NATURAL VENTILATION OR MIXED MODE?
AN INVESTIGATION USING SIMULATION

Andrew Wright, EA Technology Ltd., Chester CH1 6ES, UK, Virginia Cooper, and Geoff Levermore, UMIST, Manchester, Dept. Building Engineering, M60 1QD, UK

ABSTRACT

This paper decribes a research project to compare, using simulation, the summertime comfort and energy use of naturally ventilated and mixed-mode (limited cooling) UK office buildings. A large number of simulations were run to investigate the effects of different design factors, on four facades. Various novel graphical methods, and regression equations, are used to present the results. It was found that without cooling, comfort could only be achieved by using several passive features to reduce internal temperatures. A wider range of mixed mode designs were shown to be low energy than natural ventilation designs, with better daylighting compensating for the cooling energy.

INTRODUCTION

This paper describes the results of investigations into the mixed mode operation of UK office buildings compared to natural ventilation only. It is based on work carried out by VA Cooper for her PhD thesis[1].

Until the 1960s few buildings in the UK were air conditioned. Then changes in architectural design lead to more use of deep plan, taller buildings, high levels of artificial lighting, and very high levels of glazing in lightweight structures. These factors, combined with increasing traffic noise in cities, often made it desirable to seal windows. With an increased level of solar gains, comfort could no longer be achieved with natural or mechanical ventilation. Air conditioning seemed entirely superior to natural or mechanical ventilation in a society which believed every problem could be solved with technology. The main argument against air conditioning was its cost. Randell and Mitchell[2] reflected the general view held in 1969: *"No one would doubt the desirability of air conditioning, but what is generally questioned is whether the cost is justified. . . . Hardly anywhere in this country [the UK] is it likely that an entirely satisfactory environment will be achieved, in general, throughout the year, without air conditioning".*

Yet even then there were dissenting voices with views remarkably similar to those of 30 years later. At the same conference Thornley[3] put forward the view that *". . . there is no need to hold the temperature constant in a building providing that the temperature lies within an acceptable range for comfort. The limits of 'swing' can be controlled by window size and shading devices, the mass of the structure, or by designing an air conditioning system of smaller capacity than would otherwise be the case if a close control of internal conditions was decided upon."*

By the late 1980s, concern over the effects of CFCs and HCFCs on the ozone layer, a general view that Sick Building Syndrome was associated with air conditioning (though without much hard evidence), and the high energy costs of air conditioning compared to natural ventilation, were causing many to doubt the value of air conditioning in the UK climate. Atria and internal 'streets' suddenly became popular, allowing stack-driven natural ventilation in deep plan buildings, and environmentally-inclined designers returned to classical principles of exploiting natural ventilation and daylight. But despite this trend, air conditioning continued to grow strongly in the 'mass market' of new and refurbished offices, partly due to the spread of computing from a few mainframe terminals to a PC on almost every desk. It caused the strongest growth in energy use, and associated carbon dioxide emissions, of any building sector.

The results of studies of real buildings were inconclusive on whether occupants preferred air conditioning or natural ventilation, showing that many other factors were involved. A big debate about whether natural ventilation was preferable to air conditioning began, with almost religious fervour on both sides. But then a 'third way' began to emerge, already hinted at by Thornley[3]. This was 'mixed mode' operation, where natural ventilation is used for most of the time without cooling, but some cooling is available to 'peak-lop' in hot weather so that the internal temperature is limited to, say, 25°C - higher than in a closely controlled air conditioning system, but sufficient to avoid the more severe discomfort of higher temperatures. Various definitions for 'mixed mode' have been proposed, but for the purposes of this work Cooper's[1] will apply:

It is a building in which occupants can open windows, and which is designed with effective passive strategies for limiting the effects of the external climate. The passively designed building is utilised to provide acceptable conditions for the majority of the year, and is supplemented by a *mechanical system, either on an 'as and when required' basis, or on a seasonal basis.*

Providing comfortable conditions in the winter is relatively easy with good basic design and a well-designed heating system. For modern offices, meeting current insulation standards, the main comfort problems are likely to occur in the summer due to overheating. These can either be avoided by installing cooling, or by designing the building with sufficient passive features to achieve adequate summer conditions with natural ventilation alone. This led to two fundamental questions for office building design in the UK:

1. What are the limitations of natural ventilation in the UK?
2. Could a mixed mode building use less energy, and cost less to run, than an equivalent building with natural ventilation only?

It might be assumed that a mixed mode building would always use more energy than one without any cooling, but this is not the case if the mixed mode building uses less energy for some other service. In particular, it was hypothesised that a naturally ventilated building would have to limit solar gain and hence daylight, such that it could require more artificial lighting than the mixed mode building. The additional lighting energy in this building could then be more than the energy used for cooling in the mixed mode building.

WEATHER DATA

A typical summer in the UK only produces a few hot spells, but sometimes very hot sunny weather can persist for several weeks, such as in 1976 and 1995[5] when almost any building without cooling will become very warm. To investigate mixed mode, a selection procedure developed by BRECSU[4] for the BRE Office of the Future was used. This calculates the daily mean temperature for June, July and August and ranks years on this basis, then selects the centre of the upper quartile as the sample year. This was applied to the years 1975 to 1995, and resulted in 1989 as the sample year. For the population of years as a whole in an unchanging climate, one in eight years would be hotter than years lying at the centre of the upper quartile. However, there is growing evidence of a warming climate in the UK which may mean years exceeding this level will become much more frequent[5]

SIMULATION PROGRAM

The APACHE[6] suite of programs was chosen for simulation. This was selected because it has an established track record in building design, can model plant, runs quickly, and because there was already experience of using the software at UMIST.

BUILDING

The office model chosen for simulation was based on the CIBSE rectangular office room described in the 1986 CIBSE Guide[7], but with insulation upgraded to current UK building regulation standards. It was 6m deep from the external wall, considered sufficiently narrow for natural ventilation, 35m long, and 3m high. For the simulations it was oriented to face north, east, south and west, so that each simulation corresponded to an office room on one facade of a larger building. It was always assumed to be on intermediate floor with thermally identical spaces below the floor, above the ceiling and on the other side of internal walls. Table 1 summarises the fabric elements. Admittance was not used in the model but gives a good indication of thermal mass.

Table 1: Fabric elements of office room used in simulations.

Element	Construction (out to in)	Area m^2	U W/m^2K	Y W/m^2K
Floor[i]	Screed, concrete, carpet	210	1.77	3.61
Ceiling[i]	screed, concrete	210	2.05	6.28
External wall[o]	brick, insulation, block, plaster	105 inc glazing	0.45	6.66
Internal side walls[i]	plasterboard, air, plasterboard	2x18	1.54	1.14
Internal back wall[i]	plaster, brick, plaster	105	1.77	3.61
Window[o]	normal double glazed	variable	3.30	3.30

[i] adjacent to internal wall, [o]adjacent to external wall

A very large number of runs was carried out for different combinations of facade orientation, internal gains, lighting control, day and night ventilation, and solar control. These used the assumptions described here.

INTERNAL GAINS

Office equipment and people gains were assumed to occur from 09:00 to 17:00.

Base case 17.3 Wm^{-2}
'Low' case 18.6 Wm^{-2}

Lighting was assumed to be operational from 09:00 to 19:00, with target illuminance 500 lux, gain 15Wm^{-2}. Some runs used lighting control. The room was split into two control zones, a 4m zone adjacent to the windows and a 2m zone along the rear wall. Within each zone there were two banks of lights which could be independently switched, to maintain 500 lux (the recommended maintained illum level in UK) using a combination of natural and artificial light. Lighting models were carefully developed to be in agreement with empirical data[8].

INFILTRATION AND VENTILATION

Natural ventilation was modelled as the sum of two components; infiltration, and deliberate ventilation from window opening by occupants. The infiltration rate was held constant at 1ach^{-1}. An algorithm for the ventilation rate was developed using the work of Warren and Perkins[9] on window opening as a function of external temperature. For the temperature range 5.6°C < T_e < 22°C, ventilation rate V is described by the equation

$$V = N\psi = 0.0611T_e - 0.3444$$

where N is the maximum number of air changes, occurring at 22°C, T_e is the external temperature, and Ψ is the proportion of maximum air changes. For an outside temperature of 22°C the ventilation rate V is N, and below 5.6°C the ventilation is zero. The constant infiltration rate is always added to V. Maximum ventilation rate N was varied between runs from 0ach^{-1} to 16ach^{-1} in steps of 2ach^{-1}.

Night-time ventilation strategies are a research area in their own right. An effective strategy should ensure that cooling is available from outside air, the external air is not too cold, and the building is not over-cooled. A simple strategy based on work by BSRIA[10] was used here. Night ventilation was employed in some runs between 20:00 and 07:00 when all the following criteria were satisfied:

internal air temperature > external air temperature
external air temperature > 12°C
internal air temperature > 18°C

SOLAR SHADING

Horizontal external overhangs above the window were used for solar shading, varying in vertical position above the window from 0.1m to 2m, and extending horizontally by 0.5m, 1m and 2m.

Five scenarios of window shading were also used:

1. No blinds
2. Venetian blinds, shut, down 09:00-17:00 Monday to Friday
3. Venetian blinds, open, down 09:00-17:00 Monday to Friday
4. Mid-pane blinds, down 09:00-17:00 Monday to Friday
5. Mid-pane blinds, controlled by incident radiation; down at 250Wm^{-2}, up at 200Wm^{-2}

COMFORT CRITERION

Based on the work of BRECSU[4], the percentage of occupied hours in the year above 25°C dry resultant temperature (defined as 0.5 air temperature + 0.5 mean radiant temperature) was used as a measure of overheating, and given the symbol Ω (on a scale from 0 to 100). The BRECSU comfort criterion that Ω should not exceed 5% was adopted. Buildings with fewer than 5% of hours were deemed to ‘pass’, while those with more were deemed to ‘fail’. This criteria is in contrast to many approaches which take the maximum internal temperature in the year. This is felt to be less reliable because it does not integrate over time, and can be affected by short-term weather conditions; indeed it was found that one building could have a higher peak temperature and a lower value of Ω than another building. Another criterion sometimes used alongside the one adopted is that, in addition, buildings should not exceed 28°C for more than 1% of occupied hours. However, in practice it was found that if the <5% above 25°C criterion was met, then the <1% above 28°C would also be met, so this was not considered further.

OPERATION OF MIXED MODE PLANT

Operation of mixed mode plant has to be carefully defined to avoid the system becoming full air conditioning, and to avoid conflict with passive strategies such as a high natural ventilation rate (windows open) during cooling.

If a building requires significant cooling outside June, July and August to maintain the temperature below 25°C then it is likely to require air conditioning. Therefore the mixed mode plant was only operated during June, July and August. The plant was modelled as ‘ideal’ cooling, removing just the right amount of heat to achieve the set point air temperature. Further calculations were then used outside the simulation to calculate energy use for a fan coil system with air supply and extract. Finding a suitable control temperature was difficult, because comfort was measured using dry resultant temperature while a fan coil system can only realistically be modelled by controlling on air temperature. Even using 24.5°C as the cooling set point air temperature sometimes resulted in the comfort criterion not being met because the dry resultant temperature was often above 25°C. Therefore the set point was ‘fine tuned’ for different runs so that comfort was just achieved, with minimal cooling. Feedback from real mixed mode buildings shows that occupants learn to close windows when the cooling plant is operating to increase its effectiveness. This was modelled by assuming windows were closed (i.e. deliberate ventilation was stopped) when the internal temperature reached 1°C below the set point for cooling.

Heating is less important for this study, since it is relatively easy to achieve comfort in cold weather and the main interest was in summer performance. However it is necessary to calculate heating requirements, which vary with the building configuration, in order to obtain annual energy requirements. Heating was modelled as a gas-fired boiler serving wet radiators, with a set point of 19°C and a dead band of 2°C, operating from September to May.

RESULTS

In the first stage of analysis, only naturally ventilated buildings were considered in order to find the 'design spaces' within which natural ventilation achieved comfort, full air conditioning would be needed, and, between these, mixed mode operation would be feasible. In a typical simulation exercise, time series of typically hourly data are analysed from a modest number of runs. This can be daunting, so the mass of data is usually reduced to a few key statistics such as maxima, minima, means and totals. There is usually a clear 'cost function' to optimise, such as minimising energy use or minimising peak summer temperature.

However, in this study there is a potentially huge number of combinations of input parameters and hence runs to investigate. If all the main combinations were considered, the number would be

9 glazing × 6 vent. × 4 orient. × 12 shading × 4 blinds × 2 gains × 3 night vent. × 10 mass = 622,080

simulations. While only a subset of these were of interest, it still numbered several thousand runs. It was only practical to consider a small number of numerical output from each run, with a single number to represent each aspect of behaviour. In most cases, three outputs were used:

- comfort parameter Ω (used to determine whether buildings 'pass' on comfort)
- total annual heating energy
- total annual lighting energy

Glazing area and ventilation rate were identified as two key input parameters. The first step was to look at the effect of varying these while other inputs were held constant. Figure 1 shows the effect of varying both parameters, to produce a 3-dimensional surface of Ω values. While this type of plot is good at showing behaviour in a qualitative way, it is no good for quantitative analysis. The strong curvature of the surface indicates that interactions are occurring between the two inputs - that is, the effect of a given change in glazing varies for different ventilation rates. On the left-hand side, with 0% glazing, the response to air change rate is clearly non-linear, while at 100% glazing on the right-hand side it is close to linear above about 4 air changes.

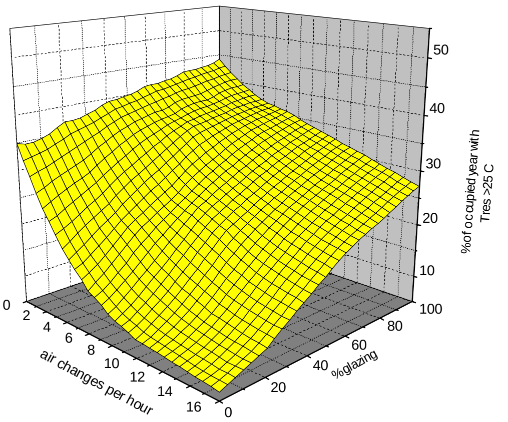

Figure 1: Easterly External Facade - effect of glazing level and ventilation rate on Ω

Another way to present this information is using 2-dimensional line plots of, for example, Ω against glazing area, with different lines for different air change rates. This is effectively plotting slices through the 3-dimensional plot, and is better for quantitative analysis.

These approaches work for ratio scale quantities, which can be meaningfully interpolated, but for ordinal or nominal scales used for quantities such as thermal mass or type of blinds, continuous plots are inappropriate. In this case discrete bar charts can be used. For example, Figure 2 show the effect of blind types and blind operation on comfort Ω, heating energy and lighting energy.

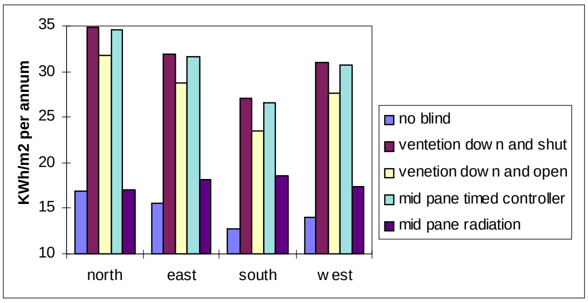

Figure 2: Effect of blind types on energy use for lighting.

However, all these graphical techniques are still only looking through one or two dimensions of a multi-dimensional space of results, with all other factors held constant. They are not very helpful in considering the effects of combining a large number of factors.

To overcome this problem, linear mathematical models were developed from the results obtained from each set of simulation runs. These multiple linear regression models were used to assist in the identification of important parameters and to aid in the identification of interactions between the passive design features. These were firstly developed for pairs of factors, such as glazing and ventilation rate, including where necessary transformation of variables to make the response more linear, and interaction terms. From this work, general linear models were produced, one for each facade, that could be used to predict Ω in terms of all factors. The linear models were produced using standard least-squares algorithms in a statistics package. Though the simulation results are not stochastic, these techniques entirely applicable to finding a 'best fit' response surface.

The magnitude of the Sum of the Square of the Errors (SSE) represents how good a fit the plane is to the data, and the standard deviation of the residuals (RSD) represents an 'average' deviation from the point to the plane. If the all the data points lie on the fitted plane then the SSE and RSD will be zero. Hence a value predicted from the equation will have an 'average' error of ± RSD. Pearson's correlation coefficient (r^2) is often used to indicate the 'goodness of fit' of a line to data points. However, this is a statistical procedure and is biased around the mean of the data points. For this reason RSD was used instead of r^2. These models can be used very easily in a spreadsheet to investigate the effects of different design options on Ω, or on some other parameter such as annual heating energy, for a given location and weather year. As an example, the following equation gives Ω for the west facade:

$$\Omega_{west} = 0.19G - 2.98(\ln V) - 2.27H - 0.99M + \frac{19.45}{(1+N)} - 1.30B - 0.05BG + 5.67B(\ln V) - 0.06GH + 0.94(\ln V)H - \frac{4.73(\ln V)}{(1+N)} - \frac{0.09(\ln V)G}{(1+N)} + 1.27BH + 7.72$$

with RSD=1.39, where G is glazing level (%), N is daytime ventilation rate (h^{-1}), H is overhang length (m), M is thermal mass, N_n is night ventilation rate (h^{-1}), and B is blinds type. Note the interaction terms such as BG, GH, and transformations of ventilation rates.

Linear models can be used to predict whether naturally ventilated buildings pass or fail the comfort criterion (Ω < 5). But it is still important to have a feel for which buildings are likely to pass, and this is best done graphically. Figure 3 shows isopleths for each facade where Ω=5, i.e. the design is on the pass/fail boundary. These are plotted against percent glazing and daytime ventilation rate for the modern office, with blinds and 12 ach^{-1} night ventilation. For the base case, all except the north facade failed completely. Designs to the right fail, those to the left pass. (Initially, shading of pass and fail regions was used, but this only allows one facade at a time to be plotted.) The much greater likelihood of the north facade passing, due to low solar gains, is very evident; without exception this always had the lowest Ω for a given design. The 'pass' region for other facades is limited to a small design region of low glazing area and high ventilation rates; the south facade only just passes, with minimal glazing, at an air change rate of at least $15ach^{-1}$.

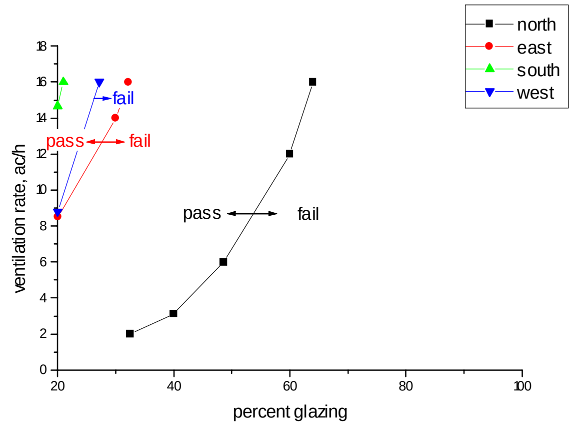

Figure 3: Boundary conditions for base + blinds + $12ach^{-1}$ night ventilation

To achieve a reasonable choice of glazed area and ventilation rates, it is necessary to use several passive features. Figure 4 shows the boundary conditions with external shading, night ventilation and blinds. With strong control of solar gains, all except the north facade are very similar, allowing glazing over 40% with ventilation rates as low as 6 ach^{-1}, or higher levels of glazing with increased ventilation.

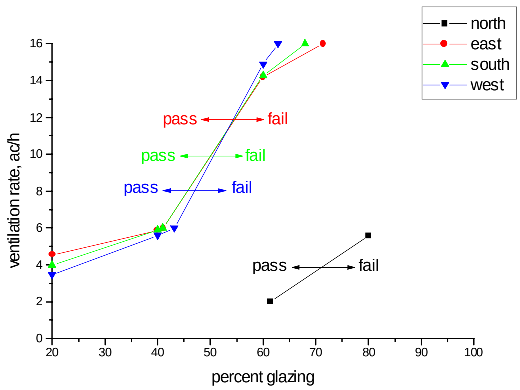

Figure 4: Boundary conditions for base + 2m overhang + $12ach^{-1}$ night ventilation + blinds.

Increasing glazing area on the north facade still increases overheating. This suggests that as glazing increases, the amount of increased diffuse solar heat gain is greater than the amount of increased heat loss through the windows, in conditions close to the comfort limit. Perhaps this is a surprising result. The imbalance will be much greater for better insulated windows.

After the north facade, the south facade came next in how easily comfort could be achieved. This was because solar angles are higher for the south, so that shading is more effective. While the east and west facades are often assumed to have very similar thermal performance, this was not found to be the case. Comfort was consistently harder to achieve on the east facade than any other. Why this should be is not entirely clear, but it may be because the solar gains come earlier on the east and ‘use up’ the thermal capacity of the structure before the end of the working day, causing overheating. On the west, solar gains arrive later, a significant proportion arriving after the end of the working day, so that high temperatures are delayed longer than on the east and there is less overheating.

As stated earlier, the simulations also tried to determine whether a mixed mode building could use less energy than a naturally ventilated building meeting the comfort criterion. The problem arose of how to compare results for many design options of both building types. This was overcome by showing distributions of consumption for many different runs meeting the comfort criterion,.

The calculated total delivered energy for each simulated mixed mode office building, and the naturally ventilated buildings which pass the comfort criteria, were presented as histograms. Lines instead of columns were used for the mixed mode results to improve clarity. The 'mm' on the graph legend represents a mixed mode design. The COPa, COPb and COPc represent the COP determined for different ambient temperatures, with the approximate COPs being 4.1, 3.4 and 2.3 respectively (depending on the specific cooling plant for each design scenario).

The number of cases which relate to each category for energy consumption have been normalised and expressed as a percent of the total number of cases. Figure 5 shows the delivered energy results for the east facade. This uses energy results from 110 naturally ventilated buildings, and 162 buildings with mixed-mode cooling.

Other facades show a broadly similar pattern, with a double distribution for mixed mode. The distribution for natural ventilation is always shifted to a higher average, with a single peak; north and south facades show greater spread. Similar distribution patterns were shown for carbon dioxide production; Figure 6 shows the carbon dioxide results for the same runs. The differences between delivered energy and carbon dioxide arise because of the different weightings given to gas for heating, and electricity for lights, cooling and office equipment. It was assumed that 1 kWh delivered electricity produces 0.52 kg of CO_2, and 1 kWh delivered gas produces 0.20 kg of CO_2, appropriate for the current UK generation mix.

It is not clear why there is a double distribution for mixed mode. Possibly the higher energy distribution results from designs requiring a high level of cooling, while the lower energy distribution results from buildings with low cooling which still make good use of daylight.

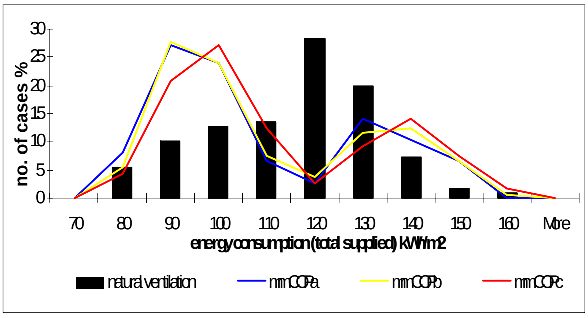

Figure 5: Distribution of total delivered energy for naturally ventilated and mixed mode office buildings, East external facade.

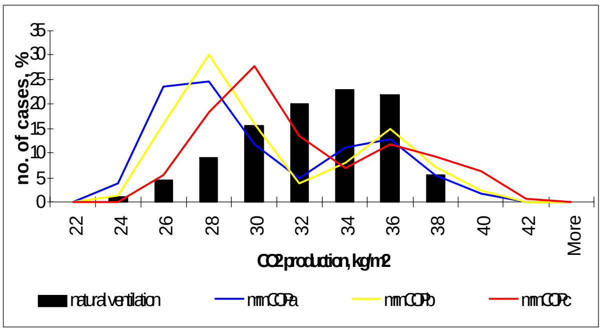

Figure 6: Distribution of CO_2 production for naturally ventilated and mixed mode office buildings, East external facade.

CONCLUSIONS

This work has explored a wide range of design options for achieving summertime comfort in UK office buildings with limited or no cooling. Novel graphical techniques have been developed to present facets of a multi-dimensional design space, and regression methods used as an alternative to full simulation. It has been demonstrated that, for a hot summer in the south-east of England, comfort can only be achieved by using several passive features, or active cooling. Discomfort is likely to be greatest on the east facade, followed by the west, south and north. Therefore it is easier to maintain internal comfort in buildings with their main axis lying east-west, giving mainly north and south facades. It has also been shown that limited cooling, widens the design options and, through more use of daylight, can actually use less total energy. While it is still easy to design mixed mode buildings using more energy than naturally ventilated buildings, there are many more low energy mixed mode designs to choose from than low energy natural ventilation designs.

Although control of ventilation by occupants opening and closing windows is not the most thermally efficient method, it is fundamental to occupant control, which has been shown to be an important psychological factor in overall comfort.

The results on energy assumed effective lighting control and windows closed when cooling was operating. Without careful design of controls, offices may have blinds down and lights on, or windows wide open with cooling systems full on.

The 'hot summer' for this work was based on temperatures during the months June, July and August. Significant overheating was found to occur during the 'shoulder months' of April, May and September, when solar angles are lower and shading therefore more difficult. Therefore, in new guidance[11] it is recommended that selection of similar 'hot summers' is based on the period April to September.

Although the specific results only apply to offices in the south-east of England, similar techniques could be used in any temperate region where air conditioning is not regarded as essential. The results also call into question whether high levels of insulation, intended to reduce winter heating, are necessarily desirable when summer comfort is so hard to achieve without resort to cooling. In the future, there are likely to be further efficiency improvements in energy for electric lighting and office equipment leading to reduced internal gains. Since the work was done, there has been a trend towards lower levels of illumination, of 300-400 lux, which also reduces the lighting energy significantly.

On the other hand, global warming may make warm summers more frequent and increase the pressure for reduced energy use, so that achieving summertime office comfort will remain an important issue.

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