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An Application of Mixed Mode Cooling using Termodeck with CHP

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Abstract

The paper examines the use of Termodeck with a mixed mode cooling strategy incorporating CHP at the Innovate Green Office in Leeds. The particular characteristics of the Termodeck allowed development of a control strategy that maximised the energy supplied from CHP in order to allow an apparently oversize plant to operate for the target 4000 hours per year. This scale of CHP generation helped to minimise the CO_2 emissions related to heating cooling and ventilating the building.

Keywords

Mixed Mode Cooling, Termodeck, Combined Heat & Power.

Figure 1: The Innovate Green Office

Introduction

The Innovate Green Office in Leeds *(fig. 1)*, is a demonstration for a sustainable commercial office built speculatively by developer Innovate Property. This 4350m^2 building demonstrates a wide range of techniques for reducing resource consumption in construction and use. With mechanical ventilation and comfort cooling the annual CO_2 emissions from building services are predicted to be less than 23kg/m^2, a reduction of over 80% compared to previous office projects by the same developer.

The building demonstrates mixed mode cooling using Termodeck, a proprietary system that creates a thermal labyrinth within pre-cast concrete floor slabs. The hollow cores of the pre-cast planks are cross connected internally by core drilling to create a serpentine labyrinth through which ventilation air is passed. This additional contact between the environmental air and the interior of the floor planks engages virtually the entire mass of the concrete, not just that which is exposed at the external surfaces.

Termodeck has a number of possible applications for thermal energy storage and has been used extensively in heat recovery applications. However approaches to cooling using Termodeck vary widely from purely passive cooling such as the well known Elizabeth Fry Building at University of East Anglia[(1)], with the addition of terminal cooling units such as at the Jubilee Library in Brighton through to central chilled air supply with the facility to bypass the Termodeck altogether at peak times as at the new Met Office Building in Exeter[(2)].

The Innovate Green Office provides mixed mode cooling using either passive night cooling with fresh air or active cooling of the supply air using the Termodeck to affect energy storage in an application similar to ice storage. A large part of the building's cooling demand can met from conventional night cooling, with the cooling energy being stored in the Termodeck. However under peak conditions active cooling is still necessary to augment the passive cooling. The capacity to store cooling energy in the Termodeck allows a small, CHP fired, absorption chiller to operate for extended periods to meet the much higher, short term peak demand. This extended operation period, coupled with a new form of HVAC control strategy, creates the ideal running conditions for CHP to minimise the CO_2 emissions associated with the active cooling.

Building Form and Fabric

The building comprises two office wings separated by a glazed atrium *(fig. 2)*, a form well recognised for maximising daylight availability in buildings whilst reducing the surface area available for the loss of thermal energy. The floor to ceiling clear height was fixed at 3.0m to maximise the penetration of daylight into the plan and to allow headroom for some stratification of the air within the space.

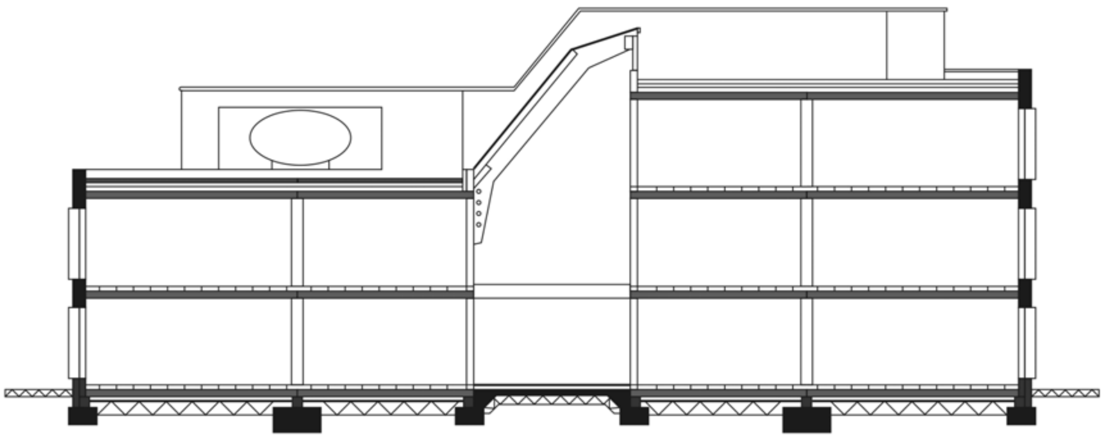

Figure 2: Building Section indicating the central atrium

Pre-cast load bearing concrete wall panels, frame and floor were chosen for the construction in order to maximise the thermal mass of the building available to moderate the internal environment. The nature of this construction also provided the frame, thermal mass, airtight and weatherproof envelope all in a single site operation. All that was necessary to complete the envelope was to fit the windows and doors and apply the insulation and roof membrane. Additionally offsite fabrication allowed a high quality of concrete finish to be achieved so that it could be left exposed internally and window openings to be optimised within the wall panels.

The concrete structure is externally insulated with glued polystyrene blocks and a through coloured render finish achieving a U-Value of 0.15W/m²K. Windows use solar control low emissivity glass in timber frames to achieve a component U-Value of 1.67W/m²K. The roofs are insulated and waterproofed with a single ply membrane to achieve a U-Value of 0.15W/m²K.

Heating Ventilation and Air Conditioning Systems

It became apparent that, although the intention was to design an exemplar low energy building, within the target office rental market there would be an expectation of air conditioning and therefore an entirely naturally ventilated building would prove too great a commercial risk for the developer. It was also necessary for the building to meet institutional funding criteria which generally means compliance with the requirements of the British Council for Offices (BCO) Guide[(3)]. It was decided therefore to adopt mechanical ventilation with comfort cooling that would use the thermal energy storage potential of the construction for passive and active night cooing.

The summer design temperature was set at 24^{o}C, a relaxation of 2^{o}C from the standard requirement of 22^{o}C called for in the BCO Guide. However in order to avoid unnecessary over-sizing of the cooling plant it was decided to allow the temperature to rise to a limit of 26^{o}C if the external temperature rises to 32^{o}C, above the current recommended summer design temperature[(4)], thus allowing for a degree of climate temperature rise.

The building's heating and cooling is provided from a gas fired tri-generation plant, comprising a packaged combined heat and power unit rated at 35kW electrical output with 55kW heat output, two high efficiency gas boilers for peak conditions and an absorption chiller rated at 35kW cooling, the smallest unit available, energised by the heat from the CHP. An electric chiller is provided in support for peak conditions. Consideration was given to the use of a second absorption chiller, but small absorption chillers have a poor co-efficient of performance (COP), just less than unity, compared with electric chillers with a COP of around 2.5. Thus, taking into account the boiler efficiency and the carbon intensities of the primary fuels, the use of a small absorption chiller can only be justified in combination with heat from a CHP unit.

The building is mechanically ventilated to provide 15l/s per person of fresh air for the design peak occupancy of 420 people in accordance with the BCO Guide. To minimise the energy required to heat fresh air and to utilise the casual heat gains from occupancy the air handling units incorporate heat recovery wheels. Approximately 80% of the heat available in the exhaust air is collected and delivered onto the fresh air. The supply air is then circulated through the floor / roof slabs before entering the occupied spaces. Thus any difference between the air temperature and the concrete in the floors causes the air to absorb or give up heat, regulating the supply air temperature to the space and allowing any surplus heat gains from people and computers to be stored in the thermal mass for later beneficial re-use.

In summer the building is cooled using similar principles. Fresh air ventilation is provided via the floor / roof slabs and if the outside air is warmer than the building it is cooled by contact with the thermal mass thus moderating the supply air temperature. If the exhaust air is cooler than the fresh air then the thermal wheel can be used to remove some of the heat. If it is warmer than the fresh air then the thermal wheel is stopped and the heat exhausted from the building.

The ventilation continues to run overnight with cool outdoor air to draw out any excess heat stored in the thermal mass, recharging it for the following day. In the peak summer condition the daily gains may exceed the capacity of the building to passively reject heat and the chillers are operated. However, the thermal mass is again essential as the total installed chiller capacity is less than half of the peak cooling load. The absorption chiller is run overnight to store as much additional cooling in the thermal mass as is necessary to be drawn on during the day whilst the chiller continues to operate. Thus the chiller runs continuously at full load for extended periods, the ideal scenario for utilising heat from the CHP.

The total fan power of the air handling units is 30kW and the pump energy associated with the CHP unit and absorption chiller accounts for another 2.5kW. Thus when the CHP is operating to fire the absorption chiller the electrical output is closely matched to the demand of the ventilation plant and the surplus meets a proportion of the building's electrical baseload for IT and maintained services. In this way the CO_2 emissions associated with the overall HVAC installations are minimised.

CHP Sizing

It is generally accepted that in order to operate economically it is necessary for CHP to run for more than 4,000 hours per year[5]. To maximise the operating hours the CHP needs to be controlled as the lead heating plant but, whilst modern boilers have very good modulating controls, a CHP generator has a virtually fixed heat output and does not take kindly to frequent stop start operation. It is therefore essential that the CHP is closely matched to the heat baseload for the building to avoid constant cycling which would quickly lead to excess wear and tear. Typically the use of CHP in office developments is limited as it is difficult to find sufficient summer demand for heating. However the use of absorption cooling during the summer months can effectively extend the baseload operation for the CHP.

The building performance was analysed using Termodeck's own proprietary calculation package to size plant and in parallel using IES Virtual Environment to model the annual energy demands *(fig. 3)*. Perversely the application of Termodeck with heat recovery coupled with the high levels of insulation in this building reversed the typical situation so that annually the demand for heat energy to fire the absorption chiller dominates.

Thus the CHP was selected to provide 55kW of heat to match the demand of the absorption chiller to avoid firing boilers to make up the shortfall. The typical heating load profile *(fig. 4)* clearly indicates the efficiency of the heat recovery systems with thermal energy storage as a difference in heating demand of some 40kW between working days and the end of the weekend, when there has been two days without significant internal heat gain.

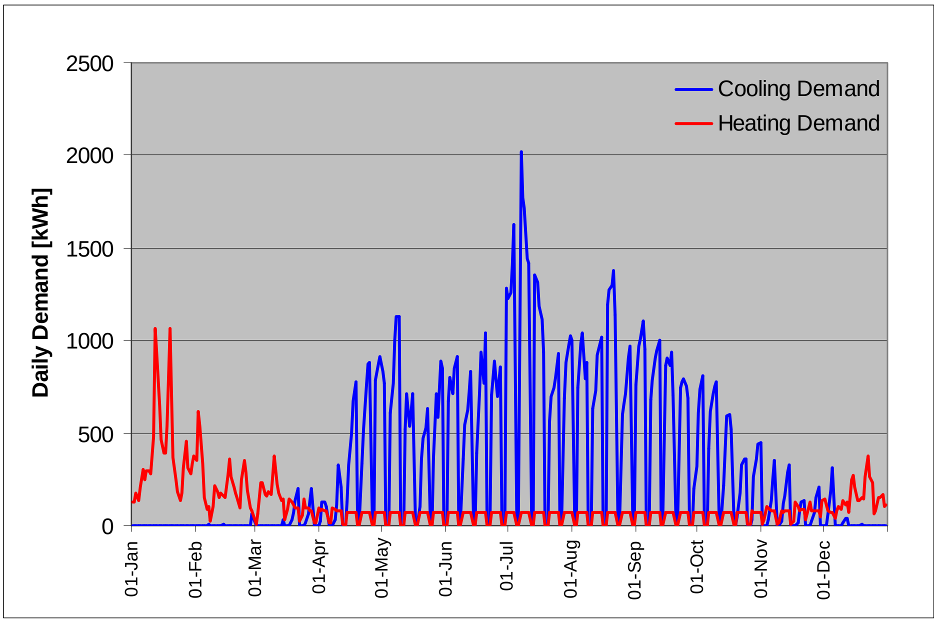

Figure 3: Annual energy demand profile

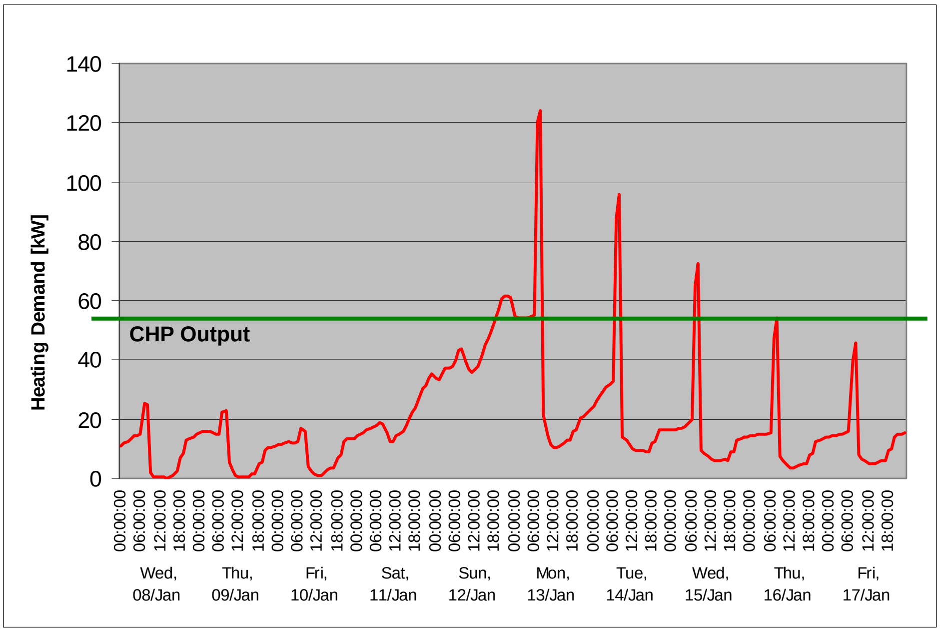

Figure 4: Typical hourly heating load profile

Matching the CHP to the absorption chiller meant that it was significantly larger than the optimum size for baseload operation in winter which meant that the CHP would be unsuitable for use as the lead plant in the heating installation. To protect the CHP unit from damage due to frequent cycling it is necessary to hold it off until sufficient load is established to start and maintain its operation. Thus in order to avoid the boilers constantly operating in the lead to satisfy demands at the expense of CHP operating hours it was necessary to develop an alternative control strategy for the plant operation.

Thermal Energy Storage Control

The cooling for the offices operates in mixed mode using the thermal mass of the Termodeck, for thermal energy storage. The building is primarily cooled at night using outdoor air circulated by the air handling units following well established principals for passive cooling demonstrated in previous Termodeck buildings such as Elizabeth Fry. However the passive cooling capacity of the Termodeck is insufficient to meet the peak summer demands and control the temperature to the design setpoint in this building and so, at times, additional cooling is required from the chiller.

Rather than operate the electric chiller during the daytime peak, the absorption chiller is run overnight to boost the night cooling effect and store additional energy in the thermal mass. The system is controlled by a strategy akin to a demand limiting cooling system using a chiller with ice storage. Thus the chiller is run for sufficient hours overnight to store enough energy to limit the daytime demands as far as possible to within the absorption chiller capacity. Thus the operation of the absorption chiller is maximised in order to maximise the run hours of the CHP unit to offset the electrical demand of the air handling units, pumps and controls associated with the Termodeck system.

This strategy is applied in steps to favour extended operation of the absorption chiller over infrequent operation of the electric chiller at the peak *(figs. 5 & 6)*. Ultimately the absorption chiller is anticipated to run continuously for 24 hours per day during the peak summer days with additional support from the electric chiller during the peak hours. This control strategy is predicted to increase the absorption chiller hours run from approximately 1,300 under conventional control to approximately 2,900 utilising thermal energy storage. The same strategy is also applied to the heating controls again to increase the operating hours for the CHP, but in this case the quantum of the increase is much smaller due to the already inherent efficiencies of the heating.

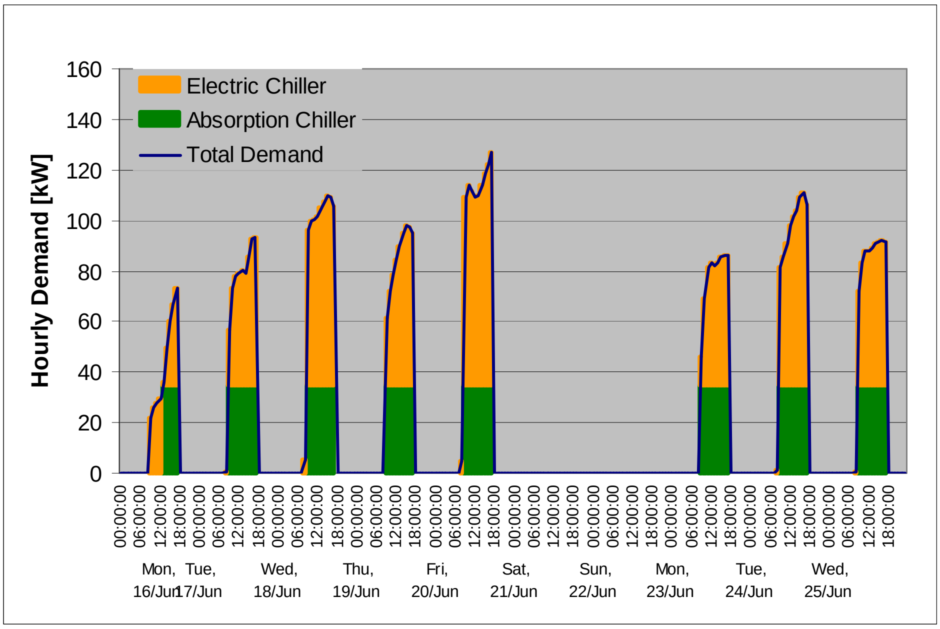

Figure 5: Typical hourly cooling demand without thermal energy storage

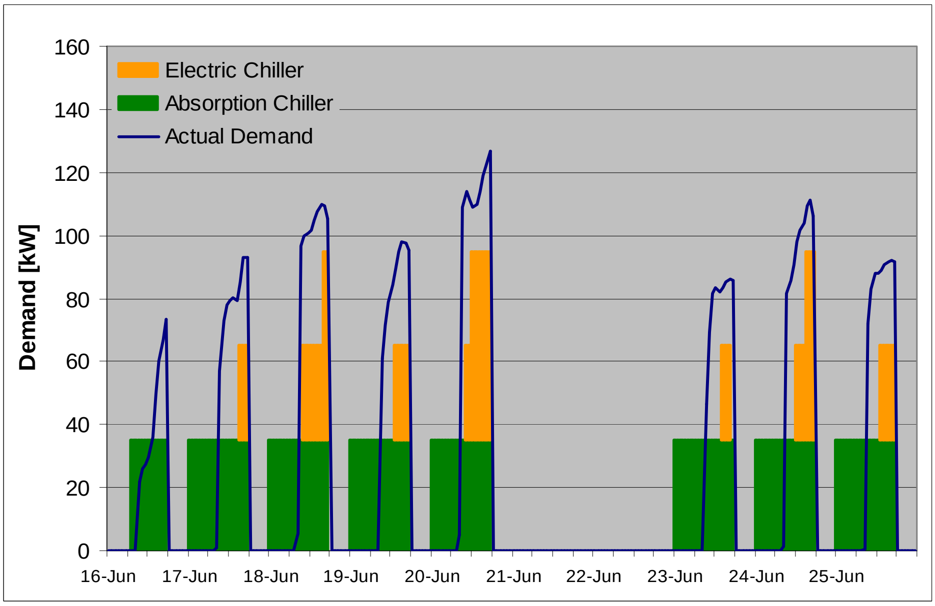

Figure 6: Typical hourly cooling demand with thermal energy storage

Cumulative Deadband Control

In a conventional control strategy the various zones within the building will control independently within their deadbands. The central plant will be energised by a demand in any zone and will operate until that zone is satisfied. If the demand of that zone is insufficient to warrant starting the CHP it will be met by the boilers with the burners modulating to match the load. If a demand from a second zone then occurs the plant will continue to operate until this zone too is satisfied. If however the combined demand of the all the zones exceeds the CHP capacity it will then fire for as long as the demand remains above its capacity.

Thus the boilers would respond first to meet any small changes in demand and may well satisfy it before sufficient load develops to justify starting the CHP. Thus the CHP will often only operate during the morning pre-heat period and periods of peak heatloss. Run the CHP during the heating season was actually reduced.

With the developer's agreement the building was specified with wide deadbands for the control of space temperature, 22+/-2^{o}C in winter and 24+/-2^{o}C in summer, in order to accumulate as much load as possible before the plant is called into operation and to extend the period of plant operation before the demand is satisfied.

However the very high thermal mass in the building creates a slow response to changes in energy input and allows thermal energy to be stored without being expressed as significant changes in internal temperature. The control system has therefore been designed to take advantage of this lag and includes a novel routine to accumulate further load in order to increase the likelihood of operating the CHP.

When there is a demand for thermal energy in any of the building's control zones, whether heating or cooling, the building management system examines all the other zones that are still within the dead-band to establish whether they have the capacity to absorb additional energy which can be used later *(fig. 7)*. This function allows the system to build up a larger overall demand than would be required to meet the single zone alone and can therefore start and run the CHP engine more often, rather than fire a boiler at reduced load. The CHP output is then distributed across all zones that can absorb the energy and the plant continues to run until all the zones are satisfied. If any zone drops below the lower deadband this is excluded and the energy demand re-evaluated across the remaining zones.

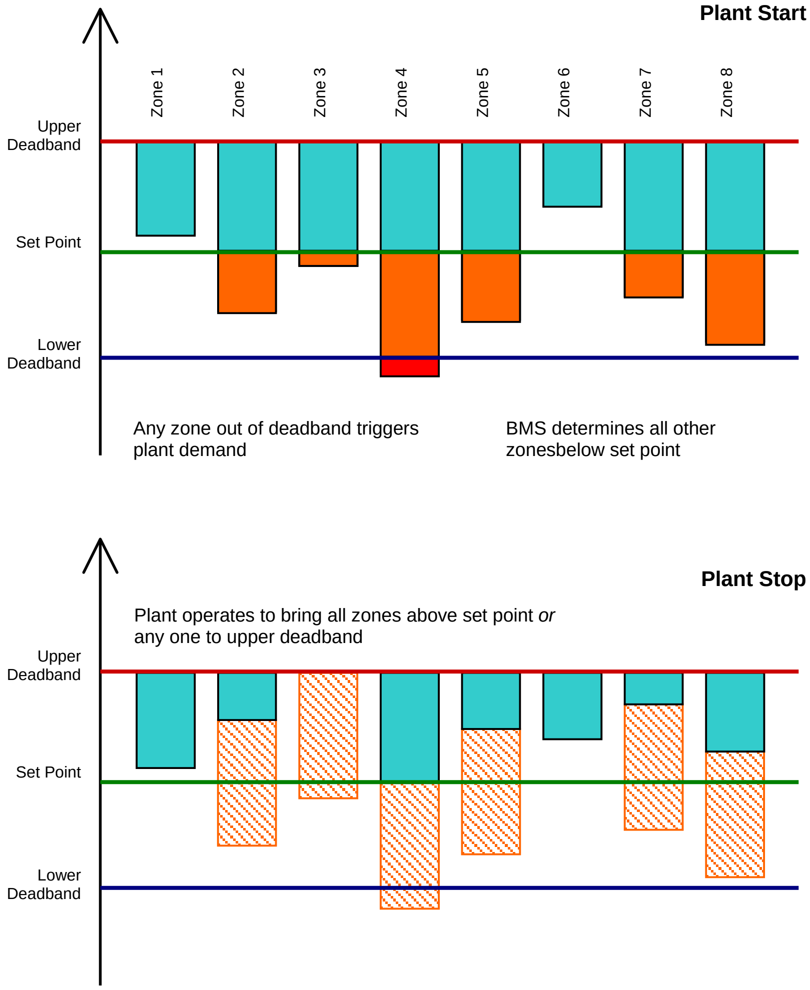

Figure 7: Illustration of the Cumulative Deadband Control

The thermal energy that is stored in this way is then available to maintain the space condition for an extended period until the load has again built up to a sufficient extent to start the CHP once more. Thus the plant is operated for continuously for extended periods of time at fixed output when there is demand and any surplus above that needed to meet the load is diverted to storage in a manner akin to a load levelling cooling system using a chiller with ice storage. In this case however the storage medium is the thermal mass in other building zones.

It has not been possible to effectively evaluate the benefit of this particular strategy at design stage as it has not possible to construct a simulation sensitive enough to model the zones within deadband. Nevertheless it is hoped that ongoing analysis of the CHP operation and building performance will demonstrate whether this approach is worth developing further in the future.

Conclusion

The very high efficiencies to be gained from heat recovery with passive thermal energy storage systems such as Termodeck can impact on the sizing and control of plant, particularly

CHP, in counter-intuitive ways. Nevertheless the presence of thermal energy storage capacity allows the adoption of alternative, perhaps simpler methods of controlling plant that can improve overall efficiency.

In the example of the Innovate Green Office it has been possible to develop a range of control strategies that utilise the properties of the building structure to store thermal energy in order to create favourable conditions for a CHP plant that would otherwise be substantially oversize for baseload operation. This has resulted in a predicted increase in the CHP operating hours from less than 1,500 to just over 4,000 the accepted tipping point in favour of CHP. The efficiency of operating the CHP in this manner, offsetting CO_2 emissions associated with the fans and pumps in the HVAC systems has played a significant part in the building achieving an overall 80% reduction in CO_2 emissions from the building services when compared with previous buildings by the same developer.

Further Work

There is still further scope for investigating and developing control systems that can make full use of the thermal mass properties of building structures. It is hoped that the Innovate Green Office can be used to explore and demonstrate these opportunities.

The School of Civil Engineering at University of Leeds is monitoring the building performance over the first two and a half years of operation. Unfortunately the building has only been partly occupied since completion of the tenants fit out in April 2007 reaching 20% occupancy by December 2007 and 30% by April 2008, so there is as yet no operational data for a fully occupied building. Nevertheless the first year's data indicates CO_2 emissions equivalent to $27kg/m^2$, about 17% over the target. This discrepancy can be partly attributed to delays and problems in fully commissioning the CHP unit.

Acknowledgments

The idea for the cumulative deadband control arose from joint development between King Shaw Associates as consultant, Goodmarriot & Hursthouse the Mechanical & Electrical Contractor and IBMS the controls specialist.

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