An exemplary low-energy office building incorporating phase-change material

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1. ABSTRACT

The Academic Offices Building Stage 3 on the Charles Sturt University Albury-Wodonga campus has been designed to be a very low-energy building. An innovative iterative design process supported by rigorous scientific investigation and analysis has led to a very energy-efficient design solution, with the overall energy efficiency performance modelled to be well above the NABERS maximum 5 star greenhouse standard.

The two-storey building incorporates passive elements, which are enhanced through the use of a phase-change material. Cooling is achieved through the use of a cooling tower only, and is supported by a control strategy that optimises the potential of the encapsulated phase-change material. This material has been incorporated into the building as either plaster board fixed to the underneath of the ceiling slabs or in a floor screed.

The hydronic system delivers heating or cooling water as required to the slabs. Natural ventilation is used.

This building has achieved a 6 star Green Star rating under Office Design. Actual performance is still a work in progress but a performance significantly better than 5 stars NABERS appears likely.

2. BACKGROUND

The Academic Office Accommodation Stage 3 (AA3) building (Figure 1) at the Albury Wodonga Campus of Charles Sturt University (CSU) in New South Wales, Australia, was preceded by the construction of Stages one and two. These earlier buildings were constructed from rammed earth and were intended to provide a good level of thermal comfort while having low energy use. They have been described as “deep green” (Johnson 2001) and have won a number of awards but a close analysis of the operation of the rammed earth offices indicated serious shortfalls in areas of environmental design and energy usage (Taylor, 2004 and Taylor, Fuller and Luther 2007).

CSU has accepted the findings and was eager to overcome the design flaws with a new building. Therefore CSU has determined that the last of the series of offices should be both exemplary in its design and performance, such that it would achieve measurable performance outcomes that align with the campus’s low energy ethos while achieving a comfortable indoor environment.

The design team was charged with ensuring that the new office design made use of passive elements in preference to active refrigerative systems that would maximise the use of opportunities presented by the local climatic conditions. The active systems eventually proposed were assessed on their ability to enhance the unconditioned performance of the building and to meet the briefed functional, energy and comfort requirements. In order to achieve this outcome, CSU and the design team developed and adopted a new design process that focused on the functionality and performance of the building that could be “proved” through the use of thermal modelling. In conjunction with the selection of a suitable system the control strategy was developed.

Figures 1–3. Left to right: AA3 building north exterior, interior and south exterior views.
A comprehensive building monitoring system was also developed, which will allow analysis of the building in operation and allow refinement of the control.

3. CLIMATE
The climate of the Albury Wodonga inland region is characterised by cool winters, hot summers, high solar loads and high diurnal temperature swings. Figure 4 shows the average maximum and minimum dry bulb temperatures for the year. A large variation across the year is visible, with maximum summer temperatures over 35°C while frosts occur in winter.

Of particular interest for this building is the ambient humidity. The 9am humidity in the summer is typically 50% and by 3pm this has fallen to 30%, giving wet bulb temperatures of 16°C and 18°C respectively. Wet bulb temperatures will be examined in more detail later, as they are crucial to the successful operation of the building in the summer months.

4. DEVELOPING THE SOLUTION FOR AA3
The client brief determined that the office building should:
• provide office accommodation for 36–40 staff
• meet the requirements of the ASHRAE 55 thermal comfort standard during occupied hours
• preferably be naturally ventilated
• be designed in a manner that maximises passive design elements to the extent that the building design is able to meet or exceed the 5 star rating under the Australian Building Greenhouse Rating (ABGR) scheme (now NABERS Energy).

The generally accepted passive solution for keeping the building cool in the hot inland climate is through the use of thermal mass, which evens out the large ambient diurnal temperature range within the building. In order to prevent overheating of the thermal mass walls, the mass needs to be well insulated from excessive direct solar gain and exposure to high external ambient temperatures.

The same thermal mass solution can be used to some extent for heating the building in winter through the allowance of solar penetration into offices, although glare, loss of insulation and the possibility of summer overheating work against this.

A two-storey 750 m² building concept was developed using a heavyweight, well-insulated envelope with added thermal mass in concrete floors and ceilings. Initially the building design was thermally modeled in its “free running” state (i.e. no heating or cooling except via outside air exchange, modelled as varying amounts of economy cycle air (two, five and eight air changes per hour) available at any time over the 24-hour period).

The internal temperatures for a number of hourly bins for the year are shown in Figure 5 and assume typical office heat loads.

The results show the advantage of the increased ventilation rates but also show that for much of the occupied time the building is too hot. Even with eight air changes per hour approximately 400 hours of overheating occur, equivalent to more than 40 days during the summer period.

On this basis it was determined that some form of active cooling was required. However, the design team and client were reluctant to go down a conventional air conditioning path. On reviewing the “free running” model, two issues were noted:

1. The thermal mass available is apparently insufficient, as even with high overnight ventilation rates there is still considerable overheating.
2. The rate of heat transfer from the thermal mass also appears insufficient, as real night purge rates are likely to be well below eight air changes per hour.

To resolve these issues, the following design approaches were identified:

• In order to increase the thermal mass of the building, encapsulated phase-change materials would be used within the structure of the building. While there has been some use of phase-change materials in active components of other projects in Australia, the use of structurally incorporated phase-change material appears quite novel. The advent of encapsulated phase-change materials provided an ideal opportunity for the application, as these can be incorporated into concrete mix and are also available in the form of a plaster board. As the phase-change materials hold temperature at the melting point (typically 24°C), they have the further advantage of providing enhanced temperature stability over sensible thermal mass such as concrete (which warms as it absorbs energy).
In order to increase the heat transfer rate, a solution utilising water cooling of the structure through embedded pipes was adopted. This provides far higher – and more controllable – heat transfer rates than a simple night purge.

Given the low-humidity climate of Albury, it was proposed that the heat rejection for the water cooling system should be via cooling tower only, with no refrigerative cooling. The basis of this decision is shown in Figure 6. In this figure, the cumulative load is compared with the current (instantaneous) wetbulb, and the average and minimum wetbulb over the previous six hours. As can be seen in Figure 6, the vast majority of the cooling load occurs when the outdoor wetbulb is below 19°C. This means that there is strong potential to use an evaporative solution – in this case a cooling tower – to provide the cooling for the building. The graph shows that all the cooling load occurs at wetbulb temperatures below approximately 21°C. It also indicates that 90% of the cooling loads occur at or below wetbulb temperatures of 19.5°C. Furthermore, if the system is able to use of the minimum wetbulb temperature in the previous six hours through its thermal storage the wetbulb temperature in question falls to approximately 18°C. Assuming that cooling water can be produced within a 3°C approach of the wetbulb temperature by the cooling tower a very useful cooling flow temperature of 21°C or less can be achieved for most of the time and thus the building can be kept cool using this strategy.

Thermal comfort is realised in the summer by augmenting the high thermal mass of the building with a phase-change material (PCM).

Heat is removed from the building by a conventional hydronic in-slab system, with the water being cooled by the use of cooling tower that runs during the night for the most part.

Heating is provided by a condensing boiler.

Control is unusual in that it is in part dependant on operative temperature and part dependant on PCM temperature.

The building itself is insulated to more than double the standard specified by the Australian Building Code.

The phase-change material selected is a hydrocarbon (wax) phase-change material. The material is called Micronal and is produced in tiny encapsulated spheres (diameter 2-20 μm) (BASF 2007). The PCM is introduced into the building as a composite material by embedding it in 12mm thick gypsum plaster board or in a 50mm thick cement-based floor screed (Figure 7). The plasterboard is affixed to the underside of the concrete slab with a cementious adhesive ensuring a good thermal bond is achieved. In this way the hydronic system in the slabs is able to remove or add heat to or from the PCM as well as the indoor environment.

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7. CONTROL METHODOLOGY

A control method has been designed to exploit the characteristics of the phase change material and ambient conditions. The year has been divided into two so that heating is available from and including May to September and cooling is available during the remaining six months.

7.1 Heating

In heating mode, the building is considered to be simply a high mass building and no particular attention is given to the PCM. In the winter the room thermostats provide local control only (typically over 18 – 21°C with 0.5°C hysteresis) and do not participate in the control of the zone pump. A separate BMS-connected sensor controls this pump.

7.2 Cooling

In cooling mode four layers of PCM within the building (ground floor, ground floor ceiling, first floor screed and first floor ceiling as shown in Figure 7) are separately controlled. A lockout is provided when the difference between the zone PCM temperature and the flow temperature is less than 2°C because effective cooling would not be achieved. As no cooling is provided in this circumstance, the building will tend to overheat as a result.

7.2.1 Cooling during occupied hours

The cooling strategy has to take account of two key factors:

- There is more cooling power available from the ceiling than the floor surface; and
- The operation of the middle slab is complicated by the fact that it is coupled to both upper and lower floors, albeit more strongly to the latter.

Therefore the control of water flow to the slabs is as follows:

- First-floor ceiling: controlled by first-floor zone temperature and PCM temperature.
- Middle slab: controlled by the warmer of the first and ground floors and by the high select of either the ground floor ceiling of first floor screed temperatures.
- Ground floor slab; controlled by the ground-floor zone temperature and by its temperature

There is no individual circuit control in cooling – the room valves are set to be open in the cooling season. Likewise, the temperature of the water in the secondary circuit is not controlled by the mixing valves, as there is no particular benefit from zone-by-zone modulation of flow temperature.

An optimum stop algorithm is used to determine when the pump turns off while permitting the zone temperature to rise to 27°C by the end of the occupancy period. This ensures that the phase change is used to its maximum advantage.

7.2.2 Overnight cooling

Between midnight and the commencement of occupancy, a zone pump turns on if the zone PCM is not “frozen”. An optimum start algorithm is used to determine the optimum starting time for the pump to “reset” the phase change for the start of occupancy. In order to ensure that the most critical slabs are cooled first, the target time for completion of “freezing” is as follows:

1. First-floor ceiling PCM: occupancy start time minus one hour
2. Middle-slab PCM; occupancy start time minus half an hour
3. Ground-floor PCM; occupancy start time.

8. PREDICTED PERFORMANCE

As a result of installing twice the level of insulation required by the Australian Building Code and with high-quality double-glazed windows, only a relatively small boiler is necessary to provide the peak heating requirement of 34 W/m².

The use of a cooling tower running for the majority of the time at night has the twin benefits of low power consumption and load shifting outside of peak demand times.

The modelling of the building’s expected energy efficiency performance indicated that it had the potential to achieve well over 5 stars (maximum rating) on the NABERS scheme.

Table 1: Predicted NABERS benchmarking factors (formerly known as normalised emissions (kg/m²))

<table>
<thead>
<tr>
<th></th>
<th>Typical office building</th>
<th>Best practice office building</th>
<th>Predicted greenhouse gas emissions of AA3</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Star NABERS</td>
<td>135</td>
<td>71</td>
<td>24</td>
</tr>
<tr>
<td>5 Star NABERS</td>
<td></td>
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</tbody>
</table>

The predicted base building energy consumption was 5,100kWh of electricity and 7,200MJ of gas.

9. REALITY VERSUS THEORY

This is a unique building in many aspects, and the construction and commissioning phases of the building have been somewhat drawn out as a result. Key issues that have arisen since completion include:

- Incorrect pump and valve selections by the contractor;
- Commissioning difficulties arising from both process and equipment issues;
- Limited hydronic system expertise availability, particularly in a regional location;
- Limited technical support generally, resulting in long problem-detection and problem-resolutions cycles;
- Apparent underperformance of the cooling tower;
- No initial structured building tuning process, due to drawn out-commissioning problems;
- Organisational changes within the university leading to loss of continuity in operation and management.

A consequence of these issues was that in the second summer of operation (summer 2010/11) a contractor error on site disabled the cooling system entirely, and this was not detected or rectified until March 2011.

As a result of these issues the building has yet to operate as originally intended. Nonetheless, available results provide promising indications for the operation of the building, as outlined on the next page.
9.1 Operation in heating mode

Operation in heating mode has been successful, with building temperatures generally well maintained throughout the majority of the building. A sample operating trend for a cold week is shown in Figure 8.

![Winter cold week – room 2.07](image)

Figure 8: Sample performance in a cold winter week

It can be seen that the high mass and insulation of the building leads to remarkably stable indoor temperatures throughout the week. Gas consumption (heating and DHW) has been 6700 MJ over the 12 months to March 2011, which is remarkably close to the predicted figure.

9.2 Operation in cooling mode

As noted earlier, the building’s cooling system was inoperative during the last summer, so available results represent the performance of the building without any cooling. Given this limitation, the temperature response was found to be remarkably robust, with room temperatures (in an upper floor room) peaking at 28–29°C after a series of days above 30°C peak outdoor temperature, plausibly in line with the no-cooling simulation analysis shown in Figure 5. While it is disappointing not to be able to present figures including the operating cooling system, the performance in an entirely passive operational mode is promising.

Total mechanical system energy consumption in the year to March 2011 was 10,030 kWh; unfortunately deficiencies in installed metering have prevented evaluation of total base building energy use, although non-mechanical consumption for the base building is expected to be very low. Irrespective, the base building electrical consumption – although very low in an absolute sense – is more than twice the simulated figure. As it is known that there were ongoing and significant flaws in the operation of the hydronic pumping systems for this building through the measurement period, this is explicable, if disappointing.

9.3 Estimated NABERS performance

The current estimated NABERS base building performance is 5 stars (NABERS Benchmarking factor 32, compared with 5 stars threshold of 71) and NABERS whole building is also 5 stars (NABERS Benchmarking factor 60, compared with 5 star threshold of 134). These are estimates only and are not accredited ratings.

To put this in perspective, the estimated gross emissions of the base building are only 26 per cent of the gross emissions of a 5 star NABERS base building of the same size and hours, and the equivalent figure for the whole building is 41 per cent.

10. CONCLUSION

This building has taken the concept of an insulated thermal mass building and enhanced it through the incorporation of PCM, together with an ultra-efficient heating and cooling system to provide a year-round comfortable office environment. This has occurred due to two key aspects:

- the development and availability of encapsulated PCM that allows one to efficiently position additional “lightweight” thermal mass throughout the building envelope
- the development of a novel control strategy that is designed to use climatic conditions to fully exploit the opportunity to produce a low-energy-consuming but comfortable building. Importantly, cooling is achieved without the use of refrigerative plant.

The performance of the building to date has yet to fully demonstrate the operational potential of the design due to a range of problems. However, the initial results are promising and currently assessed emissions are 59 per cent and 74 per cent below that had the building been performing at the NABERS 5 star thresholds for the whole and base building ratings respectively.

11. ACKNOWLEDGEMENTS

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12. REFERENCES


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