IOR
Founded 1899

THE INSTITUTE OF REFRIGERATION

Hybrid Cooling Solutions: Night Cooling and Mechanical Refrigeration

by

Nick Barnard, BA MSc CEng MCIBSE

FaberMaunsell

(Session 2006-2007)

To be presented before the Institute of Refrigeration
at the London South Bank University, London SE1
(see map at back)
on 7th December 2006 at 5.45pm

INTRODUCTION

Thermal mass can be used in conjunction with night ventilation of a building to provide passive cooling. Outside air is circulated through the building where it comes into contact with and cools the building fabric. The cooling that is stored in the building fabric is then available to offset heat gains the following day and keep temperatures within comfort limits (Figure 1).

Night ventilation is most effective in moderate climates such as the UK where the diurnal swing is sufficient that ambient temperatures at night fall below normal day time internal comfort temperatures. It is suitable for buildings with periodic daily loads such as offices. The use of thermal mass in conjunction with night ventilation can be used on its own in some cases or in combination with mechanical cooling in a hybrid solution to maintain comfort. Hybrid solutions offer a balanced approach to best satisfy the often conflicting requirements of cost, comfort and energy.

Night Cooling Systems

Most systems utilise floor slabs as the main thermal store. Systems can be categorised as "direct" and "indirect" depending on the mechanism by which heat is transferred between the thermal store and conditioned space (Figure 1). Direct systems have exposed surfaces in the space which are in direct thermal contact with the conditioned space. The simplest type of direct system is an exposed soffit. The exposed soffit cools the occupied space during the day by both radiative and convective cooling. However, exposure of the soffit raises a number of design issues that need to be addressed including

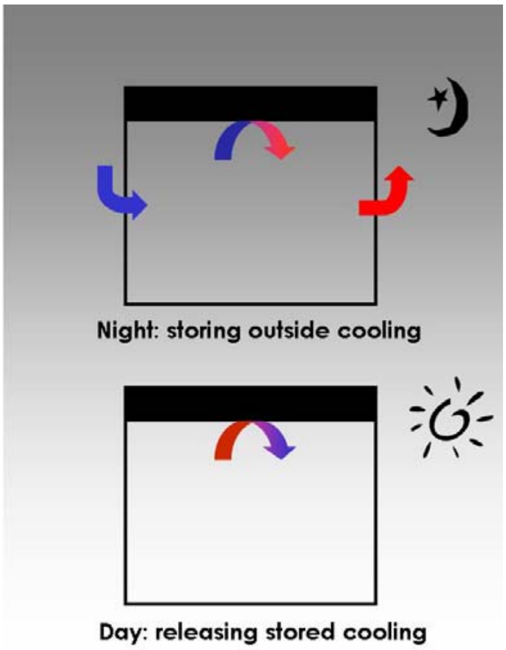

Figure 1. Direct night cooling.

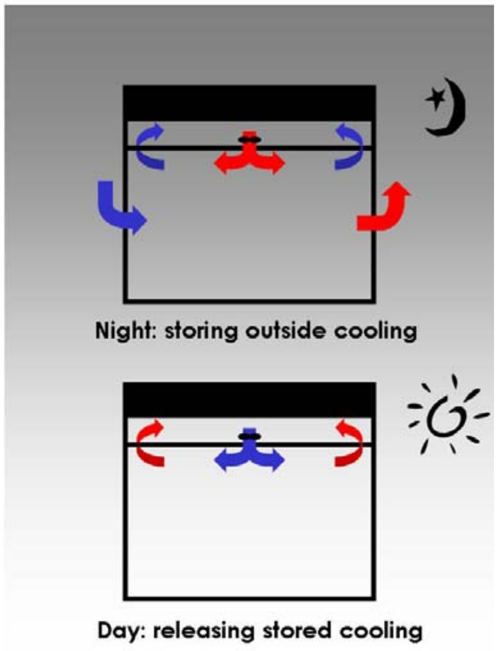

Figure 2. Indirect night cooling.

aesthetics, acoustics and integration of high level services.

Indirect systems rely on circulating air to transfer thermal energy between the thermal store and the conditioned space (Figure 2). Air may be passed through a false floor or ceiling void where it exchanges heat with the slab before entering the conditioned space. Heat exchange is primarily reliant on convective heat transfer.

Combined direct and indirect systems have also been used in buildings. A common example is a false floor ventilation supply in conjunction with an exposed soffit in the space. Hollow core slabs with air supplied through the cores in the slabs are also used in conjunction with exposed soffits.

Direct exposed mass can be used in conjunction with natural ventilation systems. Indirect systems are predominantly used with mechanical ventilation systems to circulate air. Whilst natural ventilation systems avoid the use of fan energy, they may not always be appropriate due to reasons such as high levels of external noise and pollution. Opening windows and vents in the occupied space may also be undesirable from a security point of view, particularly when used out of hours for night ventilation.

Coefficients of performance for mechanical ventilation systems (cooling delivered / fan energy) can vary widely depending on the fan pressure drop. Typical values from Reference [1] are ~25 for a local ventilation system down to ~3 for a centralised ventilation system. In addition to increasing fan energy consumption, fan pick-up will also increase with fan pressure drop reducing the cooling potential of systems. Minimising the fan pressure drop is therefore a key design aim for mechanical systems to minimise energy consumption and maximise performance.

Research and Development

The cooling performance of thermal mass storage systems is reliant on three primary factors:

- The amount of cooling introduced into the building at night (the night ventilation rate)
- The surface heat transfer between the air and the thermal mass
- The capacity of the thermal mass to store the cooling energy.

If any of these factors is poor, then the performance of the system will be poor regardless of the others. For most buildings there is sufficient mass in building floor slabs to effectively store the amount of cooling introduced at normal ventilation rates. Research work (Reference [1]) has identified that it is the surface heat transfer that limits performance, in particular for indirect systems where air was passed through floor and ceiling voids. Radiative and convective surface heat transfer values for direct exposed soffit systems sum to approximately 7-8 W/m^{2}K. The corresponding surface convective heat transfer values achieved within the voids are in the region of 2-3 W/m^{2}K. Typical overall cooling system performance values for the UK are 20-30 W/m^2 for exposed soffit systems compared to 10-15 W/m^{2}K for false floor systems. The difference in overall performance can be attributed directly to the

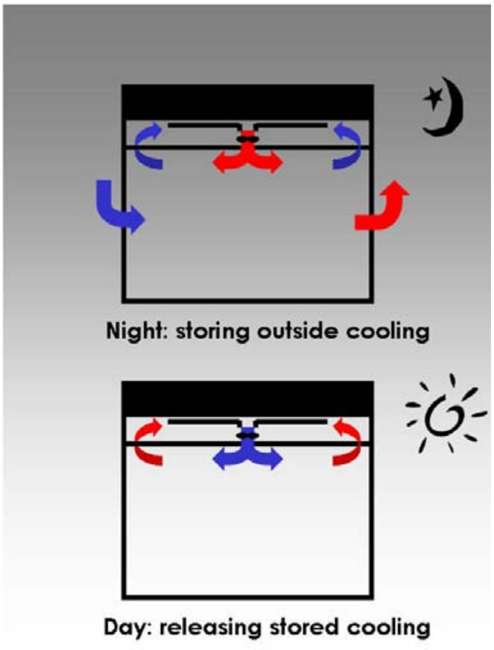

Figure 3. CoolDesk concept.

difference in the underlying surface heat transfer values.

Improving surface heat transfer between the circulating air and the thermal mass has the potential to significantly improve the performance of indirect systems using floor and ceiling voids. Faber Maunsell and Corus have worked collaboratively to research and develop one such concept aimed at achieving this. The concept is to attach sheeting elements to the slab surface in the void and circulate air by a fan through the narrow paths formed (Figures 3 and 4). The turbulent air flow created through the paths enhances heat transfer between the slab surface and the circulating air (Figure 5). The system is currently referred to as "CoolDeck".

A key parameter in the design of the sheeting elements is the air flow velocity and the height of the air path. This affects the rate of surface heat transfer

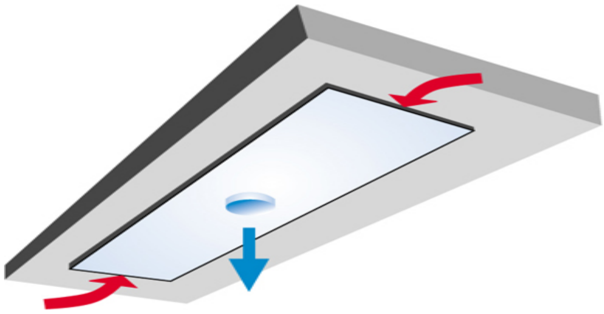

Figure 4. CoolDesk element.

per unit area. Taken in conjunction with the area of the elements (length x width), it determines the overall surface heat transfer performance of the elements.

Reducing the height of the air path increases the air velocity and flow turbulence and so in turn the rate of heat transfer. However, pressure drop and heat transfer are linked by the common underlying mechanism of turbulent air movement. The penalty of increasing the turbulence of the air to enhance heat transfer is an increase in the differential pressure and hence of the fan energy required to drive the air movement. The height of the air path was therefore designed so that a reasonable balance was struck between heat transfer enhancement and fan energy consumption.

"Admittance" values (Reference [2]) are a measure of the conductivity of a material under dynamic heat flow conditions. For a 24 hour charge/discharge cycle a dense concrete slab will typically have an admittance value Y_c of 10 to 20 W/m^2K. This compares with a surface convective heat transfer coefficient h_s which is normally in the region of 2 to 3 W/m^2K. The overall heat transfer coefficient h_{as} between the air and the slab (h_s and Y_c considered as conductances in series) can be approximated by:

$$h_{as} = (h_s \times Y_c) / (h_s + Y_c)$$

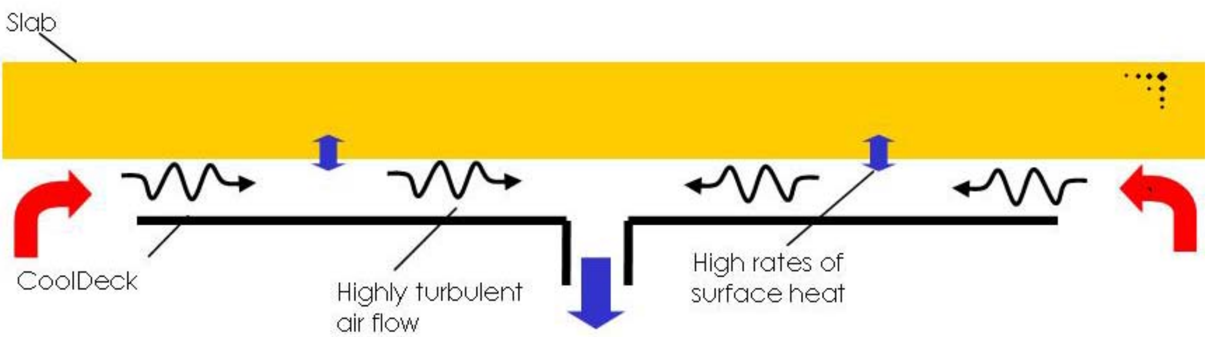

Figure 5 CoolDeck surface heat transfer.

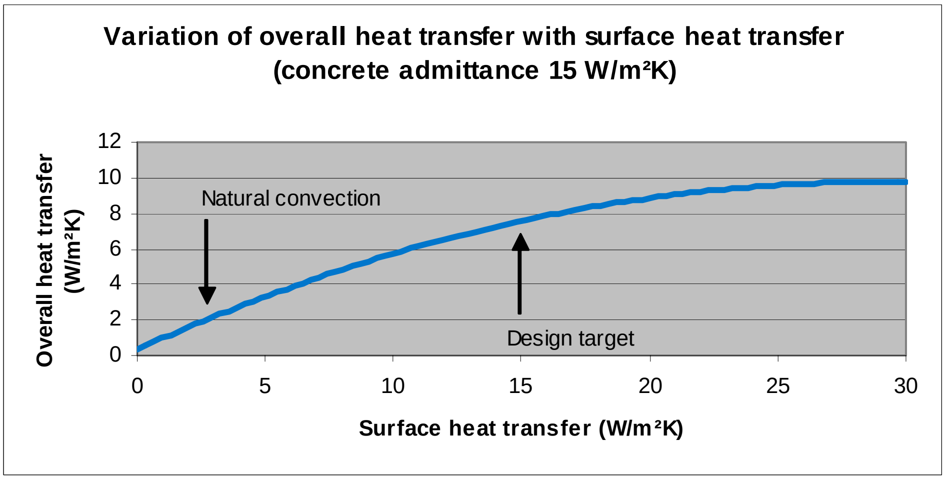

Figure 6. Variation of overall heat transfer with surface heat transfer.

Normally $h_s << Y_c$ so that h_{as} approximates to h_s, and the surface convective heat transfer coefficient governs the overall heat transfer. Initially increases in h_s will be accompanied by comparable increases in overall heat transfer h_{as}. However, the rate of improvement in overall heat transfer will diminish as h_s increases, particularly when h_s exceeds Y_c. At this point Y_c becomes the dominant factor in limiting overall heat transfer (see Figure 6). The fan energy consumed by the heat transfer process increases in proportion to h_s. Thus there is a diminishing improvement in heat transfer performance to fan energy consumed.

The design target set was to increase the value of the surface convection heat transfer coefficient to around 15 W/m^{2}K (approximately 5 times the typical unenhanced value) to provide effective storage of night cooling introduced at normal ventilation rates.

A test rig was built to measure heat transfer coefficients and pressure drops for a range of standard sheet metal profiles. Findings were used to establish the parameters for a full sized mock-up that was subsequently built and tested. The system developed has been used as the basis for the night cooling solutions described below.

Cooling Solutions

A number of phases of refurbishment work have been undertaken in Stevenage Borough Council's offices (Figure 7) over the past 5 years or so. The first phases of refurbishment were based on night cooling as the sole source of cooling. An introduction to these is given in this section. More recent installations have used a hybrid approach incorporating mechanical refrigeration and these are described in the following sections.

(NB SBC is participating in a European funded research project called REVIVAL. Monitoring of the systems described is ongoing and results will be made available via the project publications.)

SBCs offices had been suffering from summer time overheating as a result of increased use of computers. Rather than resort to a fully air conditioned solution, as part of the Council's Best Value approach to dealing with comfort conditions it was decided to try to implement passive measures where feasible and effective.

Figure 7. Stevenage Borough Council offices.

The target design comfort criteria were:

- less than 5% of occupied period >25°C dry resultant temperature
- less than 1% of occupied period >28°C dry resultant temperature

These are suitable for buildings using passive cooling

Figure 8. CoolDeck Installation.

solutions as they provide for internal temperatures drifting up during periods of high ambient temperatures. Thermal modelling predicted that in most of the zones solar blinds (to reduce solar gains) and night cooling would be sufficient to achieve the design comfort criteria.

As false ceilings were installed throughout the offices a solution was required that would provide a thermal link between the slab and the occupied space if the thermal mass was to be used effectively. The simplest solution would have been to remove the false ceiling and expose it directly to the space. However, as identified above, this approach had a number of drawbacks including:

- aesthetics – the appearance of the slab was not conducive to exposure
- acoustics – the additional hard reflective slab surface would have had an impact on the acoustic environment
- integration – a suitable solution would have had to be developed to integrate high level services.

The possible impact of exposing the slab on the heating system was also a concern – the exposed slab could also act as a thermal store for unwanted heat losses at night in winter (Reference [3]). For these reasons the CoolDeck solution was adopted to enable the integrity of the false ceilings to be maintained.

At night in the summer, cool outside air is introduced into the space by window fans. The CoolDeck fans operate in parallel to store the cooling in the slab, circulating air under the elements to exchange heat with the slab. The fans are controlled to operate when the temperature the previous day exceeds 24°C (ie a cooling requirement exists). Night ventilation will be held off when the internal temperature falls to 18°C (to prevent overcooling).

During the day the CoolDeck fans operate to release the stored cooling from the slab when the temperature exceeds 24°C. Outside air ventilation is provided naturally during the day by manual windows under occupant control.

A modular arrangement has been adopted with four CoolDeck elements per circulating fan (Figure 8). Both the night ventilation fans and CoolDeck fans are sized to provide an air flow rate of 5 l/s/m^2.

Monitoring was undertaken in areas throughout the building in the summer before the refurbishment works were undertaken and again in the following summer with the remedial measures in place. Results give a comparison of thermal conditions “before” and “after”. These indicate that a reduction in the region of 5 K in internal temperatures has been achieved relative to ambient temperatures. This is consistent with the modelling predictions from the initial thermal analyses. Approximately 1–2 K of the reduction is attributed to the solar blinds, the remaining 3-4 K to the CoolDeck system operating in conjunction with night ventilation.

In addition to the reduction in temperatures there is also appreciable air movement created by the CoolDeck system. It has also been noted that the

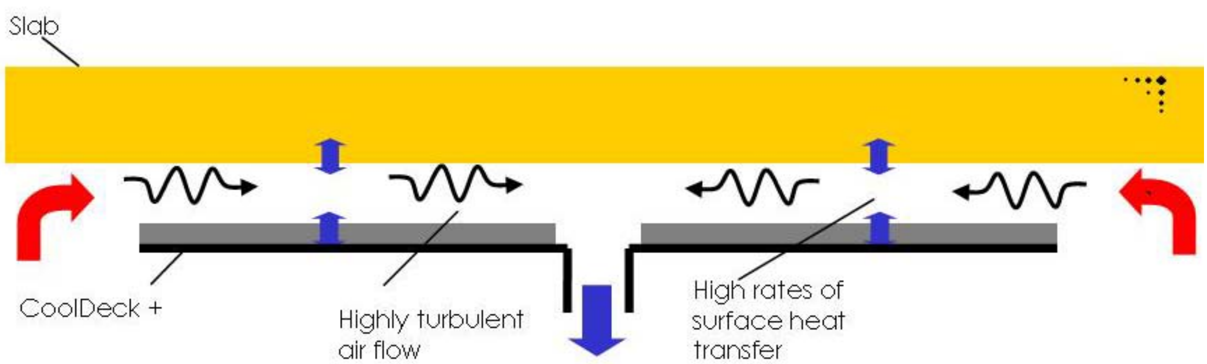

Figure 9. Cooldeck & PCM surface heat transfer.

areas with night ventilation are "fresher" in the mornings. This perceived improvement in indoor air quality has been attributed to the night ventilation.

The energy consumption of the installation has not been monitored. However, the design Coefficient of Performance (cooling / fan energy) is in the region of 20. This is due to system pressure drops being kept to a minimum through the use of window fans to bring outside air into the space and small modular systems to recirculate air between the space and the CoolDeck elements.

Estimated costs for the system are in the region of £40/m^2. The estimated cost of the air conditioning alternative was £180/m^2.

In a subsequent phase of the refurbishment work, it was necessary to reduce the number of CoolDeck elements in the ceiling void for coordination purposes. The solution adopted was to integrate Phase Change Material (PCM) into the element to increase the thermal storage per element (Figure 9). The PCM is contained in flat pouches approximately 10 mm thick. These are joined together to provide a sheet of PCM half the area of the CoolDeck elements. These lie in the CoolDeck elements so that the air passing through the gap exchanging heat with the slab above and the phase change material below. The sheets of phase change material can be slid in and out from each end for cleaning purposes (see Figure 10).

Figure 10. Installing PCM pouches.

This has approximately doubled the storage capacity of each of the CoolDeck elements. In this installation there are only two CoolDeck elements per circulating fan as air flow rates to each are doubled to utilise the additional storage capacity provided by the phase change material (Figure 11). The gap between the CoolDeck elements and the slab has been increased to accommodate the

Figure 11. CoolDeck + PCM installation.

additional air flow and the pouches.

The phase change material is a salt that changes phase between approximately 20°C and 24°C. The phase change temperature needed to be high enough such that it could be frozen by summer night ambient temperatures and low enough that it could provide a significant cooling effect to the occupied space.

The cost of the system using the phase change material is approximately the same as that for the system without – the cost of the phase change material being offset by savings on the number of elements and fittings. Pouches from the original installation have been removed and opened to inspect the condition of the phase change material itself. No visible deterioration was observed.

The monitored performance of these passive night cooling solutions was in-line with design predictions. However, peak temperatures experienced in the offices were still high as a result of a series of very hot summers. For the most recent installation phase in the offices a hybrid solution was developed incorporating local refrigeration units.

Hybrid Cooling Solution 1: Local refrigeration + night cooling + thermal mass + phase change materials

The design concept was to use the local DX refrigeration units only during the hottest weather to limit peak temperatures to 28°C. This would improve comfort conditions for the occupants for a minimal energy penalty.

The passive night cooling system described above has been augmented with local refrigeration units mounted in the ceiling void. During most of the summer the system operates purely on passive night cooling. The local DX refrigeration units operate during periods of peak temperatures to provide

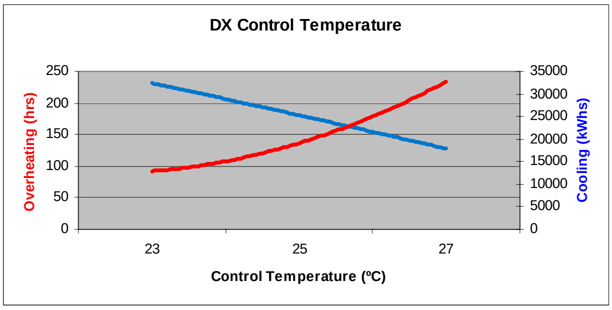

Figure 12. DX control temperature.

additional cooling during the day and storage at night.

The local refrigeration units are sized to provide approximately 30 W/m^2 of cooling, ie only a fraction of the full cooling load capacity. Thermal modelling was to analyse the performance of different sizing options in combination with the night cooling system.

One of the key issues for the council in operating this type of system is the balance between comfort and minimising energy. The more the local DX refrigeration units operate the cooler the conditions but the higher energy consumption, and vice versa. Figure 12 illustrates variations in overheating and energy with control temperature for the local refrigeration units. An initial control temperature of 27°C has been selected.

The energy consumption with a control temperature of 27°C is predicted to be less 25% of that of a conventional cooling system, with the capital cost around 50%. (If the control temperature was reduced to 23°C energy consumption is predicted to double to approximately 50% of that of a conventional cooling system.)

Relative to the night cooling system on its own the addition of the local DX refrigeration units is predicted to reduce peak temperatures from 30+°C down to 28°C. However, overall costs are double the passive system, 50% (as compared to 25%) of

Figure 13. Customer Service Centre.

that of a conventional cooling system.

Hybrid Cooling Solution 2: Central refrigeration + night cooling + thermal mass + phase change materials

The solutions developed for the offices were based on design comfort criteria which permitted space temperatures to rise with ambient temperatures, ie X°C could be exceeded to Y% of the occupied period. This is suitable for some applications, but in others it is desirable to adopt a more rigid fixed maximum design temperature criteria which should not be exceeded.

This was the case for the Customer Service Centre installation at SBC (Figure 13). This is a key area for interaction with the public, essentially a shop-front for the council. For this area it was considered necessary to set a maximum design temperature criteria of 25°C. To achieve this required mechanical cooling. The space itself was enclosed with very few windows to the outside so mechanical ventilation was also needed to provide fresh air to the occupants.

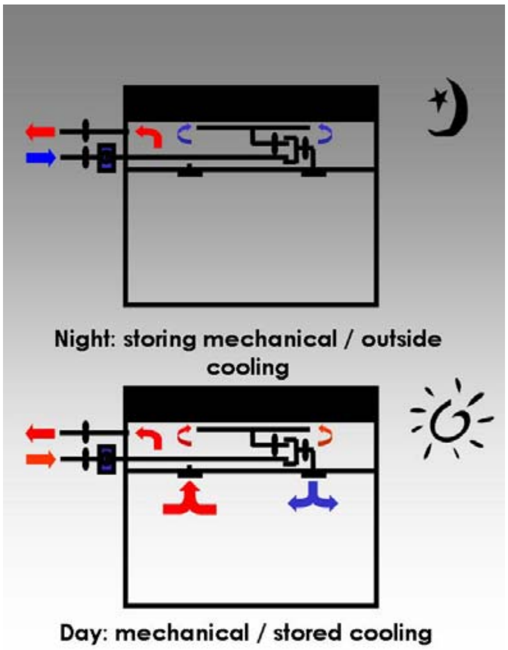

Figure 14. Customer Service Centre concept.

These requirements led to a solution based on central mechanical ventilation providing fresh air and cooling to the space. The central unit operates at night to provide night cooling. Cooldeck elements provide local storage of night cooling.

At night during the summer the central unit operates to supply cool air at 16°C into the ceiling void

(Figure 14). Depending on ambient conditions this may be direct from outside if temperatures are low enough, or air cooled by mechanical refrigeration. The air is circulated through the CoolDeck elements storing cooling in the thermal mass and PCM. The distribution fan units serving the supply grilles are off so no air is drawn from the ceiling void into the space.

The following day the central plant operates to provide fresh air and cooling to the space. The supply rate is around 2.5 $l/s/m^2$ based on occupant fresh air requirements. This is sufficient to meet approximately 50% of the peak cooling load. The CoolDeck system is sized to provide the balance. The CoolDeck fans operate to augment the central plant cooling by releasing the cooling stored locally in the thermal mass and phase change material.

The PCM has been selected with a phase change temperature of 18ºC, lower than for those systems using only night cooling. This temperature provides a significant cooling differential relative to the space design temperature of 25ºC. Because of the presence of mechanical refrigeration we were able to ensure that this could be frozen at night.

In this installation, the use of night cooling in a hybrid solution with mechanical refrigeration has enabled the size of the central air handling / refrigeration plant and distribution system to be halved. The system also provides some energy savings but these will not as dramatic as for the local night cooling systems as the fan energy requirement for night cooling using the central system will be considerably higher (due to higher fan pressure drops). The design coefficient of performance for the night cooling system is of the order 5.

CONCLUSIONS

Night cooling can provide a low cost low energy solution to cooling. However, hotter summers may mean that in some applications acceptable comfort conditions can only be achieved with the incorporation of some mechanical refrigeration in a hybrid solution. Hybrid solutions potentially offer a balanced approach in terms of cost, comfort and energy.

Night cooling can be used reduce central plant and distribution requirements in hybrid approach. This can be particularly beneficial for reducing plant and distribution space requirements.

PCMs can be used in a cost effective manner to provide thermal storage within a building. The phase change temperature should be selected to suit the cooling source temperature and space design temperature.

References

[1] Dynamic energy storage in the building fabric, BSRIA Technical Report TR9/94, N Barnard

[2] CIBSE Guide A: Design data, section A3: Thermal properties of buildings and components, 1986.

[3] Barnard N, Concannon P and Jaunzens D, Modelling the performance of thermal mass, BRE Information Paper IP 6/01, Garston, Construction Research Communications Ltd, 2001

Acknowledgements

Corus – research and development

Stevenage Borough Council – case studies

This event will be held at the London South Bank University.
Main Entrance, Keyworth Building Entrance (opposite Lancaster Street) London South Bank University, Borough Road, London SE1 0AA.
The nearest tube stations are Southwark (8 mins walk), Elephant & Castle (6 mins walk) or Borough (10 mins walk).