Mixed-Mode HVAC—An Alternative Philosophy

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ABSTRACT

This paper examines an alternative strategy for heating, cooling, and ventilating buildings that attempts to combine the best features of both natural and mechanical systems. It involves a holistic approach to design that treats the building and engineering equally. Such climate-responsive integrated building/engineering systems are intended to operate in the natural mode whenever possible to minimize energy use and only use mechanical systems under peak conditions at the extremes of external temperatures.

The period of use of natural systems can be extended by using passive cooling techniques and fabric thermal storage. Some of the building mass, walls, ceiling slabs, etc., are used as thermal storage media and are allowed to cool overnight and absorb heat the next day. The technique requires some automated control of natural ventilation but both reduces energy use and, by virtue of the thermal mass involved, limits the rise in internal temperature on occasions when normal design criteria are exceeded.

The paper describes the philosophy and operation of mixed-mode systems used in conjunction with fabric thermal storage and suggests some guidelines for the development of the design of a practical system.

INTRODUCTION

For many years, the options for heating, ventilating, and cooling large buildings such as offices have been polarized into two separate and usually isolated strategies—either heating coupled with natural ventilation or air conditioning. However, research in real buildings (Bordass et al. 1995) has shown that there is little to choose from between them. A good naturally ventilated building can be as comfortable as a good air-conditioned one and vice versa. Clearly, achieving this degree of satisfaction is easier for buildings in temperate climates, but, even in extreme climates, temperate conditions can prevail for a large portion of the year when natural systems may be able to provide comfort.

Architecture (i.e., building form and fabric) has an important influence on the internal conditions, but, more often than not in North America, it is not used to advantage; air conditioning is installed automatically.

There is, however, an alternative approach that only uses mechanical systems when natural means are inadequate and avoids the cost, energy penalty, and consequential environmental effects of full year-round air conditioning. This approach is called *mixed mode*, i.e., providing both natural ventilation and mechanical systems (such as forced ventilation and refrigeration) but using different features of the systems at different times of the day or season of the year. The technique has been in use, in one form or another, for around 20 years in the U.K. A recent study of such buildings (Willis et al. 1994) concluded that they are generally successful, popular with the occupants, and able to convey the feeling of a prestige building. The technique is now being used increasingly in the U.K. and has applications to other climates. It requires a whole-building, i.e., holistic, approach to design and takes advantage of the ability of human beings to accept and feel comfortable over a range of temperatures during the course of a single day. In principle, the occupied spaces start the day as comfortably cool as acceptable and finish as comfortably warm as acceptable.

The principal advantages of this method of providing ventilation and cooling to buildings that cannot be satisfied year round by natural ventilation alone are twofold. First, the introduction of openable windows into what might otherwise be a sealed building provides *user control*, the opportunity for users of the building to exercise direct control over their local environment, both in terms of the rate of ventilation and, when outside temperatures are suitable, cooling. Second, by only using mechanical systems such as forced ventilation and/or cooling when necessary, much less energy is used. The energy use can be further reduced by using passive cooling techniques. This only requires that, at some point in a cycle, the external temperature be lower than a comfortable indoor temperature. This occurs in most populated climatic zones.

Overnight cooling by ventilation is possibly the simplest passive technique and utilizes the thermal storage capacity of the building mass to overcome the asynchronous demand for cooling. This includes partitions, the floor slab, furniture, and even the inner portion of the outside wall. The technique, sometimes called *fabric thermal storage* (FTS), can extend the period of the year when mechanical cooling can be avoided. The FTS technique also reduces the size of the mechanical plant necessary to

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meet the peak cooling demands on the hottest days of the year. In addition to these advantages, mixed-mode systems can leave the option open to change to full air conditioning if necessary.

A DIFFERENT DESIGN PHILOSOPHY

Hawkes (1982) considers the design philosophies for fully air-conditioned buildings and those where natural systems predominate as different approaches to the same design problem (i.e., determining the relative environmental functions of building form, fabric, and engineering). In the former, the priority is to isolate the internal environment from the external using mechanical systems. In the latter, the building envelope is given priority and configured to (a) maximize the use of ambient energy and (b) achieve an effective balance between the use of advanced automatic controls and the opportunity for the users of the building to exercise direct control of their environment. He illustrates the difference between these approaches by reference to Olgyay's (1963) principle of selective design, shown (adapted) as Figure 1. Applying this principle of effective use of the natural environment reduces the loads for mechanical systems from the gap between curves 1 and 5 to the gap between curves 3 and 5. By relaxing the requirement for constant internal conditions, the gap is further reduced to that between curves 3 and 4, the internal conditions resulting from a mixed-mode approach.

The holistic approach to the design of a mixed-mode building starts with an analysis of the building that first optimizes the use of passive devices such as solar shading and exposed thermal mass and then carries out any calculations or thermal modeling to determine the resulting internal conditions and what, if any, mechanical cooling is required. To justify the case for mixed mode, comfort requirements must be met and the overall life-cycle cost should be less than that with air conditioning, including the total cost of mechanical and natural systems.

A simpler solution might seem to be to provide a conventional air-conditioned building with openable windows. This has been done in the past and the result is that with constant internal temperatures there is no stimulus to open windows (Warburton 1995). The potential energy savings are lost and the building owner ends up paying twice—for both openable windows and

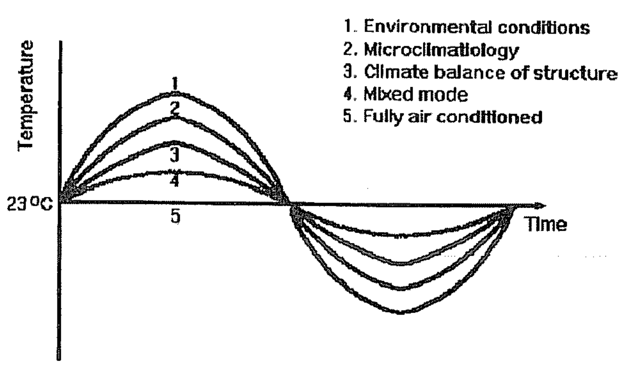

Figure 1 Olgyay's (1963) principle of selective design with the addition of mixed-mode HVAC.

air conditioning. This lack of stimulus was overcome in one German office building by using different colored lights that indicated to occupants whether they should open either windows or the air-conditioning dampers (Fitzner 1993). Although this solution may seem impractical in some cultures, it more than halved the running time of the air conditioning. There is nothing new in the principle; some of the earliest air-conditioned buildings in the U.S. gave occupants the option to open either the windows or the air-conditioning dampers (Worsham 1929). Even installing an extract fan or a packaged air conditioner in a naturally ventilated room meets the definition; however, this paper is concerned with optimizing the systematic application of the principle to entire buildings.

The key features or subsystems of a whole-building system are controlled natural ventilation and either/or mechanical ventilation and/or cooling. Controlled ventilation simply means either automatically controlled vents or a regime of manual window operation that can be changed or encouraged to change, depending on the weather.

The key principle is that inadequate ventilation must be avoided when it is cold outside and excessive ventilation avoided when it is hot. The mechanical system can be either a combined all-air or air-and-water system that supplies both ventilation and cooling or separate systems such as displacement ventilation and chilled ceilings. With direct cooling systems, such as chilled ceilings and chilled beams, it may be necessary to dry the air at times to prevent condensation on cool surfaces.

MIXED-MODE OPERATION

For the large portion of the year in which mixed-mode systems are intended to operate in the natural mode, building users are expected to open and close windows as a reaction to the normal stimuli. These have been shown to be predominantly either a change in temperature or a desire for fresh air (Warren and Parkins 1984). Heating can be hydronic radiators or part of the air supply system, and control can be limited to simply preheating the building in the morning and ensuring a reasonable provision of heat during the day. If inadequate ventilation is sensed at any time of the year by, for example, CO_2 sensors, automatically controlled natural or mechanical ventilation can be used to rectify the situation. During warmer periods, the ventilation is increased either as a result of the normal opening of windows or by automatic control.

At the point when natural systems are no longer adequate to restrict the rise in temperature during the day to within whatever limits have been set, mechanical systems are used to provide sufficient cooling. This can be achieved by using some form of *free cooling* from an ambient source, such as overnight air (Arnold 1978) or refrigeration.

It is important to allow the temperature to rise, within limits, during the working day, as this both stimulates window use (i.e., natural ventilation) and reduces the period when mechanical systems operate and, consequently, the amount of energy used. This is in contrast to the basic philosophy of air conditioning, which attempts to maintain a nearly constant condition of around

23°C, resulting in continuous use of fans and pumps, etc., irrespective of whether any cooling is necessary. In the U.K., the energy cost of fans and pumps represents around 60% of the total for air conditioning and is one of the main savings created by using a mixed-mode strategy (EEO 1991).

DESIGN DECISIONS

The main design decisions necessary to make the optimum provision of each of the subsystems are

(a) the extent, type, location, use, and control of natural openings;

(b) the rates of natural ventilation required in each mode;

(c) the flow rate, distribution, and control of mechanical ventilation;

(d) the provision, if any, and rate of mechanical cooling (refrigeration); and

(e) the changeover conditions triggering the use of mechanical systems.

While opening windows is fundamental to the philosophy, there are often times of the year when building users will not be stimulated to open windows, for example, in winter in northern latitudes. "Trickle" ventilators have proven effective in providing the background ventilation necessary at these times of year (Perera et al. 1993). These slot ventilators, with or without dampers, can be used in conjunction with automatic roof lights in open atria or dampers in natural exhaust shafts to control the rate of ventilation without relying on occupants. Prediction of the natural ventilation rates generated by wind pressure and stack effect can be calculated from first principles or by using commercial software (BRE 1991).

The conditions at which mechanical systems, ventilation or cooling, are set into operation can in practice be easily identified, for example by setting temperature or CO_2 limits. However, in terms of design, at each changeover condition there is the opportunity to increase or decrease the provision of one subsystem or the other (see Figure 2). For example, as the outside temperature increases, more ventilation is required to maintain the same internal condition. This can be achieved by either increasing the area of natural openings or by using a mechanical system. As a mechanical system is being provided in any case, the proportion of opening windows can be less than in an entirely naturally ventilated building. The optimum provision lies somewhere between the minimum necessary to give the users the confidence that they will be effective and the entire glazed area. The solution can most easily be achieved by life-cycle costing, comparing the extra costs of opening windows with the running costs of mechanical systems.

Similarly, if both mechanical ventilation and cooling are provided as the outside temperature increases, mechanical cooling becomes more energy efficient than mechanical ventilation (see Figure 3). It is based on sensible cooling only and shows that a low-pressure-loss mechanical ventilation system is more efficient, in energy terms, than a refrigeration system, provided that the external temperature is more than two or three degrees lower than the internal temperature. However, if a typical high-velocity air-conditioning system is used to provide *free cooling,* the outside temperature needs to be around 14 to 15 degrees lower to make it more efficient than direct mechanical cooling by refrigeration.

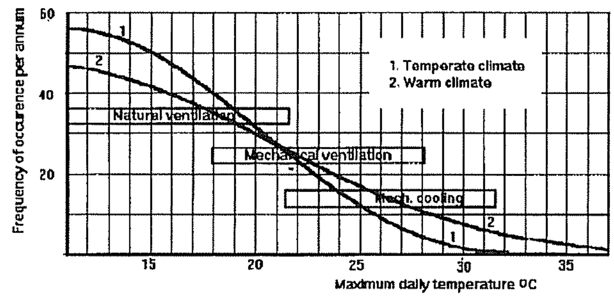

Figure 2 Typical operating ranges for mixed-mode HVAC.

The design decisions necessary to optimize the provision of each subsystem and justify the case for mixed-mode use are also affected by the extent to which use is made of the building thermal mass.

FABRIC THERMAL STORAGE

The basic principle of building mass absorbing and releasing heat applies to any building with a cyclical variation in temperature. The effect can be enhanced by exposing a larger amount of thermal mass to the space (e.g., removing a lightweight false ceiling and exposing a concrete slab). The usefulness of the exposed fabric depends on the surface area exposed, the thermal properties of the material (conductivity, density, specific heat), the frequency of the cycle, and the swing in temperature. Although limited research has been carried out specifically into fabric thermal storage for overnight cooling (Barnard 1994), most of the results of the extensive research into passive solar heating (Balcomb et al. 1984) apply equally well to this complementary application of the same basic technique. In particular, the supplement to the original publication (Balcomb and Wray 1987) describes and analyzes the effects of thermal storage in passive solar buildings.

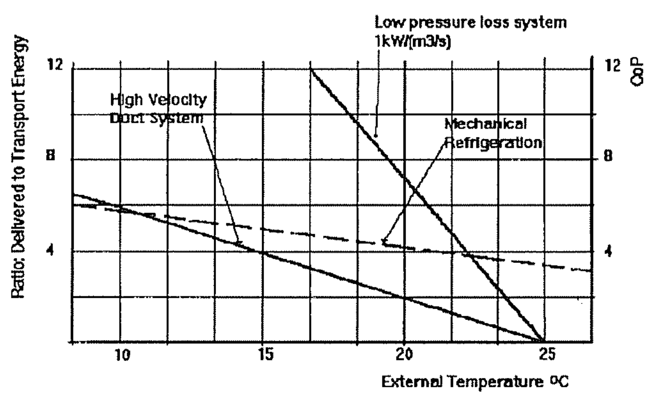

Figure 3 Energy required for cooling: mechanical ventilation vs. refrigeration.

One of the key concepts of mixed-mode HVAC is that the building users will experience a swing in temperature, particularly on warm days. The magnitude of this swing is restricted by the acceptability to the occupants. Experience quoted by Balcomb and Wray suggests that this should be limited to 5 K to 6 K, with a maximum of around 4 K occurring during the occupied period. Clearly, application of fabric thermal storage that creates a larger variation in temperature would be unacceptable.

The quantity of heat that can be stored in the fabric is restricted both by the maximum thermal capacity of the material and the amount that can conduct through the material in each cycle. The fundamental frequency for buildings is usually the 24-hour cycle, although this can be overlaid by weekly and even seasonal cycles. Consequently, the daily cycle is most important; however, with heavyweight materials such as concrete slabs, the more deeply stored *coolth* of the weekly cycle can limit the excursion of temperature under extreme conditions. The surface area—the limiting factor for transfer in and out of the material—can, to an extent, be determined by the building designer. For example, the use of vaulted or coffered ceiling slabs can increase the surface area of the slab in contact with the space by 50% to 150% compared to a flat slab. The designer can also influence the thermal properties or effectiveness of certain materials. The location of insulation in an external wall is an example and has a significant effect on the thermal performance of the space. If it is placed on the inside, the thermal capacity of the wall is lost, whereas if it is placed in the center or on the outside of an external wall, greater use can be made of the thermal mass.

The combined effect of the heat storage capacities of the building fabric bounding the space and even the fixtures and furniture can be estimated using the diurnal heat capacity (DHC) concept (Balcomb and Wray 1987). The principle is shown in Figure 4. Balcomb and Wray also show that an optimum thickness can be determined, in terms of thermal performance, for diurnal heat capacity based on a 24-hour cycle. These curves are shown in Figure 5.

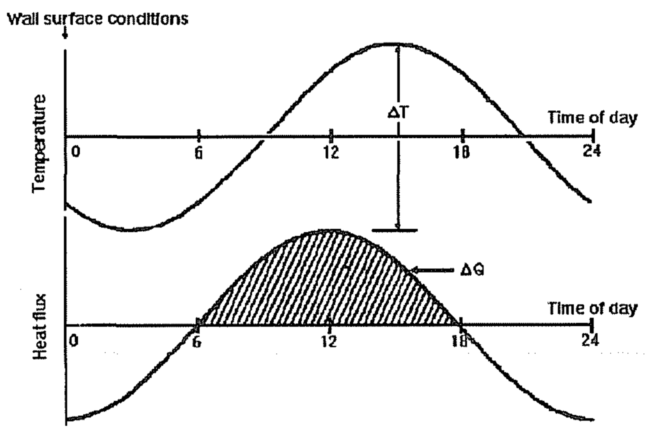

Figure 4 *Heat stored in wall shown by hatched area. Diurnal heat capacity equals heat stored/temperature swing. dhc = ΔQ/ΔT.*

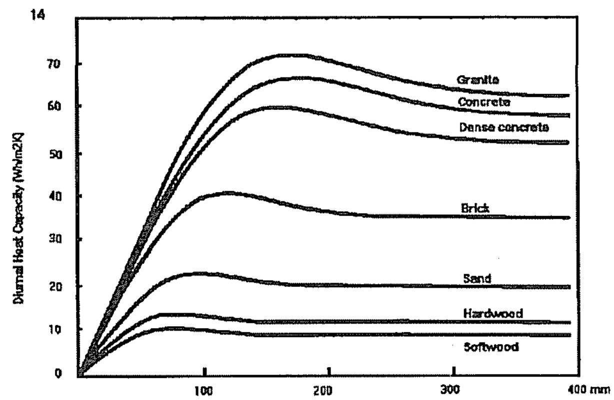

Figure 5 *Diurnal heat capacities for various thicknesses.*

The curves are shown for a single-sided slab well insulated on the outside. For slabs with both sides exposed to the same cyclic variation in heat flux, half the thickness is used. Other studies (Barnard 1994) have shown that coffered concrete slabs can be effective using night cooling, with heat gains up to 20 to 30 W/m^2. In comparison with air-conditioning systems that cool at a rate of 80 to 100 W/m^2, this appears quite low. However, many of these have been shown to be oversized, and a typical current figure for northern Europe, with good solar protection, is 50 to 60 W/m^2. Consequently, fabric thermal storage can displace up to 50% of the peak cooling duty.

The fact that an optimum thickness exists for each material means that increasing the depth/thickness, beyond around 100 mm in the case of concrete, has a negligible effect on the thermal performance of the room. If more thermal capacity is required, this must be achieved by increasing the surface area coupled to the space. Care must be taken when providing high levels of thermal capacity that they do not prevent the attainment of comfortable temperatures in winter at the beginning of the day.

The typical effect of thermal mass coupled with overnight ventilation is shown in Figure 6. It shows the results from thermal simulation for a typical module of an office building and compares the percentage of window opening as a proportion of external wall necessary to maintain a limiting internal temperature of 25°C. The thermal model is effectively used in reverse to calculate the ventilation rates (day and night) necessary to limit the internal temperature to this or any predetermined value. The rates are then transposed into the proportion of window opening necessary to achieve those ventilation rates using the software mentioned previously.

Experience with existing overnight cooling systems (Willis et al. 1994) has shown that some have failed due to a lack of appropriate control. However, the dynamic operation of fabric thermal storage is similar to other storage techniques and the control issues are similar. These include:

- When to begin charge?

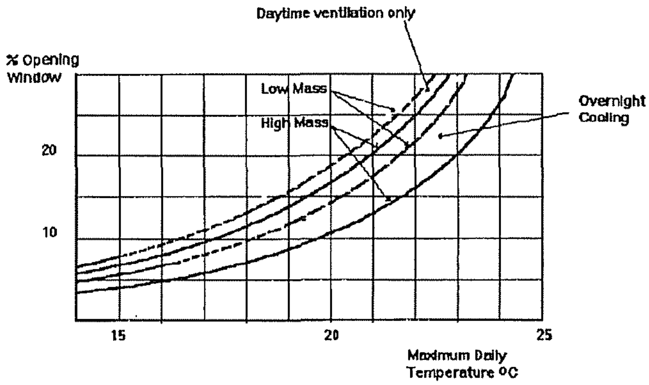

Figure 6 Typical relationship between window opening and daily maximum temperature using natural ventilation to limit internal temperature to 25°C.

- How quickly to charge?
- How much to charge?

Control of the discharge is constrained by the thermal properties of the space and the response of the building users. As the temperature rises during the day, the amount of heat absorbed by the building mass will increase as the temperature difference between the space and the bounding surfaces increases.

There are other factors to account for when using mechanical systems, as the energy source—cool overnight air—is time dependent. Minimum temperatures occur around dawn, which can be at the end of the normal off-peak tariff window. The optimum period for overnight cooling may well run into the beginning of the working day. Starting the charge earlier may be cheaper but less energy efficient. The fact that the energy store is not isolated and insulated means that it will lose some capacity while being charged. Equally, the variable availability means that there is a trade-off that varies with time between the amount of "free energy" that can be stored and the power necessary for charging. These effects must be considered carefully in each design.

As the cooling capacity is, in effect, embedded in the building thermal mass, conventional design techniques of assessing the peak load cannot be used. It is necessary to use more detailed weather patterns and look typically for the peak three- to five-day period. In addition, the period on either side should be examined to ensure that (a) the building fabric is assumed to be at a realistic temperature before the peak period and (b) the consequences of running the system with an exhausted store after peak are considered. This level of analysis can only be carried out using dynamic simulation. Experience has shown that this should be used with a degree of caution by the user. The results should be compared with both practical experience and intuition.

CONCLUSIONS

The mixed-mode strategy of providing heating, cooling, and ventilation combined with fabric thermal storage has proven successful in a temperate climate such as that in the U.K. and has applications in more extreme climates. There are significant potential advantages over conventional air conditioning in terms of both energy and local user control. It requires a higher level of integrated design between the architect and the engineer and is best integrated into buildings, new or refurbished, at the concept stage. Perhaps equally important, it represents a departure from traditional ways of running air-conditioning systems; consequently, building operators must be educated on the principles and be able to implement control easily. It does, however, present an opportunity by which to design comfortable buildings in a more sustainable and *environmentally friendly* way.

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QUESTIONS AND COMMENTS

Geoff Levermore, Senior Lecturer, Department of Building Engineering, University of Manchester Institute of Science and Technology, Manchester, England: How was the solar gain reduced but the daylight input maintained? What weather data were used for the design/simulation and the corresponding comfort criteria?

David Arnold: My presentation covered experience with five buildings. The type of solar protection was different for each one. It included automatic mid/outer-pane blinds, internal manual blinds, and brises-soleil, each intended to maintain daylight and avoid solar gain to a greater or lesser extent depending on the building mass and proportion of window area in the external wall. Weather data used for simulation was generally based on hourly readings from the closest weather station. Comfort criteria were based on limiting the rise of internal temperature to a maximum of 25°C in one case and for a maximum period of time above 25°C in the others.