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Summary The paper is the last in a series of four which describe a three-year research project into advanced fabric-energy-storage (FES) systems. It presents experimental monitoring of the first UK building to put the FES-slab into practice, showing the building's thermal performance and energy consumption during 1995. The results are discussed and recommendations made to improve the building's operation during 1996.

Advanced fabric energy storage IV: Experimental monitoring

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1 Introduction

Previous papers in this series have described studies of the FES-slab performed in the 'sanitised' environment of the laboratory or computer simulation. This paper details practical experience of the system, gained at the United Kingdom's first FES-slab building; the Weidmüller Klippon Products' office at West Malling in Kent$^{(1,2)}$. Although this particular building used the FES-slab, most of the conclusions are relevant to any form of advanced FES.

2 The building

Figure 1 illustrates the Weidmuller building, which was designed to be 'environmentally responsible' through the use of high levels of insulation, heat recovery, indirect evaporative cooling and the FES-slab thermal-storage system. Openable windows with mid-pane blinds and 300 W convection heaters provide a degree of local control.

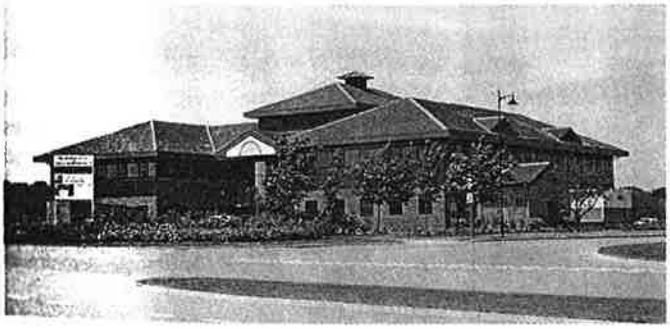

Figure 1 The United Kingdom's first FES-slab building (Weidmüller Klippon Microsystmes at West Malling, Kent)

The building has a gross floor area of 2400 m², and a 'FES-slab treated' floor area of approximately 1875 m². It was designed for the owner to occupy the first floor while leasing the majority of the ground floor to two tenants.

3 Monitoring strategy

The monitoring focused on the west facing, first-floor research and development office, as shown in Figure 2. This office was chosen owing to its orientation and heat loads which seemed likely to make it an area with a high risk of overheating.

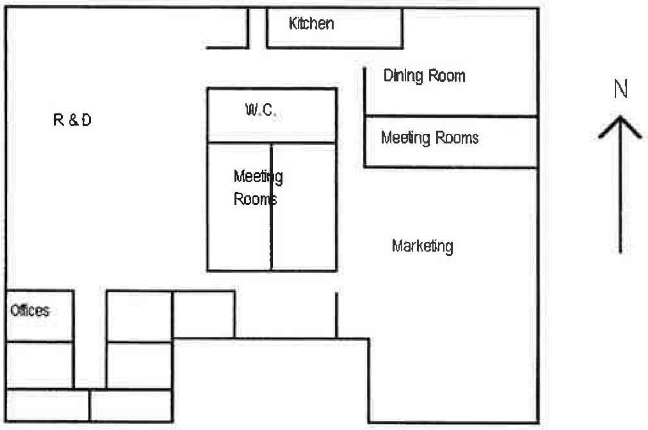

Figure 2 First-floor plan of the Weidmüller building

4 Building services

4.1 Plant layout

The building is divided into two ventilation zones: the ground floor and the first floor. Each ventilation zone is subdivided into two heating zones, broadly split along the north-south axis of the building. The first-floor heating zones therefore consist of the west-facing research and development office with associated smaller rooms and the east-facing marketing office with associated smaller rooms.

Figure 3 shows the layout of the air supply system for the research and development office and the positions and references of the sensors used for monitoring. Temperatures were recorded with a mixture of the building energy management system's (BEMS) sensors and specially placed thermocouples, where BEMS sensors have the prefix TE and thermocouples are prefixed with M.

Thermocouples were calibrated across the range; 15°C to 25°C, which corresponds to the approximate operating range of the building. The accuracy of each calibration was verified in a separate test which suggested a maximum uncertainty of ± 0.2°C. Care was taken to ensure that all thermocouples were positioned as close as possible to the centres of the ducts.

The BEMS' sensors were accepted as accurate; they had been calibrated by the installation engineer and the building owner was keen that they should not be adjusted.

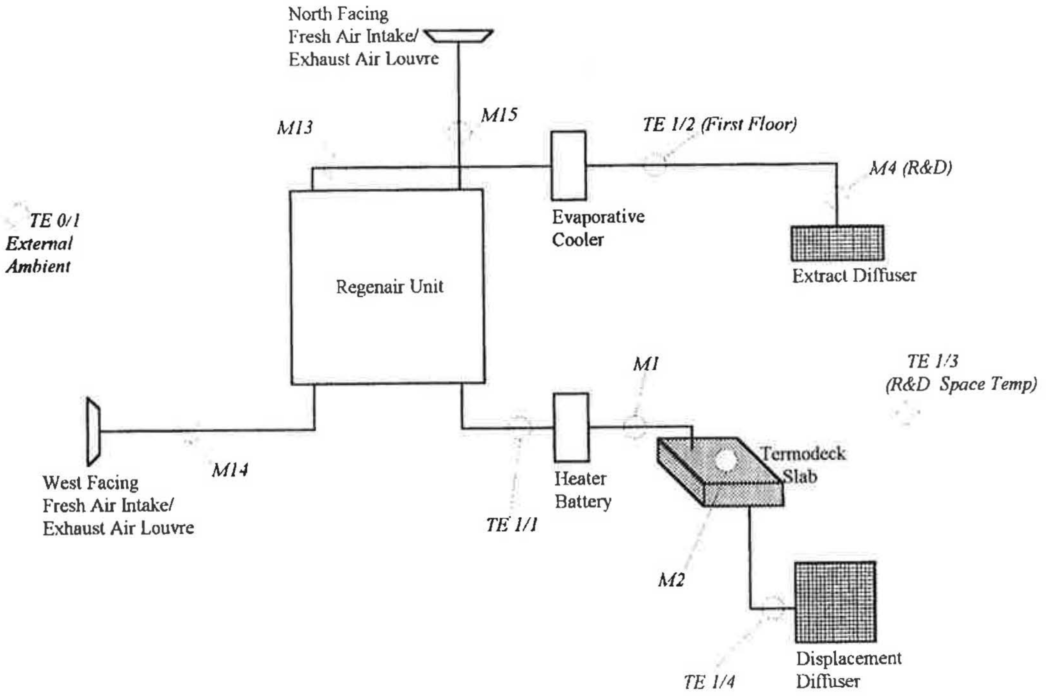

Figure 3 Layout of ventilation plant showing monitoring points

4.2 *Air-handling units*

The office's air handling units are the first UK installation of a novel Swedish design known as Regenair. The units provide direct ventilation, high-efficiency heat recovery (measured to be in excess of 89% efficient) or recirculation as the control schedule dictates.

The designed air-supply rate was 3.06 $m^3 s^{-1}$ per air-handling unit (AHU), which corresponds to an average air-flow rate of around 50 $l s^{-1}$ per active FES-slab and an air-change rate of 3.3 ac h^{-1} in the occupied spaces. The AHUs each had a fan-power rating of 9.5 kW, resulting in a specific fan power of 3.2 W $l^{-1}s^{-1}$ (the subsequent FES-slab building at the University of East Anglia achieved specific fan powers of less than 2 W $l^{-1}s^{-1}$).

4.3 *Heaters*

The electric-heater batteries each have a capacity of 15 kW. Monitoring revealed that the heaters were undersized as they were not capable of providing the entire heating requirement during the off-peak hours. This resulted in the use of significant amounts of peak-rate electricity for heating, which increased the building's running costs.

4.4 *Indirect evaporative cooler*

An indirect evaporative cooler is installed for operation during periods when the ambient air temperature is too high to provide any free cooling. The unit reduces the temperature of the return air by adiabatic humidification before passing it through the air-handling unit (in heat-recovery mode) to cool the incoming air. Analysis of operational periods showed that this produced a drop of between 2 and 4°C in the return air temperature, which compared poorly with the heat gains that the air picked up in passing through the ventilation system.

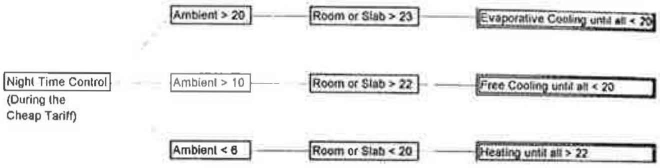

Figure 4 Night-time control schedule

4.5 *Control*

Figures 4 and 5 summarise the building's control schedule. It was designed to maintain the slab and room temperatures within the range 20–22°C, while shifting as much heating and cooling as possible to the night-time cheap tariff. Several flaws, which became apparent in both the design and implementation of this strategy, are discussed in greater detail in the following section.

5 Results

5.1 *Thermal performance*

Figure 6 summarises the Weidmuller building's thermal performance throughout 1995. It compares the weekly average

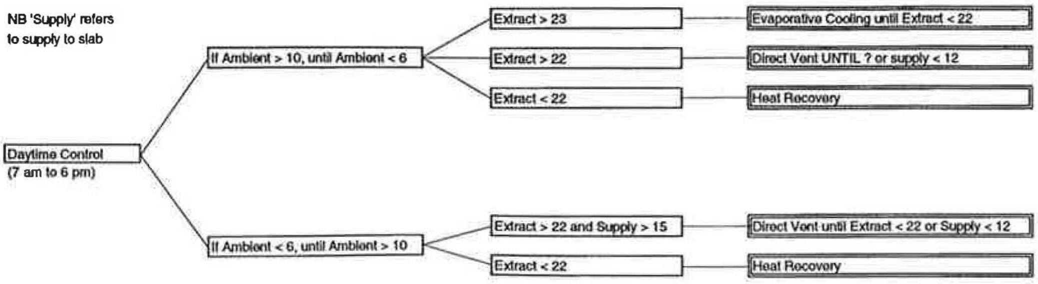

Figure 5 Daytime control schedule

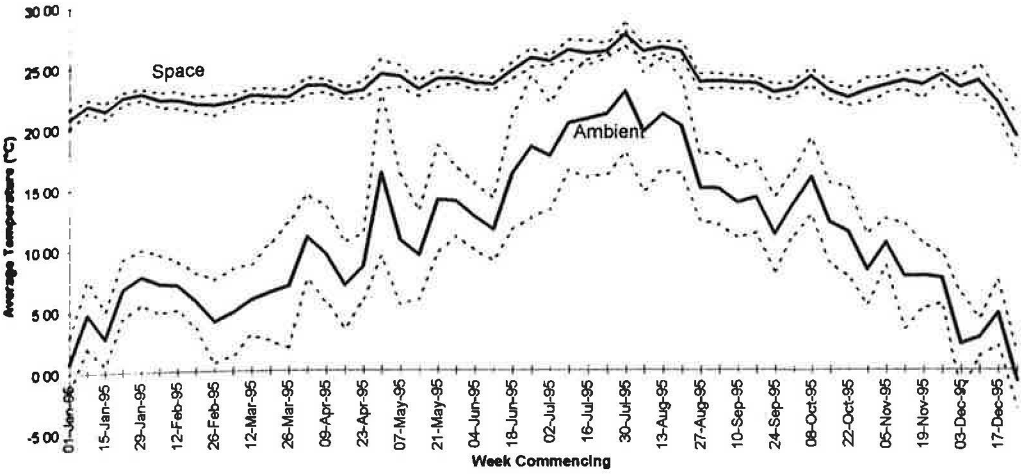

Figure 6 1995 thermal performance of the Weidmüller building

temperatures in the research and development office with the corresponding ambient temperatures; dotted lines show the standard deviation of each measurement. The figure shows that the building maintained a very steady internal temperature both from day to day and from one season to the next.

Figure 7 shows frequency plots of the space temperatures recorded in the research and development office during the high summer months of June, July and August 1995. The figure indicates that internal temperatures were higher than 25°C for about 150 h, which represents a slightly disappointing performance even though 1995 had been the warmest summer for 20 years. Further investigation suggested that the poor performance was largely due to uncontrolled heat gains to the ventilation air, compounded by inappropriate operation of the indirect evaporative cooler.

Figure 8 gives a detailed illustration of the ventilation heat gains which, during August, were found to be responsible for eliminating 67% of the available free cooling. The figure shows that on 16 July 1995, a day which included an extended period of direct ventilation, heat gains accounted for up to 7.5°C (or 27 kW) of the available cooling. The figure also indicates a further two interesting features:

(*a*) The majority of the heat gain occurred between the supply to the air-handling units and the heater batteries; as the air passed through the plant room. Fan gains would have accounted for about 1°C of this but the remainder was likely to have been due to a combination of insufficient ductwork insulation and a consistently high plant-room temperature (although this was not measured directly, Figure 8 shows the temperature of the adjacent BEMS room, which is likely to have been similar).

(*b*) The irregularities in the heat gain, such as the one that occurred at around 1520 h, were found to be due to a cleaning programme which forced the air-handling unit to perform a single cycle every three hours. The 2 h 'tail' following the irregularity was due to short-circuiting between the two AHUs. The 'tail' ends when the ground-floor unit also undergoes a cleaning cycle, making both AHUs exhaust on the same side of the building.

Figure 9, illustrates the inappropriate use of the indirect evaporative cooler, which resulted in increased water consumption as well as raised temperatures. The figure shows the temperature change experienced by the supply air as it passed through the AHU during a period of evaporative cooling. It indicates that, for a large part of the period, the evaporatively cooled return air was actually heating the supply air rather than cooling it, indicating that direct ventilation would have been a better option. Evaporative cooling first became worthwhile at around 1100 h when the ambient temperature was about 20°C.

5.2 *Energy consumption and economic performance*

Figure 10 shows the Weidmuller building's 1995 energy consumption due to the first-floor AHU and associated heater batteries. Its volatility was due not only to variations in the weather but also to frequent modifications to the control

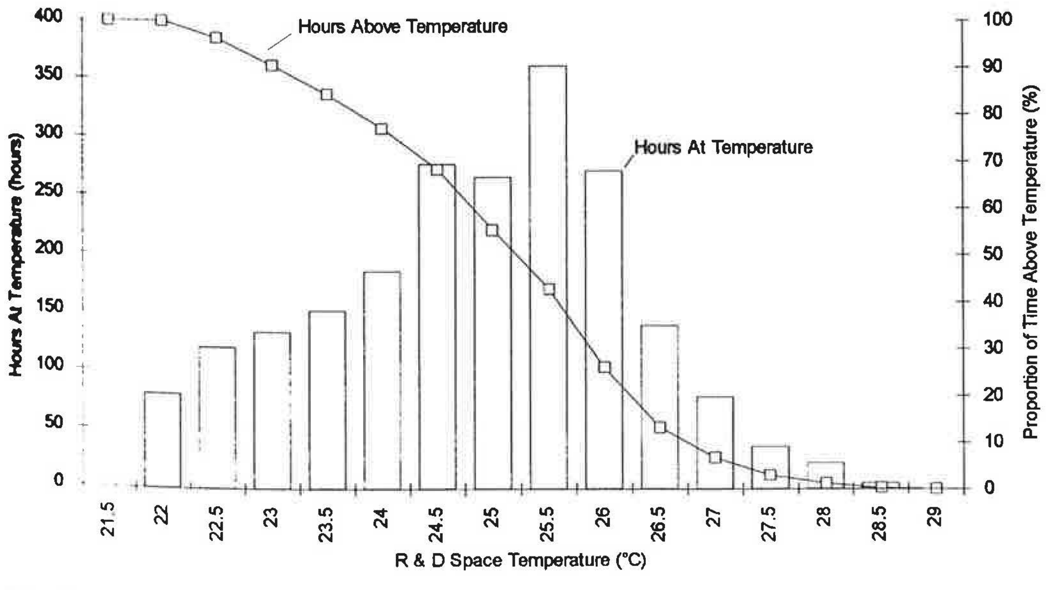

Figure 7 1995 summer performance of the Weidmüller building

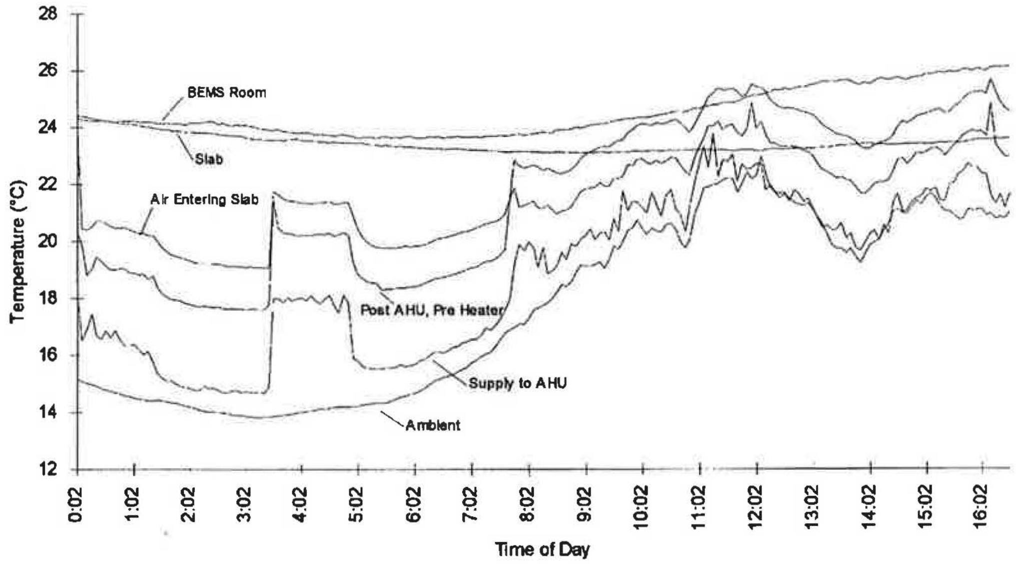

Figure 8 Heat gains to the supply air during direct ventilation, Sunday 16 July 1995

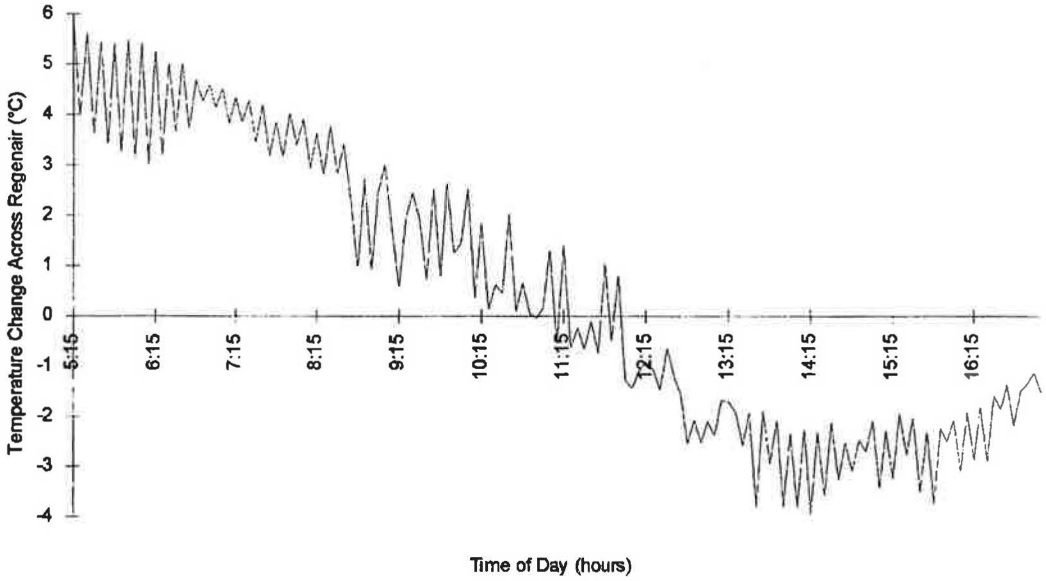

Figure 9 Temperature change of supply air across air-handling unit, during evaporative cooling, Saturday 22 July 1995

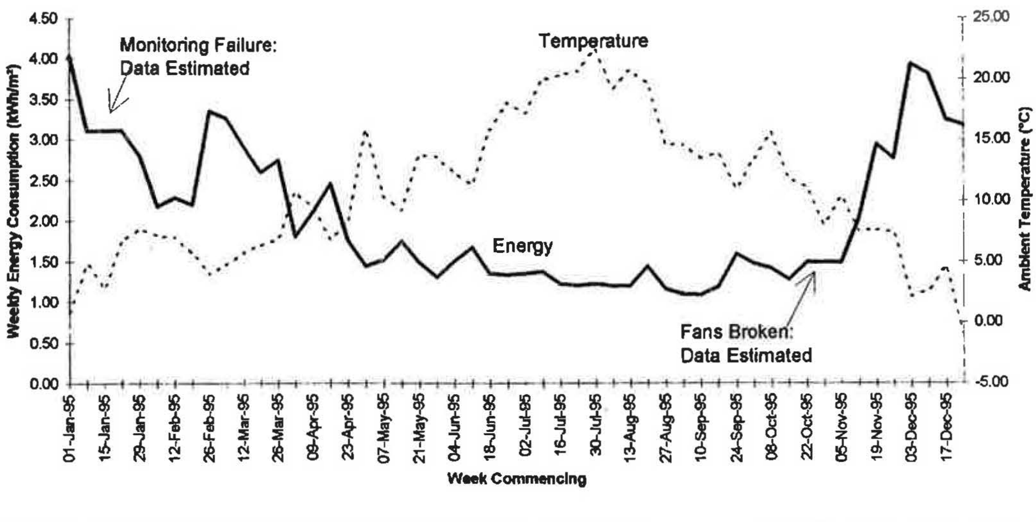

Figure 10 1995 energy consumption of the Weidmüller building

strategy. The annual energy consumption due to heater batteries and fans totalled 106 kWh m^{-2}, which was higher than had been hoped due, in part, to the following factors:

(*a*) A mismatch of heater sizing and uncontrolled heat losses through the ductwork resulted in poor efficiency during periods of winter heating. The data showed that, during March 1995, only 29% of the energy expended during night heating reached the slabs as useful heat.

(*b*) Incorrect programming of the control schedule led to actual heat recovery during some periods of attempted direct cooling. This resulted in 730 h of fan operation and was responsible for 7.5k Wh m^{-2} of wasted energy consumption.

(*c*) The control strategy failed to differentiate between weekdays and weekends, resulting in a minimum of 830 h or 8.5 kWh m^{-2} of unnecessary fan operation throughout the year.

A more detailed investigation of the Weidmuller building's 1995 energy consumption is presented in Figure 11. It shows the proportions of first-floor plant operation by run time, energy consumption and energy cost (assuming a 3p/9p off-peak/peak tariff). Analysis of this data allowed a quantitative evaluation of the building's demand-shifting strategy for winter heating. It showed that, had all of the heating been supplied during the day, the building's energy consumption would have reduced by 10% to 95 kWh m^{-2} owing to the reduction in night-time fan operation; however, the poorer peak/off-peak split would have increased the building's energy cost by 16% to £7.71 m^{-2}. Conversely, had the heater batteries been large enough to shift to the night all of the heat which had to be supplied during the day, the building's energy cost would have been reduced by 18% to £5.46 m^{-2}.

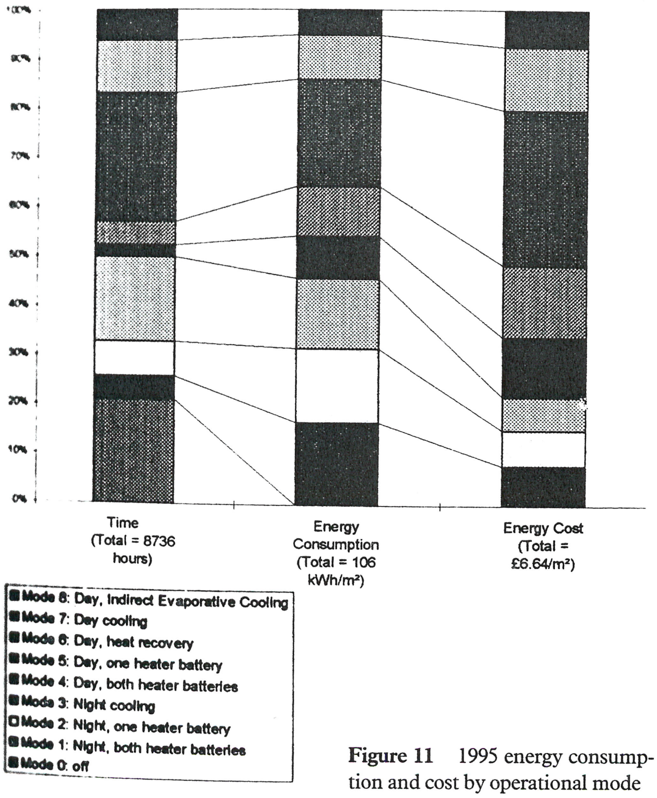

Figure 11 1995 energy consumption and cost by operational mode

Figure 12 shows a breakdown by end use of the Weidmuller building's 1995 energy consumption and cost (for first-floor fans and heater batteries). It shows that fan power accounted for 65% of the energy consumed and 72% of its cost, highlighting the dominant role of fan power in an advanced FES building. Had the Weidmuller building's fans had a specific efficiency of 2 W l^{-1}s^{-1}, as at the Elizabeth Fry building, the energy consumption would have reduced by 22% to 83 kWh m^{-2} and the cost by 24% to £5.05 m^{-2}. Another enhancement which would aid the operation of future advanced FES buildings is the specification of multi-speed fans which would reduce energy consumption by allowing a reduced air-flow rate during periods of night heating.

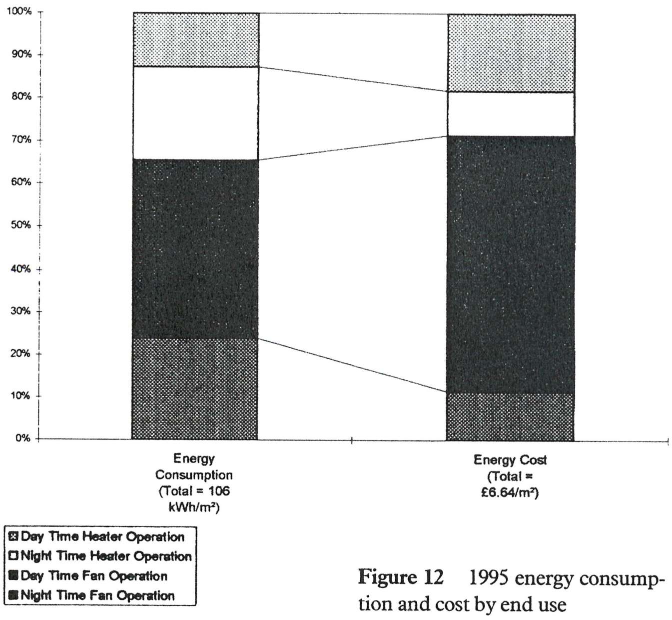

Figure 12 1995 energy consumption and cost by end use

6 Discussion

6.1 Improvements to the Weidmüller building

Several modifications are planned to the operation of the Weidmuller building during 1996 to improve both its temperature control and energy efficiency. These include the following:

(*a*) The air-handling units are to be reprogrammed to avoid the short-circuiting which occurred in 1995. When in direct ventilation, both AHUs will receive air from the north-facing openings and exhaust air through the west-facing openings. As the ductwork from the AHUs to the north wall is much shorter and straighter than that to the west wall, this should reduce the heat gain before the ventilating air reaches the AHU.

(b) The sizing of the heater batteries is to be increased before the winter of 1996/97. This should increase the proportion of heat which reaches the slabs once the distribution heat losses have been overcome, making it easier to supply the full heating requirement with off-peak electricity.

(*c*) The building's control strategy will be rewritten to improve the selection of periods of indirect evaporative cooling and to avoid unnecessary weekend fan operation.

If the building's overheating problems persist, there are plans to reduce further the uncontrolled heat gains to the ventilation by increasing the ductwork insulation and using night ventilation to reduce the plant-room temperature. Monitoring of the building will continue, with part funding by the UK Department of the Environment, and the results will be used to produce a set of guidelines for the application of advanced FES. A seminar will present the results in early 1997.

6.2 Suggestions for future advanced FES buildings

Fan power has been shown to be critical to the energy efficiency of the Weidmuller building. Future advanced FES buildings should be specified to use multi-speed fans with high specific efficiencies. The use of multi-speed fans will permit energy savings through reduction of the air-flow rate during periods of night heating and improved control through the option to compensate for the small air-slab temperature differential on warm nights by increasing the mass-flow rate.

The monitoring of the Weidmuller building showed that, especially if there are significant uncontrolled heat gains to the ventilation air, there may be a few nights in high summer when the ambient temperature is too warm to provide free cooling. There is little that can be done on such nights other than to turn the fans off and hope that the following night is cooler. This highlights the importance of ensuring that both the effective volume of the individual slabs and the amount of active thermal mass within an advanced FES building are maximised to reduce the temperature rise caused by a day with no subsequent cooling.

6.3 Good-practice energy target

Analysis of the Weidmuller data suggests that, with more efficient fans, better control and improved night heating, a Termodeck building should be able to attain an energy target of between 50 and 70 kWh m^{-2}, depending on heat gains, heat-loss characteristics and local weather.

7 Conclusions

7.1 The Weidmuller building

Monitoring of the Weidmuller building has shown that it provided stable and comfortable conditions throughout most of 1995, as well as providing the opportunity to demand shift the heating load to the night-time cheap tariff. The building's summer performance was disappointing; however, the reasons for this have been identified and solutions suggested.

7.2 The case for UK FES-slab buildings

The FES-slab's immediate future in the UK is bright; two buildings are already operational and further projects are due for construction during 1996. The disappointing results from the first year of UK FES-slab operation and the problems with the control strategy both repeat Dutch experience(3). These teething problems were quickly overcome in the Netherlands and it is predicted that they will also be overcome in the UK.

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