Phase-Change Wallboard and Mechanical Night Ventilation in Commercial Buildings: Potential for HVAC System Downsizing

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ABSTRACT

As thermal storage media, phase-change materials (PCMs) such as paraffin, eutectic salts, etc. offer an order-of-magnitude increase in thermal storage capacity, and their discharge is almost isothermal. By embedding PCMs in gypsum board, plaster, or other wall-covering materials, the building structure acquires latent storage properties. Structural elements containing PCMs can store large amounts of energy while maintaining the indoor temperature within a relatively narrow range. As heat storage takes place inside the building where the loads occur, rather than at a central exterior location, the internal loads are removed without the need for additional transport energy. Distributed latent storage can thus be used to reduce the peak power demand of a building, downsize the cooling system, and/or switch to low-energy cooling sources.

We used RADCOOL, a thermal building simulation program based on the finite difference approach, to numerically evaluate the thermal performance of PCM wallboard in an office building environment. We found that the use of PCM wallboard coupled with mechanical night ventilation in office buildings offers the opportunity for system downsizing in climates where the outside air temperature drops below 18 °C at night. In climates where the outside air temperature remains above 18 °C at night, the use of PCM wallboard should be coupled with discharge mechanisms other than mechanical night ventilation with outside air.

Introduction

In the current era of building energy efficiency, much attention is directed to reducing the energy consumption and peak power demand associated with building operation. In particular, comprehensive efficiency programs involving Heating, Ventilation and Air Conditioning (HVAC) systems are becoming increasingly popular. Such programs address a wide range of issues, from finding the most appealing incentives to promote highly efficient equipment, to financing integrated HVAC system retrofits.

Integrated chiller retrofits combine HVAC equipment upgrades with a measure or package of measures designed to reduce internal loads. Currently, the preferred vehicle for reducing internal loads is the lighting retrofit, mainly because it is achieved relatively easily, and it dramatically reduces the payback time of the associated HVAC equipment upgrade. Because of the advantages offered by lighting system retrofits, other building improvements with a high potential to reduce internal loads (e.g. improving the delivery efficiency of the HVAC system through duct system retrofits, building envelope retrofits, etc.) are generally overlooked in integrated HVAC system retrofits. In this paper we examine the load reducing potential of distributed latent storage – as offered by phase change wallboard – in commercial buildings. Because phase-change wallboard is not currently available in the U.S., we cannot provide a cost-effectiveness analysis of this measure.

Background

Phase change wallboard is manufactured by embedding a phase change material (PCM), usually a paraffin or a eutectic salt, in gypsum board or plaster. As storage media, PCMs offer an order-of-magnitude increase in thermal storage capacity, and their discharge is almost isothermal. Structural elements containing PCMs can store large amounts of energy while maintaining the indoor temperature within a relatively narrow range. The advantage of using distributed thermal storage elements is that they allow heat storage to happen inside the building where the loads occur, rather than at a central exterior location. Consequently, the transport energy required for the supply of cooling agents to the individual zones is greatly reduced. Phase change wallboard can be easily incorporated in construction, as it simply replaces conventional wallboard.

Scope

We previously reported that, when used in state-of-the-art residential buildings, phase change wallboard has the potential to eliminate the need for mechanical cooling in California coastal climates (Stetiu & Feustel 1996). This paper uses the indoor environment typically found in office buildings to evaluate the load reduction potential of phase change wallboard.

Methodology

We studied an office space equipped with a VAV system. We first performed DOE-2 simulations to obtain realistic temperatures and air flows for the VAV system; then used RADCOOL (Stetiu et al. 1995), a finite difference building simulation program written in the Simulation Problem Analysis and Research Kernel (SPARK) environment, to model the thermal performance of the same office space equipped with phase change wallboard. RADCOOL was designed to facilitate the evaluation of the dynamic response of a building to variable weather conditions and interior loads; it employs a net radiation model to evaluate the long-wave radiation exchange among interior surfaces.

Building

The study was conducted on a prototype building designed by the International Energy Agency to serve as a base-case for building energy and indoor air quality studies (International Energy Agency 1995). The design corresponds to a medium-size office building with single- and multi-occupancy offices located at the building facades and with a core space dedicated to utility activities (see Figure 1). The building is rectangular and its longer facade is oriented 45 east of north. Figure 1 shows only one floor of the building.

Building construction. To ensure compatibility of this base-case building with building standards, we simulated an office building structure complying with the California Title 24 standard (CEC 1995). It features a curtain-wall construction with a U-value of 0.45 W/m^2-K for the opaque portion. The vision glazing of the curtain-wall construction consists of double-pane windows with a center-of-glass U-value of 1.31 W/m^2-K. No drapes or mechanical shading were simulated for the windows. The interior walls of the building consist of a 6-cm air layer sandwiched between two layers of wallboard, each 1-cm thick. The U-value of the interior walls is 1.95 W/m^2-K. When investigating the thermal performance of the distributed thermal storage elements, phase-change wallboard containing 20% paraffin by mass (Stetiu & Feustel 1996) was simulated instead of the interior layer of wallboard

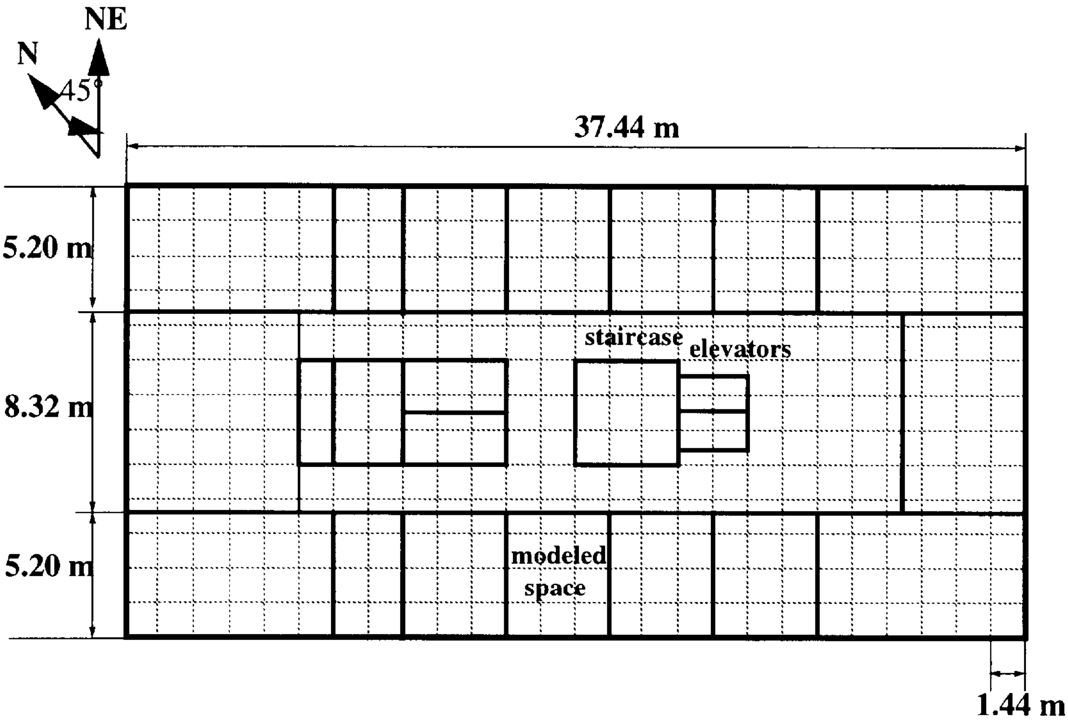

Figure 1. Building orientation and layout.

that would otherwise cover the vertical walls. The ceiling and floor are made out of 32-cm thick reinforced concrete.

Space selection. Because the modeling capabilities of RADCOOL are limited to a single-zone space, conducting the study involved the choice of one room of the base-case building. We chose the space highlighted in Figure 1 due to its orientation (45° west of south) and its position inside the building (it provides straightforward boundary conditions).

Space description. The modeled office space is rectangular with an area of 22.5 m^2 (see Figure 1). The facade window area (vision glazing of the curtain-wall construction) is equal to 20% of the floor area of the space (4.5 m^2).

Internal loads. The space model incorporated a variable weekday occupancy pattern in the range of 1 to 2 persons with a weekday schedule from 8 a.m. to 5 p.m. The model described zero occupancy during the weekend. When "present", each modeled person generated 115 W of heat (75 W sensible and 40 W latent). No other latent heat sources were simulated. Office equipment (computers, printers, lights) were modeled in the space with a constant load output of 275 W between 8 a.m. and 5 p.m. on weekdays. No equipment load was simulated during the weekend.

Infiltration. The space model included an infiltration rate of 0.2 ACH (13.5 m^3/h) when the building was not pressurized (the HVAC system was switched off). An infiltration rate of zero was modeled when the HVAC system was in operation.

HVAC system. The model included a Variable Air Volume (VAV) system, operated by a timer-based control, to provide ventilation and cooling to the space. On weekdays the simulated VAV system employed a thermostat control to supply cooled air to the space between 6 a.m. and 6 p.m. On weekends an outside air supply of 72 m^3/h was modeled between 6 a.m. and 6 p.m. To pre-cool the space during nighttime and facilitate the discharge of the PCM wallboard, the model included outside air supply between 10 p.m. and 6 a.m. throughout the week, at a rate equal to the maximum fan flow rate determined by the design daytime cooling load. To prevent space overcooling, the mechanical night ventilation was modeled as switched off whenever the indoor air temperature dropped below 20 °C. To maximize the night cooling effect and minimize fan energy use, the mechanical night ventilation was also simulated as switched off if the difference between the air temperature inside the modeled space and the outdoor air temperature became less than 2 °C.

Climates simulated. We modeled the office space in two California climates: Sunnyvale (CEC climate zone 4) and Red Bluff (CEC climate zone 11) (CEC 1995).

Time period for simulation. For each climate we simulated the week during which the VAV system must meet the highest cooling load. In California climate zone 4 the week of VAV system peak was August 23-29, while in climate zone 11 the selected week was July 12-18.

Results

California climate zone 4 (Sunnyvale)

Figure 2 compares simulated indoor air temperatures and Figure 3 indoor operative temperatures for California climate zone 4. In both figures the solid line corresponds to the space equipped with conventional wallboard and served by the optimal chiller (cooling capacity of 1.1 kW). The dashed line corresponds to the same space cooled by a system that is 28% smaller than the optimal (chiller with a cooling capacity of 0.8 kW). The dotted line corresponds to the space equipped with phase-change wallboard, cooled by the VAV system served by the 0.8 kW chiller. In Figures 2 and 3, the simulated week starts on a Friday (August 23). The second and third days are weekend days, therefore temperatures on these days may exceed the upper limit of the comfort zone.

Figures 2 and 3 show that, while the 1.1 kW chiller maintains the indoor air and operative temperatures of the space below 27 °C during work hours (solid lines), these temperatures become higher than 28 °C when the space is cooled by the 0.8 kW chiller (dashed lines). When the space is equipped with PCM wallboard, the 0.8 kW chiller can maintain the indoor air and operative temperatures below 27 °C (dotted lines). By storing a significant fraction of the space heat the PCM wallboard reduces the cooling load, thus allowing the smaller chiller to adequately cool the space. In addition to reducing the temperature peaks by more than 1 °C, the PCM wallboard also reduces the temperature amplitudes by 2 to 3 °C. Consequently, the space equipped with PCM wallboard provides more stable indoor conditions than the space equipped with conventional wallboard.

California climate zone 11 (Red Bluff)

Figures 4 and 5 show comparisons of indoor air temperature and operative temperatures for the space located in California climate zone 11. Here the optimal VAV system has a cooling capacity of 2.4 kW, and the smaller chiller has a cooling capacity of 1.7 kW (70% of optimal).

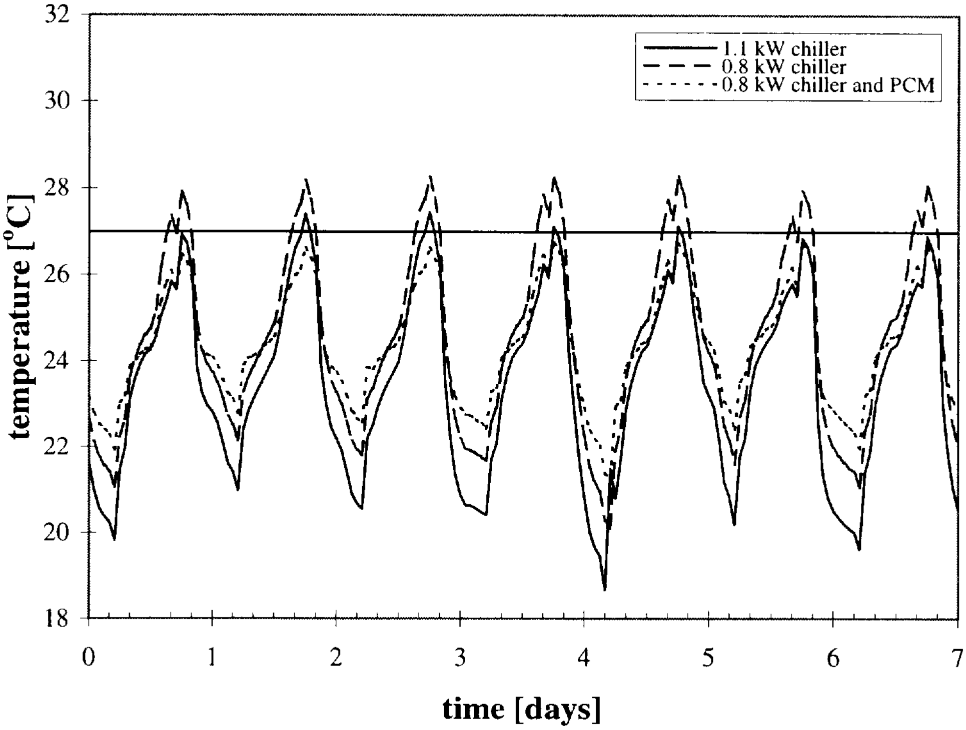

Figure 2. Comparison of indoor air temperatures, CEC climate zone 4, August 23-29.

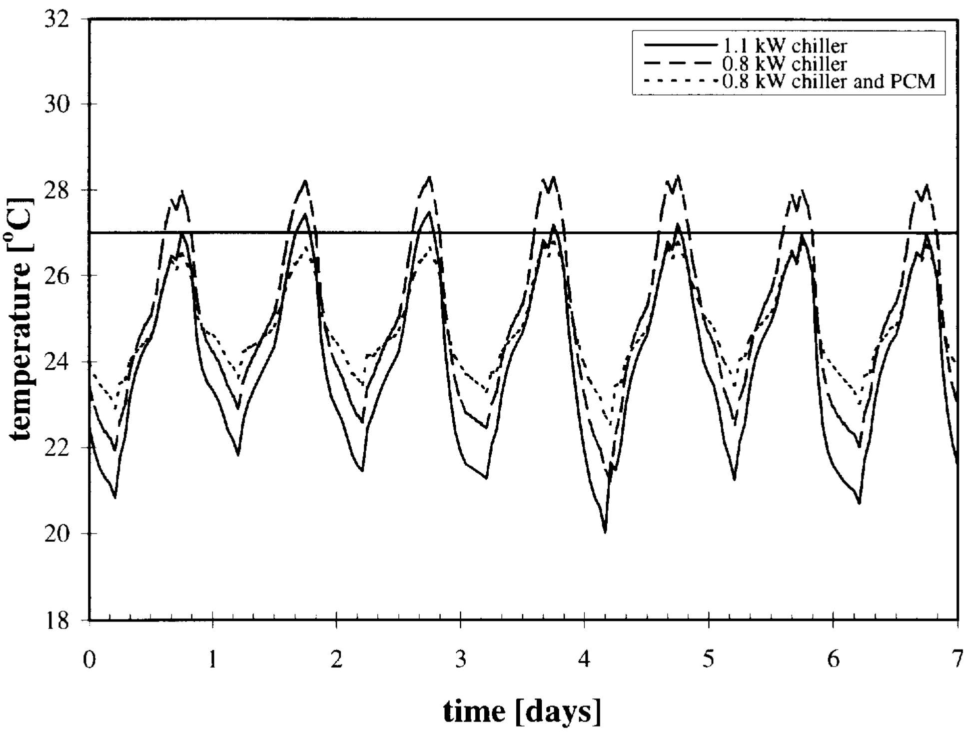

Figure 3. Comparison of operative temperatures, CEC climate zone 4, August 23-29.

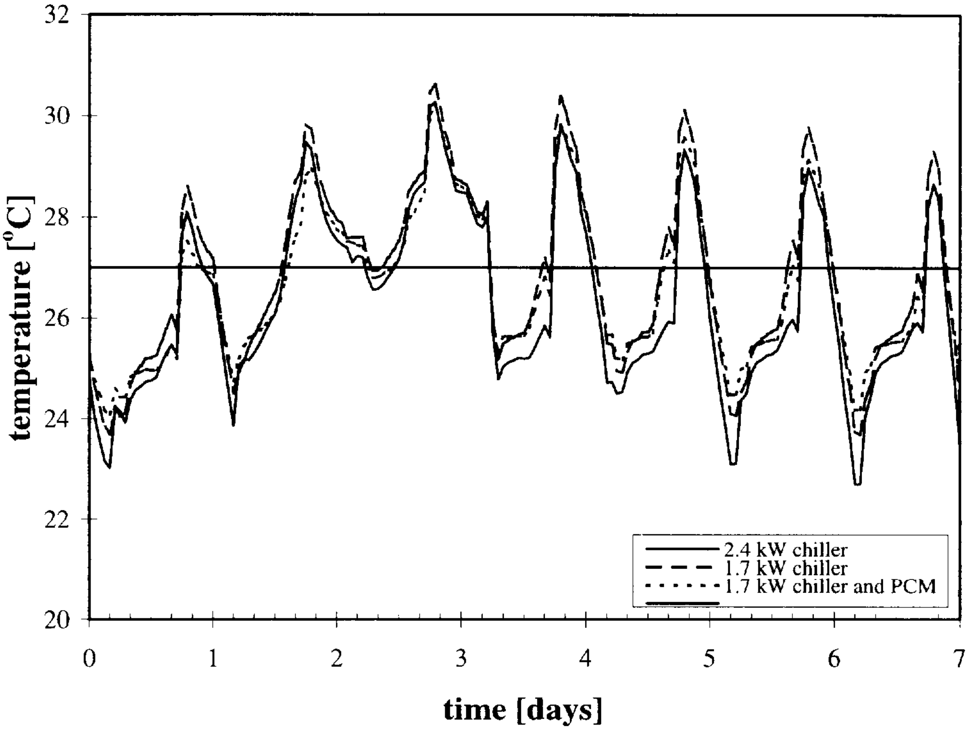

Figure 4. Comparison of indoor air temperatures, CEC climate zone 11, July 12-18.

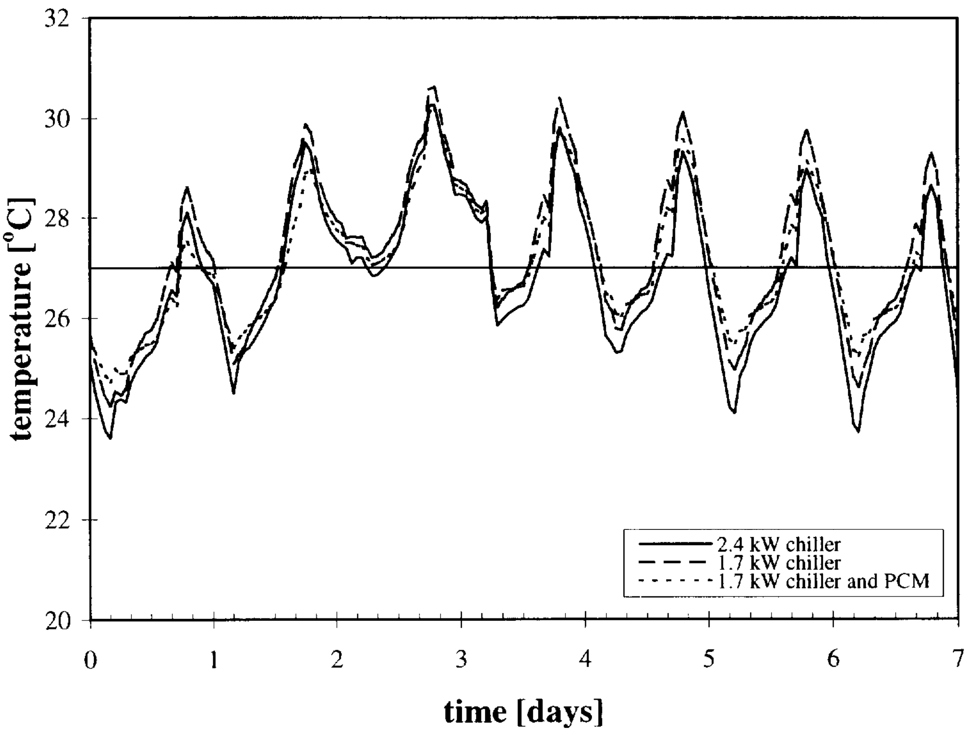

Figure 5. Comparison of indoor operative temperatures, CEC climate zone 11, July 12-18.

The results corresponding to California climate zone 11 are somewhat different from those obtained for California climate zone 4. While the indoor temperature of the space with conventional wallboard and served by the optimal chiller is maintained within comfort range (solid line in Figure 4), the indoor operative temperature increases above 27 °C during the work day (solid line in Figure 5).

When the chiller is downsized by 30%, the indoor air temperature becomes higher than the upper limit of the comfort zone at the end of the work hours on days 4, 5 and 6 (dashed line in Figure 4). The operative temperature also increases, becoming higher than 28 °C on days 4, 5 and 6 (dashed line in Figure 4). In the space with PCM wallboard and cooled by the 1.7 kW chiller, the PCM wallboard stores some heat, causing the amplitudes and peaks of the indoor air and operative temperatures to decrease, but not enough to maintain comfort.

Analysis of results

The failure of PCM wallboard to reduce the cooling load in the space located in California climate zone 11 can be explained based on the specific enthalpy of the wallboard. As Figure 6 shows, the PCM wallboard absorbs much more heat than conventional wallboard when it warms from 20 °C to 30 °C. However, once it is fully charged (temperature above 30 °C), PCM wallboard behaves similarly to conventional wallboard.

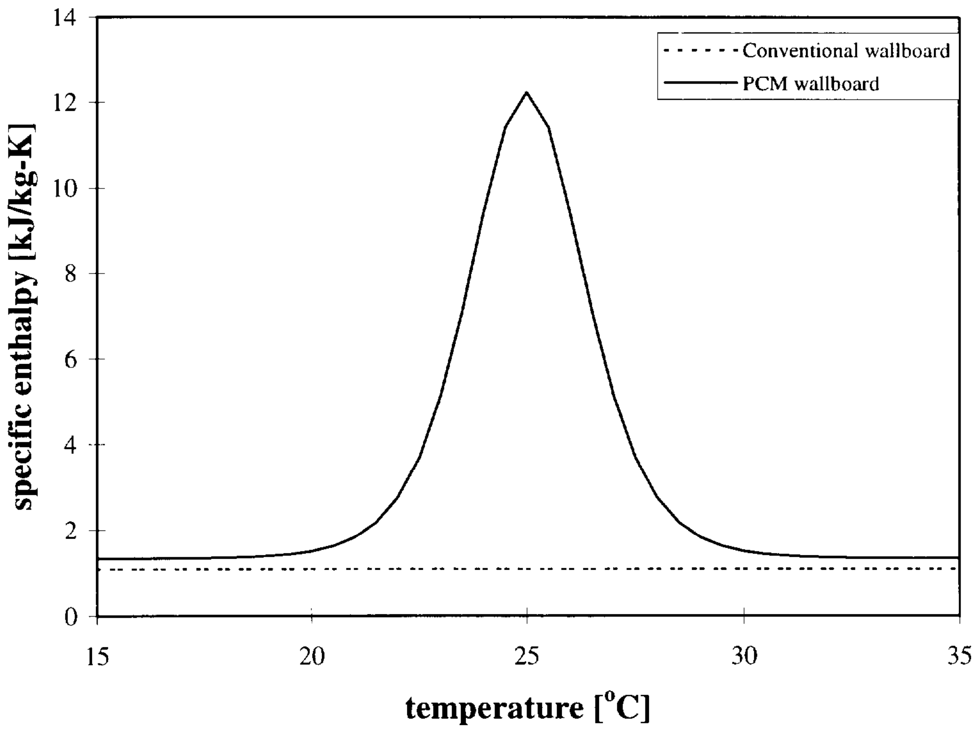

Figure 6. Comparison of the specific enthalpies of modeled conventional and PCM wallboard.

To allow the PCM wallboard to reduce the cooling load inside the space by storing a significant quantity of heat during the day, some mechanism must be provided for its discharge at night. Figure 2 shows that, in California climate zone 4, night ventilation with the system fan corresponding to the 0.8 kW chiller forces the indoor air temperature to drop under 23 °C. This in turn forces the PCM wallboard to discharge at least partially, and allows it to store part of the next day's cooling load.

In comparison, Figure 4 shows that night ventilation with the system fan corresponding to the 1.7 kW chiller cannot force the indoor air temperature to drop below 24 °C at the beginning of days 4 and 5. The corresponding radiant temperature is above 27 °C, therefore the specific enthalpy of the PCM wallboard has passed its peak. When the PCM wallboard begins to store some of the next day's heat, it charges quickly, then its capacity to store heat decreases. Operating the PCM wallboard in a temperature range close to the peak of its specific enthalpy therefore results in a decreased capability to reduce the space cooling load.

The temperature range in which the PCM wallboard operates varies with the night ventilation air temperature. While the outside air temperature drops below 15 °C during the peak week in California climate zone 4, it does not drop much below 20 °C during the peak week in California climate zone 11. Figure 6 shows that the PCM wallboard is not fully discharged unless its surface temperature drops below 20 °C. In general, this happens when the cooling air is supplied at about 18 °C. Consequently, mechanical night ventilation with outside air at temperatures of 20 °C or higher will have a reduced potential to discharge PCM wallboard.

Conclusions

The use of PCM wallboard coupled with mechanical night ventilation in office buildings offers the opportunity for system downsizing in climates where the outside air temperature drops below 18 °C at night. In the case of the IEA prototype building located in California climate zone 4, we estimate that PCM wallboard can reduce the peak cooling load by 28%.

In climates where the outside air temperature remains higher than 18 °C on the peak night, the use of PCM wallboard coupled with mechanical night ventilation *only* will not lead to peak power savings. In such climates, mechanisms such as chiller-assisted space precooling could be used during night and morning hours to lower the indoor air and operative temperatures into the comfort range.

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