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Mechanical Ventilation and Fabric Thermal Storage

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Key Words
Mechanical ventilation · Fabric thermal storage · Passive cooling · Heat recovery

Abstract
Modern UK office buildings have a reputation of being energy profligate, largely due to the fan power requirements of commercial air conditioning. Most architects and HVAC designers only associate low-energy consumption with natural ventilation. However, the UK electricity utilities have peak maximum demands in winter, and buildings need to be designed for year-round low-energy usage. Relatively few monitored studies of the total annual energy implications of natural and mechanical ventilation strategies operating in conjunction with fabric thermal storage have been published. This paper reviews independently published performance data of low-energy buildings and the impact of the various ventilation and fabric energy storage strategies now available. It demonstrates that low-energy mechanical ventilation systems incorporating efficient heat recovery and effective fabric energy storage have higher year-round comfort criteria, and significantly lower prime energy consumption, than natural ventilation strategies. Supplementary cooling and heating demands and consumption are shown to be minimal in such buildings for temperate maritime climates.

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Introduction

Several ventilation-based passive cooling systems now co-exist on the UK market using three distinct design philosophies. All claim to be low-energy and all incorporate fabric energy storage, but the philosophy behind each ventilation strategy is fundamentally different.

(1) Naturally ventilated buildings with basic fabric energy storage mechanisms based on heat transfer to/from either the exposed surfaces of the structural mass, i.e. soffits, or through air paths in the structural mass.

(2) Mechanically ventilated buildings with ventilation heat recovery and an advanced fabric energy storage in which the heat transfer primarily occurs within the core of the structural mass, with the heat transfer to the occupied space also occurring from the exposed ceiling soffit.

(3) 'Mixed-mode' ventilated buildings incorporating both natural and mechanical ventilation design philosophies, but with different ventilation priorities. These are buildings designed for: (a) Primarily natural ventilation (as 1 above), with basic fabric energy storage and supplementary mechanical ventilation during winter. (b) Primarily mechanical ventilation (as 2 above) with advanced thermal storage and supplementary natural ventilation during summer.

Contemporary architectural and building services literature and journals provide many excellent descriptions of recently constructed commercial buildings incorporating the above ventilation/fabric energy storage strategies.

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Table 1. Energy consumption and environmental conditions in the low-energy office 1981–1986 [2]

Parameter	Heating season				
	1981/2	1982/3	1983/4	1984/5	1985/6
Annual gas use, $\mathrm{MJ\cdot m^{-2}}$	705	556	649	613	678
Electrical consumption, $\mathrm{MJ\cdot m^{-2}}$	126	116	133	126	120
Annual degree days	2,499	2,294	2,326	2,394	2,558
Gas use (Oct.–Apr.), $\mathrm{MJ\cdot m^{-2}}$	620	502	590	548	585
Degree days (Oct.–Apr.)	2,111	1,949	1,986	2,054	2,196
Gas consumption (degree day) corrected (Oct.–Apr.), $\mathrm{MJ\cdot m^{-2}}$	524	460	530	476	476
Total annual energy use, $\mathrm{MJ\cdot m^{-2}}$ per degree day	0.33	0.29	0.34	0.31	0.31
Internal temperature at the start of occupancy, °C	–	18.6	18.4	19.1	19.3

Table 2. Gas consumption degree day corrected (Oct.–Apr.) [2]

	1981/2	1982/3	1983/4	1984/5	1985/6
$\mathrm{MJ\cdot m^{-2}}$	524	460	530	476	476
$\mathrm{kWh\cdot m^{-2}\cdot a^{-1}}$	145	128	147	132	132
$\mathrm{kg\,CO_2\cdot m^{-2}\cdot a^{-1}}$	29	25.6	29.4	26.4	26.4

Carbon dioxide equivalents calculated using factor 0.20 kg $\mathrm{CO_2\cdot kWh^{-1}}$ of gas consumption.

Unfortunately very little has been written about these strategies to provide even a summary of basic design criteria and HVAC equipment loads, and so enable even an elementary comparative analysis between the competing strategies and performance claims.

The scarcity of peer-reviewed feedback tends to raise serious doubts about the design claims of many so-called 'green' commercial buildings. It also prompts concerns about the environmental benefits and the year-round comfort standards claimed for some of these ventilation strategies; claims which may fail to materialise in practice. These concerns have been highlighted by the recent series of Probe Studies published jointly by the Building Research Establishment Conservation Support Unit (BRESCU) and the *Building Services Journal*, which have provided the first independent feedback for genuine performance comparison.

Natural Ventilation and Soffit-Cooled Slabs

The original low-energy office building was built at the Building Research Establishment, Garston site, and provides almost 2,000 m^2 gross floor area (GFA) of predominantly cellular accommodation for 70–80 personnel [1]. Designed in 1978, it was the first mixed-mode design to incorporate fabric energy storage using natural ventilation to cool the exposed ceiling soffit overnight. It was also the first green building to publish its annual energy consumption figures for 1981–1986 (tables 1, 2) [2].

The fabric energy storage component was provided passively within the occupied spaces, by exposed concrete slab ceiling soffits giving a moderately heavy construction (response factor 6). It was insulated to achieve a measured fabric heat loss of 1.9 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$ (U values ($\mathrm{W\cdot m^{-2}\cdot K^{-1}}$): walls – average 2.2; roof 0.62; windows 4.5). The windows were externally shaded with motorised 'shade-canopy'-type roller blinds. The measured ventilation loss was only 0.09 $\mathrm{W\cdot m^{-2}}$ GFA$\cdot\mathrm{K^{-1}}$. The total installed boiler power was 225 kW from three gas modular boilers (≡ 112.5 $\mathrm{W\cdot m^{-2}}$ GFA). The specific fan power of the heat recovery mechanical ventilation system was 4.1 $\mathrm{W\cdot l^{-1}\cdot s^{-1}}$).

The original mixed-mode strategy was to use the office windows for summer ventilation, but keep them locked in winter, and use the balanced mechanical ventilation system only during periods when the building was occupied (fig. 1). The building's heating strategy used conventional technology with all rooms having thermostatic radiator valves controlling low-pressure hot-water (LPHW) convector heaters.

In 1988, the insulation standards were improved. The new U values ($\mathrm{W\cdot m^{-2}\cdot K^{-1}}$), for the 2,000-m^2 office building were: walls 0.45; roof 0.3; floor 0.39; windows, including frames 2.20. The external canopy blinds were re-

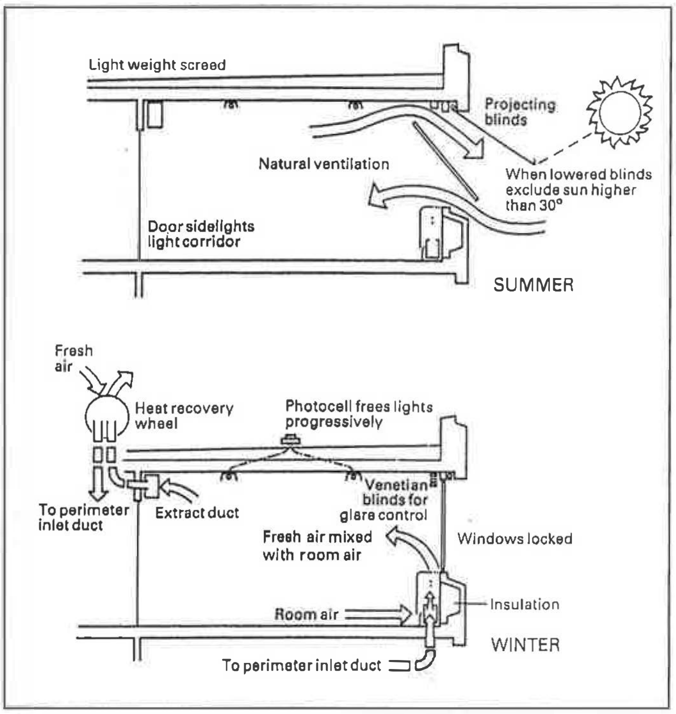

Fig. 1. Section through a typical south-facing office showing how comfort conditions are achieved in summer and winter.

moved, and the glazed areas on the east, south and west elevations were reduced. These measures reduced the installed boiler power to 150 kW from two gas-condensing boilers (≡ 75 $W \cdot m^{-2}$ GFA). During the next two heating seasons, the mechanical ventilation system was not used, and the building was naturally ventilated using horizontally pivoted windows. Two independent heating systems were installed to compare their annual energy consumption and operating costs. An all-electric system using thermostatically controlled panel heaters and the original LPHW system with two new condensing boilers and new thermostatic controls. These refurbishment measures almost halved the fabric heat loss of the original building design (table 3) [3].

The innovative design of the first low-energy office and its subsequent refurbishment to a naturally ventilated, highly insulated, building effectively established the annual energy targets and the definitive passive cooling strategy for soffit-cooled slabs, against which all subsequent mixed-mode designs are being judged.

Natural Ventilation and Core-Cooled Slabs

A second-generation low-energy office, the Environmental Office of the Future (EOF), has now been constructed and has been occupied for about 3 years. The design brief was formulated in 1991 with the subsequent design based on a highly insulated three-storey office building of 2,040 m^2 GFA with an installed boiler power of 117 $W \cdot m^{-2}$ GFA. (U values ($W \cdot m^{-2} \cdot K^{-1}$): walls 0.32; roof 0.24; floor 0.33; low E double-glazed windows fitted with external shading slats on the south elevation 2.0). The ventilation design incorporated core-cooled ceiling slabs for 2 of its 3 floors and uses natural (passive) techniques to cool the structural floor (fig. 2) [4].

The ventilation mechanism uses external wind towers to exhaust vitiated air from the occupied spaces, and also to induce ambient air through air paths constructed in the sinusoidal ceiling planks. A secondary slab-cooling mechanism uses natural ventilation from conventional high-level motorised windows, giving both side and cross ventilation across the slab soffits at night. Supplementary floor heating and cooling is provided by a plastic-pipe low-pressure pumped water system using gas boilers for heating and ground-sourced well water for cooling.

The 5 wind towers serving all 3 floors are designed with solar buoyancy boost during the day. As a precautionary measure, a small fan was installed in each stack to boost stack ventilation (and internal air change rates) when required by either excessive dry bulb temperatures or carbon dioxide levels.

The EOF building performance targets for total energy consumption are 47 $kWh \cdot m^{-2} \cdot a^{-1}$ for gas and 36 kWh·

Table 3. Monitored heating energy consumption with natural ventilation (year round) of the low-energy office improved specification

1988/89	Gas-condensing boilers and latest control technology	67 $kWh \cdot m^{-2} \cdot a^{-1}$	≡ 13.4 $kg\,CO_2 \cdot m^{-2} \cdot a^{-1}$
1988/89	Commercial electric panel heaters using BRESTART control optimiser	42 $kWh \cdot m^{-2} \cdot a^{-1}$	≡ 25.2 $kg\,CO_2 \cdot m^{-2} \cdot a^{-1}$

Carbon dioxide equivalents calculated using factors 0.2 $kg\,CO_2 \cdot kWh^{-1}$ gas and 0.6 $kg\,CO_2 \cdot kWh^{-1}$ electricity.

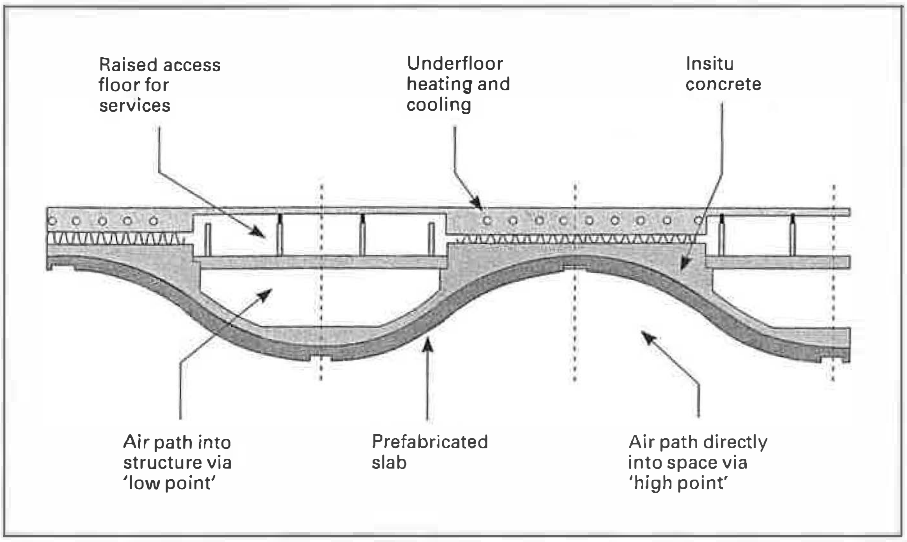

Fig. 2. Schematic of core-cooled ceiling slabs.

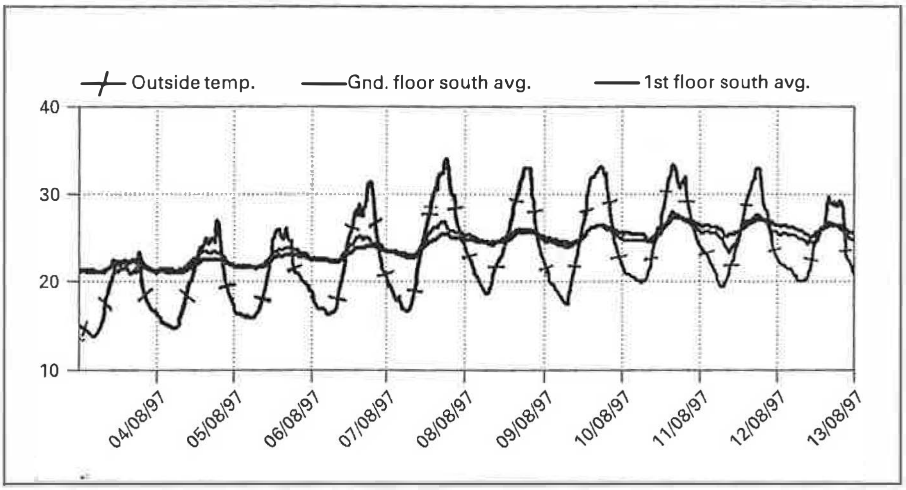

Fig. 3. Slab performance: outsideversus internal temperature.

$m^{-2} \cdot a^{-1}$ for electricity, giving a total carbon dioxide emission of 34 kg $CO_2 \cdot m^{-2} \cdot a^{-1}$. After the building structure and services have been commissioned to the designer's satisfaction, and the controls fully tuned, it will be interesting to compare the actual gas and electricity consumption with both project target values, and also with the corresponding energy consumption of the original low-energy office [5, 6].

Although it is premature for the annual slab performance characteristics of this building to be published, a preview has been released which gives the external versus the internal temperatures during the heatwave in August 1997 (fig. 3). The internal temperatures experienced on each floor at this time during the building's first summer are most encouraging (fig. 4) [BRESCU, 1998; pers. commun.]. Clearly, these values are easily within the target design criteria (i.e. internal temperatures should not exceed 28 °C for more than 1% of the year, and 25 °C for not more than 5% of the year). Nevertheless the absence of a thermally heavy ceiling at the 2nd floor level is clearly important in terms of occupant performance with the summertime internal temperatures experienced to date.

Mechanical Ventilation and Core Slab Cooling

The first UK building to be designed using mechanical ventilation with a patented multiple hollow-core slab system was the Elizabeth Fry Building at the University of East Anglia. This is a highly insulated three-storey building of 3,250 m² GFA comprising 2 floors of cellular offices, 1 floor of tutorial rooms and 1 floor of lecture

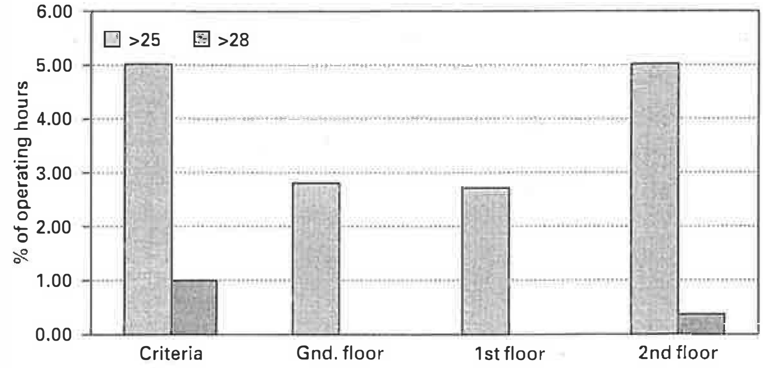

Fig. 4. Performance – operation (internal temperature).

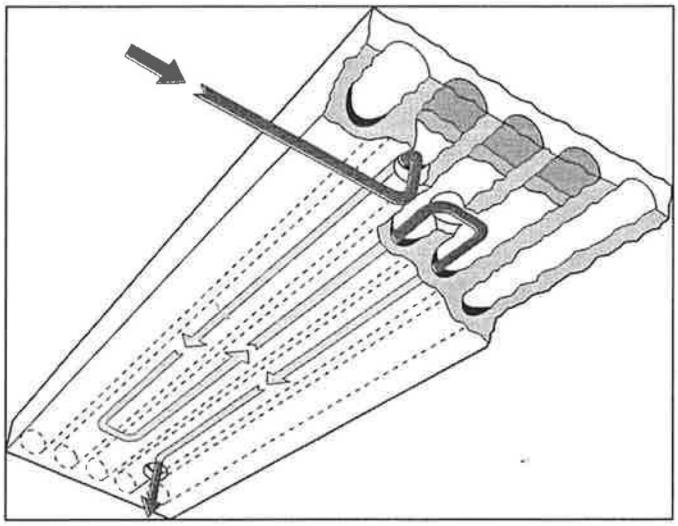

Fig. 5. Mechanical ventilation air routes through the hollow-core ceiling slabs.

theatres. The insulation standards equal the best Scandinavian practice (U values, kWh·m^{-2}·a^{-1}): roof 0.13; walls 0.20; floor 0.16; windows 1.3, with a shading coefficient of 0.2). The design strategy primarily used mechanical ventilation, but ensured all windows were openable, either for cleaning or additional ventilation (i.e. mixed-mode ventilation), the building was specifically designed to have very low infiltration (i.e. <1 ach at 50-Pa test pressure) and high thermal admittance [7, 8].

The designed total heating requirement was only 15 W·m^{-2} GFA, but the boiler installation comprised 3 domestic wall mounted boilers of 24 kW each ≡ 22.15 W·m^{-2}. Similar care was taken in designing the mechanical ventilation system, and the total installed fan power was only 5.3 W·m^{-2}, this is equivalent to a specific fan power of 1.96 W·l^{-1}·s^{-1}). Currently the annual delivered energy for this building is 87 kWh·m^{-2}·a^{-1} (electricity 60 kWh·m^{-2}·a^{-1}; gas 27 kWh·m^{-2}·a^{-1}). This is probably the lowest energy usage for any commercial or industrial UK building. There is no separate boiler room anywhere in the building. This makes the HVAC servicing extremely simple, convenient and cheap. Maintenance costs were £1.40 m^{-2} for the first year [9–11].

In any building constructed in this way, using mechanical ventilation in the form of low-energy fans to circulate ventilation air through the hollow cores of the structural ceiling or floor slabs, before discharging into the occupied space, maximises coupling HVAC loads with the thermal capacity inherent in the building's structural concrete, (fig. 5). In the EOF building, for example, using mechanical ventilation in place of naturally ventilated air flows results in: (1) improved heat transfer characteristics of turbulent heat flow within the centre of the hollow-core slab; (2) higher thermal storage capacity due to the greatly extended air paths within the slab, and (3) a more predictable and controllable rate of energy transfer to and from the slab soffit.

In addition, using mechanical ventilation allows the fresh air intakes of the central air-handling plant to be located for the highest possible indoor air quality throughout the building. It also permits the use of heat recovery from the exhaust air, in addition to filtration, humidification, supplementary heating and cooling (if necessary) of the ventilation air, and controlled room air distribution.

Studies carried out indicate that in a typical office, the diurnal energy demand becomes zero when the time constant is 100 h, i.e. when suspended ceilings are removed and less insulating carpets are used [12]. This is illustrated in figure 6 which shows the variation in room temperature during a 24-hour period, calculated by a simplified model, in which all energy is supplied during the 8 h when the building is occupied from internal gains.

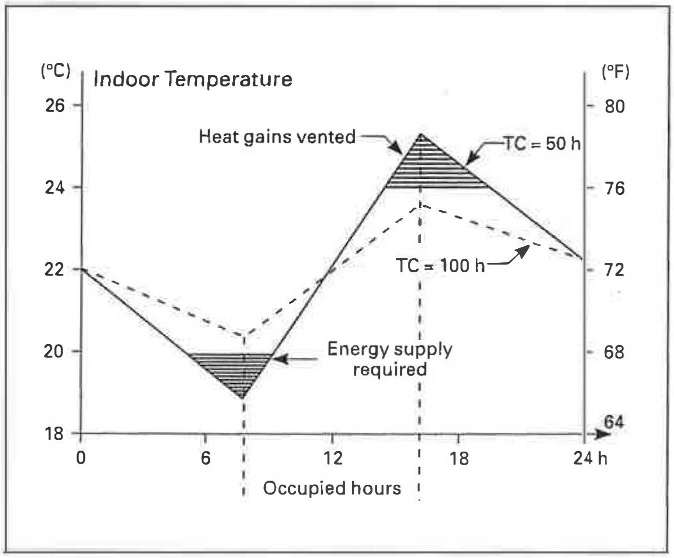

Fig. 6. Variation in room temperature during a 24-hour period.

In winter, the heat input from occupants, lights and other sources can be stored and used to compensate for night-time losses.

In summer, the slabs can be cooled to absorb the next day's heat gains without the need for refrigeration. Using low-energy mechanical ventilation, the cool night air (when 10–15 °C) can be circulated through the cores and into the rooms. In locations where the night is not cool enough, supplementary mechanical refrigeration using off-peak electricity may be required to pre-cool the air supplied to the slabs, to ensure that the hollow-core slabs are cooled sufficiently to handle the next day's cooling loads [13].

In temperate climates, highly insulated, thermally heavy and tight commercial buildings are able to provide very stable and comfortable internal conditions with only mechanical ventilation with heat recovery (i.e. without the need for active cooling or heating) for the majority of the year. Outside this thermally neutral period, there may be a small requirement for either active mechanical cooling given high internal heat gains, or supplementary heating in severe winter weather [14].

Comparative Energy Consumption

With heat recovery mechanical ventilation in conjunction with fabric energy storage systems, the installed boiler capacities in commercial buildings can be reduced from typical values of 150–200 $W \cdot m^{-2}$ GFA to below 50 $W \cdot m^{-2}$ GFA. The Elizabeth Fry Building at the University of East Anglia uses such a HVAC system and has zero mechanical cooling. Its total design heating requirement was only 15 $W \cdot m^{-2}$ GFA, although the total installed heating load was 21 $W \cdot m^{-2}$ GFA.

It is of interest that the University of East Anglia has two recently completed buildings which provide independent comparative evidence of HVAC energy use (table 4). The Queens Building is highly insulated and naturally ventilated, with gas-condensing boilers. The adjacent Elizabeth Fry Building is also highly insulated, but mechanically ventilated, with high-efficiency heat recovery using the integrated fabric energy storage design strategy. The same architects and engineers were employed for both buildings. Table 4 compares the annual energy consump-

Table 4. Measured HVAC consumption in two low-energy buildings at the University of East Anglia ($kWh \cdot m^{-2} \cdot a^{-1}$)

	Heating (gas)	Fan motor (electricity)	Total HVAC consumption
Natural ventilation – Queens Building	147	0	147
Mechanical ventilation – Elizabeth Fry Building	27	16	43
Differences	120	16	104
Conversion factor for carbon dioxide equivalents, kg $CO_2 \cdot kWh^{-1}$	0.2	0.6	
Carbon dioxide equivalents	24 kg $CO_2 \cdot m^{-2} \cdot a^{-1}$	9.6 kg $CO_2 \cdot m^{-2} \cdot a^{-1}$	

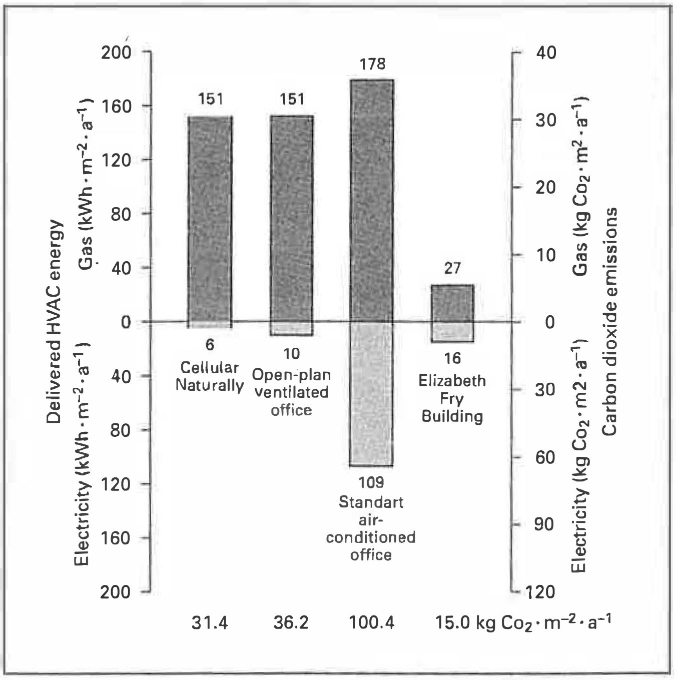

Fig. 7. Comparison with typical office.

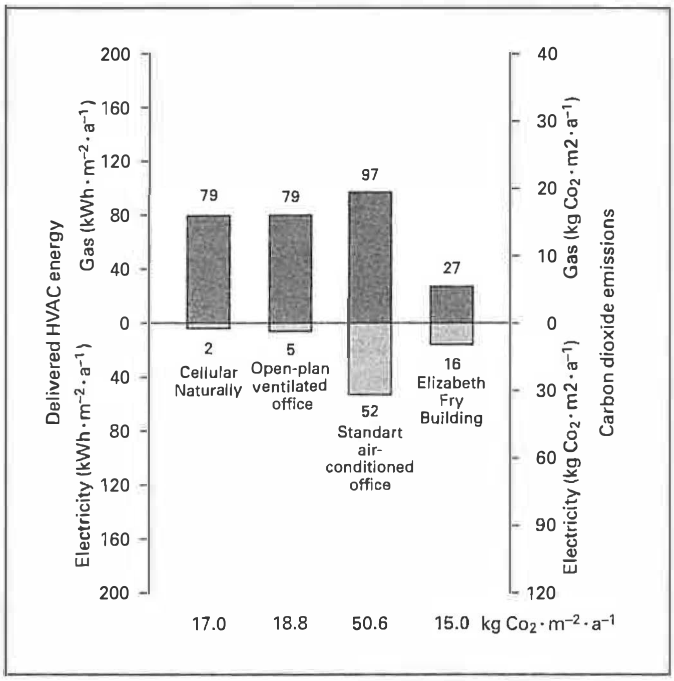

Fig. 8. Comparison with good-practice office.

tion for these buildings for 1996–1997. The saving of 120 kWh·m^{-2}·a^{-1} in heating energy is achieved with only 16 kWh·m^{-2}·a^{-1} of motive power for the supply and exhaust fans.

Using current prime energy conversion factors present practice with a specific fan power of 2.0 W·l^{-1}·s^{-1} means that 1 kg CO_2·m^{-2}·a^{-1} of fan energy saves 2.5 kg CO_2·m^{-2}·a^{-1} of heating energy. With the benefit of experience gained in designing, operating and analysing the Elizabeth Fry Building, future low-energy designs will have the capability to double this saving at a lower fan power. That is, future practice operating with a specific fan power of 1 W·l^{-1}·s^{-1} will mean that 1 kg CO_2·m^{-2}·a^{-1} of fan energy will save 5.0 kg CO_2·m^{-2}·a^{-1} of heating energy.

The UK government has published target values for HVAC energy consumption for offices with both typical and good-practice design [15]. When these values for both naturally ventilated and standard air-conditioned offices are compared with the consumption measured at the Elizabeth Fry Building, the energy-saving potential of this specific type of fabric energy storage design becomes very apparent (fig. 7, 8).

Fabric Energy Storage System Operation

The HVAC system used in the Elizabeth Fry Building is a full fresh air system combined with a highly efficient recuperative heat exchanger arrangement in each air-handling unit. This recuperative heat exchanger incorporates a damper system which alternately directs the supply and extract air over stacks of metal plates to warm them up and then cool them back down again. It achieves thermal efficiencies exceeding 90% heat recovery in both heating and cooling operation.

The HVAC ventilation system in fabric energy storage designs operates in two modes, dependent on the time of day and season.

Summer

During hot summer periods, the internal heat gains are absorbed by the concrete slab throughout the occupied period and removed overnight. The cooler night air blows through the pre-cast hollow-core ceiling slabs which then act as a cool store for the following day. During the day, the ventilation air is also blown through the concrete slabs and thereby cooled. It is subsequently discharged into the room, always within 0.5 K of the mean slab temperature. The exposed ceiling soffit also acts as a direct radiant cooling system with over 70% of the heat transfer being radiated.

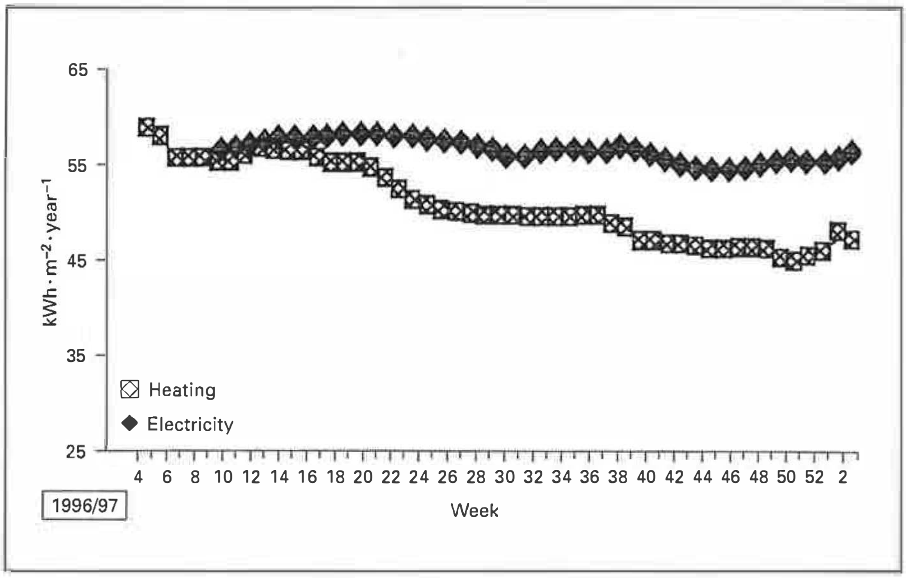

Fig. 9. Elizabeth Fry cumsum of input energy 1996/97 (kWh·m^{-2}·year^{-1} prior 52-week period).

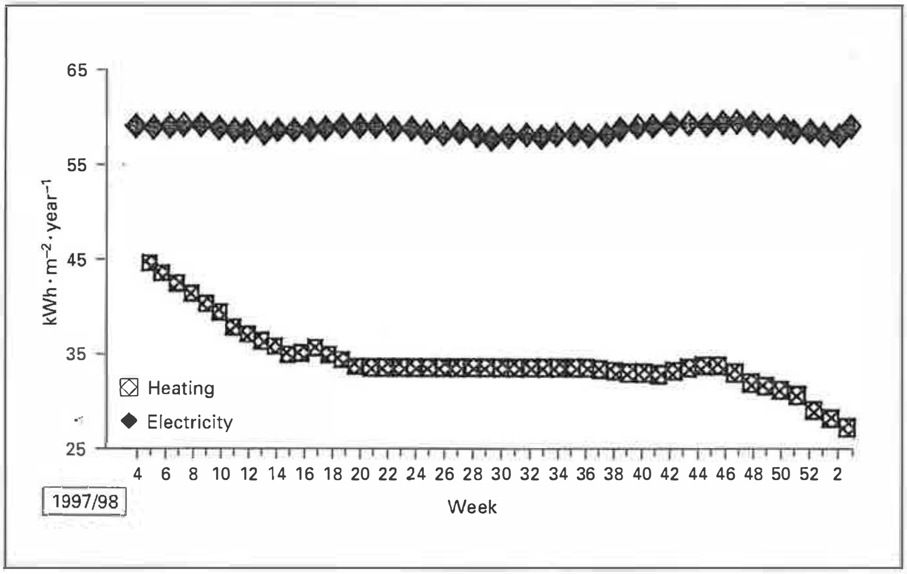

Fig. 10. Elizabeth Fry cumsum of input energy 1997/98 (kWh·m^{-2}·year^{-1} prior 52-week period).

Winter

During cold winter periods, the tightly sealed and highly insulated building retains most of the heat within the building. Heat produced by occupants and machines is recovered from extract air by the heat recovery units in the air-handling plant and transferred directly to the hollow-core slab. It is either transferred to the supply air or stored in the hollow-core slab. The exposed ceiling soffit also acts as a low-temperature radiant heating system.

At night, the building is sealed tightly, including dampers on all ductwork passing to the outside, to retain the heat gains within the building.

The annual variation in the mean slab temperature is generally only 1–2 K above or below ambient room temperatures, depending whether it is heating or cooling. These small temperature differences provide a high level of inherent temperature control, thereby effectively stabilising room temperatures during severe winter weather and/or extended unoccupied periods.

If the hollow-core slab cools down too much, the air-handling plant is activated by the temperature sensors in the slab, this establishes full re-circulation, and additional heat is supplied from the boilers. There is no fresh-air ventilation when the building is unoccupied, all dampers leading to the outside, remain closed.

Comfort Conditions

To date, two independent surveys of the Elizabeth Fry Building have been undertaken [10, 11]. Both reports conclude that 70% of the office occupants were satisfied with the conditions, only 7% considered conditions to be unsatisfactory. On average, occupants felt that their productivity increased by 7% when they moved into the Elizabeth Fry Building. This was a self-assessment survey, in which occupants were asked to rate the impact of the building on their productivity, on a scale of +40 to -40%.

During the winter, the average temperature of the building was 20 °C. Occupants responding to the survey described the conditions in winter as comfortable, with conditions neither too hot nor too cold.

The building has performed well in extreme conditions. It has been monitored through two heatwaves and came through with flying colours. For instance, during the period 8–20 August 1997, the maximum daily external temperatures were in the range of 26.4–32 °C. The lowest night temperature was 13.5 °C, and on 3 consecutive nights from 9 August the minimum temperatures were 17.9, 17.3 and 17.7 °C. These are record conditions, and temperatures inside the building overall did not exceed 27 °C at any time.

The building is controlled by a building energy management system. As a result of this, coupled with a series of regular 3-monthly meetings during the 18-month monitoring period, significant improvements have been made on the original very low-energy performance (fig. 7, 8). It is remarkable that although the building had a significant installation defect in its control system at the outset, i.e. incorrectly located sensors and a highly inaccessible front end to the building energy management system, there were no complaints of discomfort during the subsequent winter.

Conclusion

In temperate maritime climates (such as the UK), the prevailing design philosophy for low-energy buildings advocates exposed ceiling soffits in conjunction with a year-round natural ventilation strategy, thereby minimising the electricity consumption associated with both mechanical ventilation and air conditioning.

This design philosophy is now being challenged. Independent studies of new buildings using low-energy heat recovery mechanical ventilation integrated into fabric energy storage designs using hollow-core slabs have better reported year-round comfort (including summer cooling) standards, together with significantly lower annual delivered and prime energy consumption with lower maintenance requirements than even the best natural ventilation designs.

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