal blinds, although reducing air temperature by about 1 K, had little effect on resultant temperature owing to their high surface temperature. Inter-pane blinds were able to radiate more heat to the exterior, reducing resultant temperature by over 3 K, whilst external blinds achieved a reduction of 4.5 K.

Computer modelling also showed that the glazing ratio has a big effect, especially on a predominantly west-facing facade. Reducing a 60% glazing ratio to 42% by use of opaque insulated panels was found to be more effective than use of heat-absorbing glass, reducing peak resultant temperature by 1.4 K for a west-facing office.

The computer modelling concluded that peak internal temperatures not exceeding ambient values were achievable in the typical office building (25 W m^{-2} internal heat gain) during a warm UK summer, providing investment was made in appropriate solar shading, an air change rate approaching 10 ac h^{-1} in a 2 m s^{-1} wind (wind speeds at 10 m high are typically 4 m/s or greater for 50% of the time[25], use of existing thermal capacity—including night cooling—and careful control of internal heat gains. The building refurbishment went ahead on this basis.

Acknowledgements

The projects 'Refurbishment of air-conditioned buildings for natural ventilation' and 'Refurbishment of concrete buildings for the 21st century' were undertaken under the Department of the Environment, Transport and the Regions 'Partners in Technology' programme. The sponsors for the first project comprised BBC, EA Technology, Health and Safety Executive, London Electricity plc, Metropolitan Police Service and Midlands Electricity. The second project was led by the British Cement Association and the steering group consisted of representatives from Buro Happold, Monodraught Ltd, Nick McMahon Ltd, Reinforced Concrete Council, Ridd Wood Partnership and Sure Foundation Building Services Ltd.

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Models for natural ventilation

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Introduction

Natural ventilation is widely recognised as one of the most effective techniques for maintaining thermal comfort and indoor air quality in buildings. Appropriate building design and use of natural ventilation techniques when outdoor conditions are favourable can significantly reduce the cooling requirements in buildings at minimum cost.

In order to assess the impact of natural ventilation on the energy performance of a building it is important to understand the physical processes that are associated within it and then translate the interaction of the physical determining parameters into mathematical relations. Research efforts over recent decades have resulted in a number of models describing natural ventilation processes. Existing modelling tools are characterised by various degrees of complexity, ranging from the simplest to the most sophisticated. The degree of complexity of these models is reflected at the level of detail of input data they require from the user as well as the output information they provide. It is up to the designer to select the model that provides information that is required for a specific application.

This paper aims to give an overview of the existing modelling types for natural ventilation. In the following sections, the theoretical assumptions, possibilities for application and restrictions are discussed for the three major natural ventilation categories: empirical, network and CFD models.

Natural ventilation modelling

In all cases of natural ventilation, the driving forces are attributed to pressure differences that are created across all kinds of openings in the building structure. Pressure differences result from the combined action of two mechanisms: wind and the temperature difference across the opening. Their interaction is very complex, which makes the mathematical interpretation of the physical phenomena very difficult.

In reality, these two physical parameters show a high degree of variability: wind has a constantly changing character, while the temperature difference often varies with height as a result of temperature stratification in enclosed spaces. The temporal variation of the wind creates high complexity in the natural ventilation air flow. Moreover, the presence of neighbouring obstacles (ground roughness and layout of immediate surroundings) modifies the characteristics of the free stream air flow, creating a variable wind pressure distribution around the building envelope. To this date, knowledge of the wind pressure field around a building exposed to real outdoor conditions is rather restricted.

In an attempt to overcome the above complexities existing modelling approaches are based on theoretical assumptions and simplifications. The relative impact of these on the accuracy of the predicted ventilation air flow rates depends on the level of detail required in the study of a specific problem. Average values of the main physical parameters (wind speed, direction, temperature) may be used in order to derive the mean air change rate with satisfactory accuracy; the same does not apply when the problem is the air velocity field in naturally ventilated spaces.

Empirical models

This category includes simplified methodologies relating the air flow rate with the wind speed and temperature difference for the calculation of the mean air exchange rate or the average air velocity in a space under study. The following methods are representative for the estimation of the air flow rate: British Standard 5925, 1990[(26)], ASHRAE 1985[(27)], Aynsley 1977[(28)], de Gids and Phaff, 1982[(29)]. These methods refer to a single zone space without internal partitions.

According to the de Gidds and Phaff method[(29)], a general expression is given for the ventilation rate, Q, through an open window as a function of temperature difference, wind velocity and fluctuating terms. For the case of single-sided ventilation, an effective velocity, U_{eff} is defined and refers to the flow through half a window opening:

$$U_{\text{eff}} \frac{Q}{A/2} = \sqrt{C_1 U_{\text{met}}^2 + C_2 H \Delta T + C_3} \qquad (1)$$

where U_{met} is the meteorological wind velocity, H is the vertical size of the opening, C_1 is a dimensionless coefficient depending on the wind, C_2 is a boundary constant and C_3 is a turbulence constant. The term C_3 is equivalent to an effective turbulence pressure that provides ventilation in the absence of stack effect or steady wind. Analysis of data from experiments under buoyancy-driven flow has led to the following values for the fitting parameters: C_1=0.001, C_2=0.0035 and C_3=0.01.

The majority of existing empirical methods for the estimation of the air velocity in naturally ventilated buildings have been derived from parametric analysis of data from wind tunnel tests. They refer to very specific outdoor conditions and simplified geometries, opening sizes and positions.

Owing to their simplicity, empirical models provide a fast and easy first estimation of the air flow and velocity in simple configurations. However, their use is restricted to simple configurations. Moreover, as the expressions they provide are based on data from experiments under specific conditions, their limit of applicability is restricted within the range of variation of the parameters involved in the experiments.

Network models

In real conditions, the approximation of an entire building by a single zone volume is of little value, since the interaction of various zones through internal openings is of great importance, especially when the issues of thermal comfort and indoor pollutant transport are addressed. In this case, a multizone air flow network analysis is required.

A literature review undertaken in 1992[(30)] revealed 50 different multizone models since 1970. Despite the large number of existing programs, the development of multizone infiltration and ventilation models shows a relatively slow evolution. Some of the models reported in the above review have been developed as research tools rather than for the use of professional engineers or architects and are not available to the general public. During the late 1980s extensive effort to develop an airflow model for multizone structures led to the development of some of the best-known models in this category (BREEZE[(31)], COMIS[(32)], CONTAM93[(33)], ESP-air[(34)] and AIOLOS[(35)]).

According to the concept of air flow network modelling, a building is represented by a grid (Figure 1) that is formed by a number of nodes standing for the simulated zones and the exterior environment. Boundary nodes are used to represent the environment outside the building. Nodes are interconnected by flow paths, such as cracks, windows, doors and shafts to form a network. Depending on the building design, some of them communicate with exterior nodes of known pressure, while others are connected only to interior nodes where pressure is unknown. Calculation of unknown pressures is derived by application of mass balance equations in each node. The theoretical background of network models lies in the Bernoulli theory, according to which the air flow rate Q_k through a building opening k

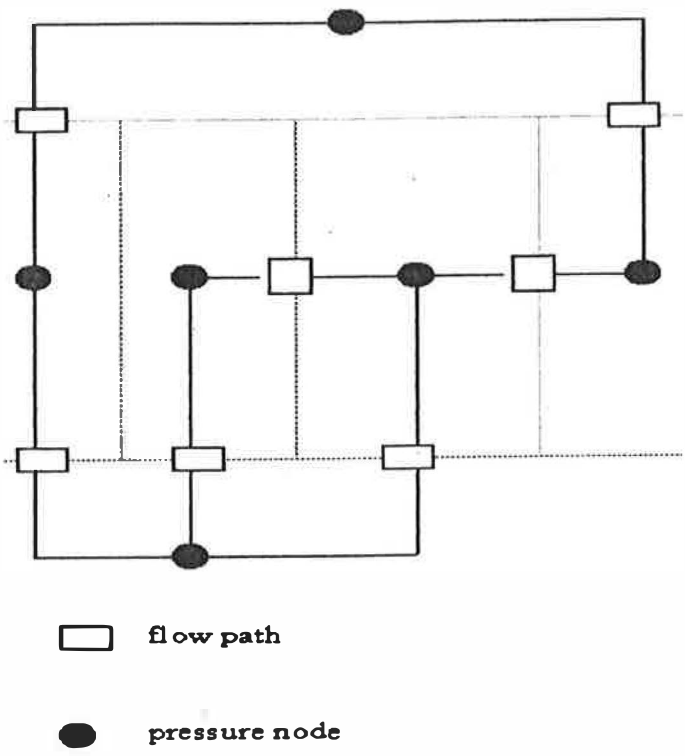

Figure 1 Network representation of a multizone building

is directly related to the pressure difference across it:

$$Q_k = f(\Delta P_k) \qquad (2)$$

Application of mass balance on a zone i with j flow paths gives:

$$\sum_{k=1}^{j} \rho_i Q_{ik} = 0 \qquad (3)$$

where Q_{ik} is: the volumetric flow from zone i to zone k ($m^3 s^{-1}$) and ρ_i is the air density in the direction of the flow ($kg\ m^3 s^{-1}$). Application of mass balance on each internal node of the network leads to a set of simultaneous nonlinear equations, the solution of which gives the internal node pressures and consequently the air flow rates.

The assumption in these models is that the flow is steady, inviscid and incompressible. Thus, these models neglect the presence of local turbulence. This assumption is valid when addressing the problem of bulk air flow rate calculation. Indeed, local eddies that are formed near the edges of a large opening are of a very small scale compared to the opening dimensions. Thus, their impact on the bulk air flow formation can be neglected without significant error. Therefore, network models can be trusted for the study of the bulk air flow rate in naturally ventilated buildings. However, when smaller-scale problems, such as the derivation of the air velocity patterns, are of interest, the above assumption causes significant inaccuracy in the predictions of the models. In this case, more sophisticated models must be applied.

Use of computational fluid dynamics

Over the past few years, extensive research on computational fluid dynamics has lead to the development of the state-of-the art models for the description of air flow processes: CFD models. Based on the solution of the NavierStokes equations for the conservation of mass, momentum and energy, these models provide a detailed description of the air velocity, pressure and temperature fields in enclosures (Figure 2). For the description of the turbulent part of the flow these models use state-of-the-art algorithms. Despite their wide application in the field of aeronautical engineering, the use of these models for the study of natural ventilation air flow processes has so far been limited to the research area. This is partly due to their complexity, which is reflected in excessive requirements in both computational time and level of expertise of the user.

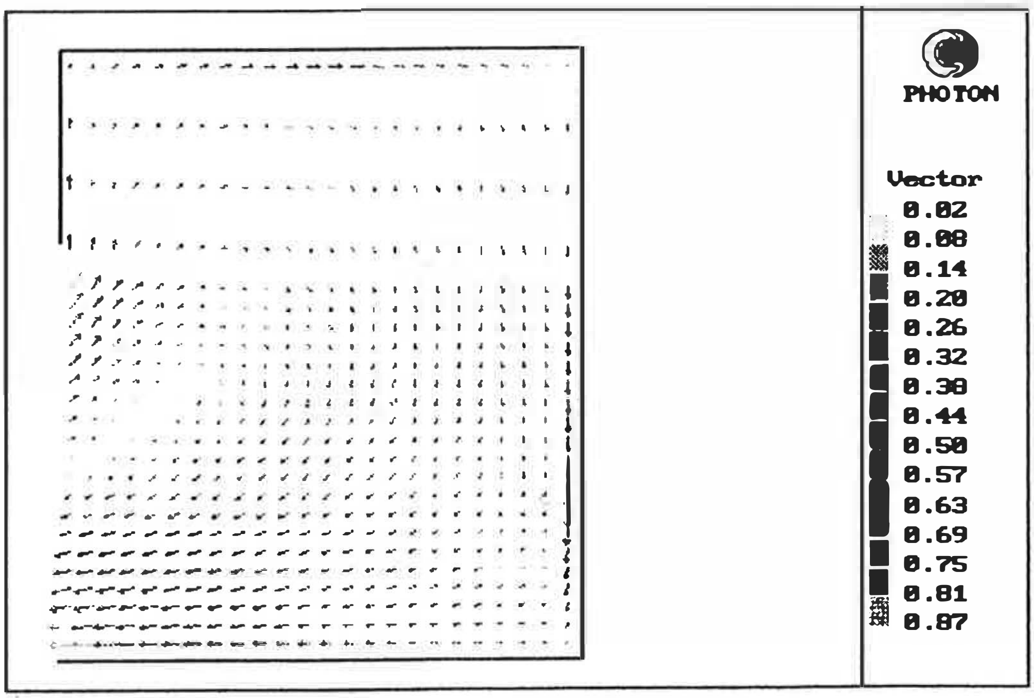

Figure 2 CFD simulation results (2-D) for a single sided natural ventilation configuration[35]

On the other hand, the credibility of predictions provided by these models depends strongly on the accuracy in the definition of the boundary conditions regarding the distribution of pressure, temperature and air velocity profiles at the edge of the solution domain. In problems characterised by controlled or well defined boundary conditions these models prove to be a very powerful tool, providing very detailed information on the air motion characteristics. In the case of natural ventilation, the boundary conditions are uncontrolled and lack of knowledge regarding the above mentioned distributions leads to the adoption of assumptions for different parameters that significantly affect the flow patterns. This introduces a source of inaccuracy at the problem definition level, which is reflected in the results obtained. Therefore, when using these models one has to be very careful of the initial assumptions that are made and very aware of their implications on the results. This is the reason for the limited published literature on the use of CFD models in studies of natural ventilation in full-scale buildings exposed to real conditions.

Conclusions

This overview highlights the advantages and disadvantages of the main modelling categories developed so far and used for studying natural ventilation processes. When used within the limits of their applicability, all existing models can provide useful information ranging from a rough estimation of the bulk air exchange rate (empirical models) to the breakdown of flow through individual external and internal openings (network models) and the detailed air velocity field in enclosed spaces (CFD models).

However, the nature of the physical parameters affecting natural ventilation imposes some barriers to the extent to which deterministic methodologies can approach the related physical processes. The latest are characterised by a high degree of uncertainty. The wind, a randomly varying parameter, creates a nonuniform field of pressure difference at the opening, which results in a constantly changing air velocity field. The random variation of the wind characteristics cannot be interpreted in a deterministic way. Artificial intelligence techniques seem to offer an appropriate alternative.

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Natural ventilation and architectural designing

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Introduction

Natural ventilation, also known as assisted natural ventilation, is an expanding design practice that has an associated series of building features; architectural decisions integral to success. Their recognition and integration provide a discipline for the systematic reconceptualisation of certain building types, as well as reconsideration of building details. Building designs conceived and built within the past decade in Britain and elsewhere illustrate a congruence of these concepts that reflect both philosophical commitments and a technical prowess with growing promise and practice[37,38].

A tradition of fresh air

In Britain there is a long tradition of well-ventilated buildings. This practice has its recent reinforcement in 19th century concepts of health and hygiene in both small and large buildings. But ventilation also accomplishes a secondary function of relieving humidity and removing moisture. Because of the damp and changeable British climate, buildings must be ventilated at a background rate by regulation, in addition to needs of freshness and thermal tempering. Thus, continuous air circulation rates need to be variable to respond to variable interior conditions as well as local climatic conditions. Especially during the very warm summer of 1995, natural ventilation was particularly appreciated for its cooling effect.

'Freshness' in building air is an aesthetic preference related to nature and the outdoors. Culturally, all of these aspects clearly outweigh any advantages of sealed buildings that are air conditioned with refrigerated air, and often dependent on continuous electric lighting. Operating costs and the environmental price of refrigerated buildings reinforce the British preference for buildings conditioned passively by the creation of open building environmental systems responsive to and interactive directly with outside conditions.

An architecture of amenity and openness

Buildings with the amenities of views of the outdoors, fresh air, daylight and openable windows are increasing in numbers not only in Britain. Natural ventilation lends itself to buildings with continuous open interior spaces where convection-driven air motion is free to follow natural paths. Generally, buildings of narrow width are preferred to give easy access to fresh air supply.

High ceilings and continuous open air paths at ceiling level for spent air to find an exhaust route suggest ceiling designs that look like flow paths. And the structural modelling of ceilings can increase thermal transfer using the building fabric for thermal storage and thermal radiation back down to the floor space. But some ceiling designs, like the precast concrete vaults at the Inland Revenue Building at Nottingham[39], offer resistance and confuse the streams of air flow with their waves that cross the air path. In contrast, the similar concrete ceiling vaults at BRE Environmental Office follow the same direction as the air flow, thus reinforcing air movement.[40]

Naturally ventilated buildings organise the airflow patterns architecturally with dispersed and controlled fresh air inlets near floor level. Obviously, the higher ceilings preferred for daylighting are an advantage for displacement ventilation because of the buoyancy of air as it is warmed. But natural exhaust, capitalising on a chimney effect, is only possible when there are several stacked floors, each contributing its spent stale and warmed air to flues or exhaust towers at the top of the system. This method of ductless ventilation works best with open planned floors and at least three storeys. Atriums and stairwell towers often provide the architectural exhaust path to accommodate the stack effect. The higher the outlet, the better the buoyancy works without assistance, so two critical dimensions are the total height of the stack and the height from the ceiling of the top floor to the top of the stack – it is that top floor that has the weakest draw.

Context of climate and site

The most successful recent naturally ventilated buildings are found in temperate climates where neither summer nor winter has excessive temperatures, typical of Britain and Central/Northern Europe. The goal of low operating energy costs implies that the outdoor air supply must be at a somewhat lower temperature than the average interior conditions. If it is too cold, there will be noticeably unpleasant drafts or a need to preheat. But temperate air supply at room temperature will minimise the opportunity for thermal tempering while perhaps requiring some blower or impeller power to induce air motion.

The interest in a healthy building environment raises the question of indoor air quality. Brown field sites with congested, polluted air and noisy locations require remediation. Site redesign may not be possible because of area restraints, or design opportunities may be inadequate. Typically, filters also provide an impediment that then requires powered fans. But greenfield sites may also not be guaranteed clean air. In both cases, site design using both architectural and landscape elements can improve natural ventilation conditions.

Powergen[40], completed in 1995, is in a green office park south of Coventry, UK. The site is at the end of the access road and next to a nature preserve. The architects, Bennetts Associates, planned the site development to encourage lateral air motion. A black asphalt parking lot on the south side exaggerates the natural solar heated condition. A meadowed nature preserve on the north side is naturally cooler, thus encouraging cross ventilation through and under the building. Both treatments keep the skies open for daylighting. By raising the three-storey scheme off the ground to continue parking underneath the building, maximum exposure of the building envelope to the natural environment upon which it depends has been achieved. A performance diagram has resulted in an architectural resolution that is also delightful.

The marriage of ventilation and daylighting

Perhaps the most reinforcing discovery of recent naturally ventilated buildings is their compatibility with daylighting. Both require relatively narrow floor footprints and both thrive on high ceilings. The traditional 19th century rule of effective daylight depth equals two and one half times the height of window head has its parallel in effective ventilation distance from the window.

In addition, there is the elementary bilateral notation: The best lighting comes from more than one source; and natural ventilation automatically requires a supply location on the opposite side of spent air exhaust. Cross ventilation thus has its counterpart in cross lighting. The quality of indoor conditions where natural ventilation and daylighting are mutually reinforcing and nature driven is best appreciated first hand. The luminous and airy quality of the work spaces in Powergen are a direct result of these linked passive strategies. And the premium top floor of BRE Environmental Office is especially satisfying as an architectural space reinforced by bilateral light and air.

Integrity and craft on the interior

The low pressure needs of a convective ventilation system require a directness and consistency of path route without spatial blockages or short circuits. Similarly, surfaces of thermal storage materials must be exposed directly without air foils or superficial coverings. Because of desirable thermal capacity and lag time, most interior designs should avoid lightweight materials such as hung acoustic ceilings, as well as decorative skins or surfaces like plywood panels or wallpapers.

Such a discipline removes certain thin decorative materials or surface enrichments from the interior design palette. Alternatively, it encourages the use of heavy, solid and continuous materials—often exposed structural elements—the bones and muscle of the building become its visible end appearance. Since they will be the finished surfaces, these materials must be placed and crafted during the roughest period of construction to anticipate their final visible effect. Thus, naturally ventilated buildings tend towards certain structural and construction choices that also require exposure—practices that encourage integrity in design and careful craft in execution.

Alternative concepts

Although the principle of air convection is easily understood and the idea of displacement ventilation is well practised, especially in the United Kingdom, the concept of natural ventilation can take many physical configurations. Thus, the particulars of any system are driven by site, building needs and construction costs. A more generous construction budget may result in more substantial and

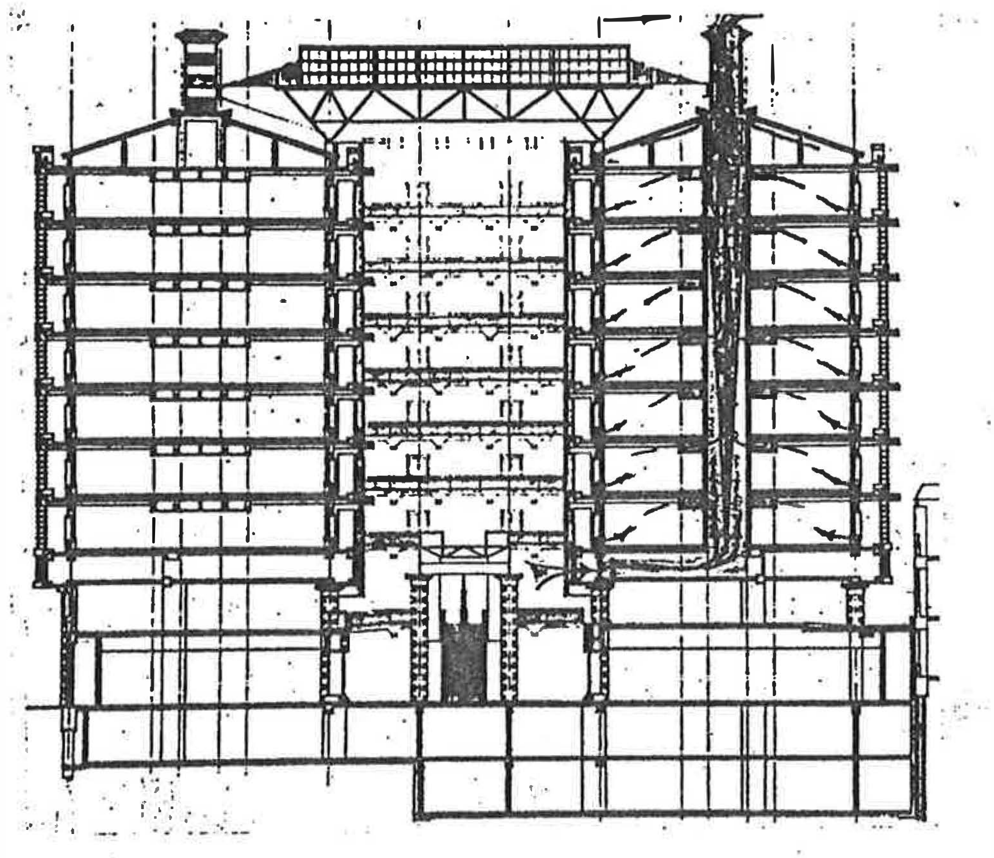

Figure 1 Section: Eastgate Complex, Harare, Zimbabwe. Ten floors, plus parking garage, 4000 workers, and a shopping centre saved $US 3.5 million on a $US 36 million building construction budget because refrigerated air conditioning was not used.

interesting materials, surfaces and forms such as the Inland Revenue Building at Nottingham. But half the budget does not result in half the performance. Rather, the design shift at Powergen allows an aesthetic based on the simplest materials, and a ventilation strategy integrated with daylighting that is necessarily more comprehensive and basic.

Alternatively, the stringent requirements of some building functions for a more absolutely controlled interior environment are not the cause to eliminate passive and low energy systems for the balance of the building, as in parts of the Ionica Building in Cambridge[42]. There the overlap of systems deliberately provides a redundancy in which the natural ventilation and daylighting provide the architectural character, as well as the daily liveliness in use. Simultaneously, there are options based on management mandate or operations style.

Lessons and transferability

Even in the most ambitious performance, as well as generous budget, such as the Parliamentary Office Building now rising in Whitehall opposite Big Ben, many of the interactive lessons of assisted natural ventilation have informed the design of the fabric as well as the interior. The site may not only be among the most prominent urban locations globally, but also at ground level among the more polluted, thus requiring extraordinary measures. Primarily mechanically driven, the ventilation system is still passively inspired in its architectural chimney exhausts, and passively informed in various thermal transfer details.

Similarly, in the arid African climate of Harare, Zimbabwe, natural ventilation alone could not drive the non-air conditioned 10-storey Eastgate office and shopping complex designed by the Mick Pearce Partnership[43] (Figure 1). But when the client agreed to pay the environmental engineer a design fee determined by what the cancelled refrigerated air conditioning would cost, the result was an assisted naturally vented building. Based on passive concepts of convection and heat transfer, Eastlake has a peak shift of interior temperature from 1400 h to 1700 h pm, as well as an amplitude reduction that can be accommodated by night-time thermal purging. The 140 000 pieces of precast concrete with many exposed surfaces are critical to the required thermal exchange strategies. The exhaust chimneys on the roof ridge give architectural expression. The building has been using less than 10% of the energy of a comparably sized refrigerated building[44].

In parallel is the recently completed Tjibaow Cultural Center in Noumea, New Caledonia, by Renzo Piano's Building Workshop. (Again, the London office of Ove Arup and Partners were the engineers.) Here 10 skeletal shells rising in height from 25.5 to 30.3 m scoop the air, promoting natural ventilation. The form of these 'cases' in the sky is romantically derived from the structural ribs of traditional shelters of the Kanak culture. But in successive wind tests, they performed as thermal chimneys, drawing exhaust air from the top of spaces. Simultaneously, louvres in the bottom of these 'cases' guide fresh air into a modern HVAC system through louvres that are computer controlled. Here a passive feature does not replace mechanical systems but heightens their performance.

Conclusion—The architectural incentive

Natural ventilation seems to have its most convincing applications in larger anonymous buildings, such as office blocks, where work processes and protocols are open and changing. Passive ventilation appears to be least applicable, or the most challenging, in highly specialised and complex buildings, such as hospitals or laboratories, and on highly polluted sites. Both functionally and aesthetically, natural ventilation and its associated strategies appear to be most compatible with the ubiquitous stock of loft buildings where they can become the geneses of character and personality.

The need for stack exhaust pathways, typically provided by ventilation towers or chimneys, automatically produces an architecture punctuated by vertical elements. Whether it is the singular exhaust lantern of St Johns Library, Cambridge, by architect Edward Cullinan; the rhythm of stacks on BRE Environmental Building, or the expressive towers above the Queen's Building for the School of Engineering and Manufacture at De Montfort University, by Alan Short and Brian Ford[(44)], or the continuous ridge crests of Powergen by Bennetts Associates, these are necessary elements that provide aesthetic distinction. The need for continuous openings along the facades, and the requirement to allow continuous open air paths on the interior, are stimulants for sensible architectural responses that are visible and readable. Thus, in parallel with other passive environmental conditioning strategies such as solar heating and daylighting, natural ventilation requires a comprehensive integrated design and construction fit, both inside and out, that inevitably informs and forms architecture anew.

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