Phase Change Wallboard as an Alternative to Compressor Cooling in Californian Residences?

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Large thermal storage devices have been used in the past to overcome the shortcomings of alternative cooling sources, or to avoid high demand charges. The manufacturing of phase change material (PCM) implemented in gypsum board, plaster or other wall-covering material, would permit the thermal storage to become part of the building structure. PCMs have two important advantages as storage media: they can offer an order-of-magnitude increase in thermal storage capacity, and their discharge is almost isothermal. This allows the storage of high amounts of energy without significantly changing the temperature of the room envelope. As heat storage takes place inside the building, where the loads occur, rather than externally, additional transport energy is not required.

RADCOOL, a thermal building simulation program based on the finite difference approach, was used to numerically evaluate the latent storage performance of treated wallboard. RADCOOL was developed in the SPARK environment in order to achieve compatibility with the new family of simulation tools under development at the Lawrence Berkeley National Laboratory (Buhl et al. 1990).

Simulation results for a living room with high internal loads and weather data for Sunnyvale, California, show significant reduction of room air temperature when conventional wallboards are replaced with PCM-treated wallboards. Extended storage capacity obtained by using double wallboard is able to keep the room air temperatures within the comfort limits without using any mechanical cooling.

BACKGROUND

Cooling of residential California buildings contributes significantly to electrical consumption and peak demand mainly due to very poor load factors in milder climates. The peak cooling load requires utilities to build, operate and maintain peak-power plants, and size their distribution network accordingly. For the building owner, the peak-cooling load determines the size of the equipment and the choice of the cooling source. Several steps can be taken to downsize the cooling systems and to allow switching to low-energy cooling sources:

- incorporate facades which provide an effective shelter from ambient conditions
- install highly efficient thermal distribution systems (e.g., hydronic systems)
- apply thermal conditioning by radiation rather than by convection
- provide thermal mass.

Large thermal storage devices have been used in the past to overcome the shortcomings of alternative cooling sources, or to avoid high demand charges. Buildings designed to make use of thermal storage include features which increase thermal mass. These may be used for storage only, or may serve both as storage and as structural elements. Several structural materials satisfy the requirements for sensible heat storage; these include concrete, steel, adobe, stone and bricks.

Latent heat storage uses a phase change material as a storage medium. This concept is particularly interesting for light-weight building construction. While undergoing phase change—freezing, melting, condensing, or boiling—a material absorbs or releases large amounts of heat with small changes in temperature. Phase change applications typically involve liquid/solid transitions. The phase change material (PCM) is solidified when cooling resources are available, and melted when cooling is needed. PCMs have two important advantages as storage media: they can offer an order-of-magnitude increase in heat capacity, and their discharge is often almost isothermal (Feustel et al., 1992).

The manufacturing of phase change material (PCM) imbedded in gypsum board, plaster or other wall-covering material would allow the thermal storage to become part of the building's structure. This would permit the storage of high amounts of energy without changing the temperature of the room envelope. Since storage would take place inside the building where the loads occur, rather than outside, additional transport energy would not be required. Considering that more than 7 billion square meters of plaster board are being produced annually in the US, PCM-treated wallboard could have a significant impact on the utility peak. At the same time, it could help to moderate temperature swings and improve thermal comfort in homes (E-Source, 1993). So far, only samples of PCM-treated wallboard exist. (For previous research, please review Feustel, 1995.)

Phase change materials can only store energy, but not remove it. In passive applications of structural thermal storage, the heat is being released into the room as soon as the room air temperature falls below the phase change temperature. This heat release mechanism keeps the surface temperatures of the room envelope at a high temperature level for a long time. This has certain advantages for the heat transfer mechanism during the discharge of the thermal storage.

Besides the passive application, treated wallboard can be coupled with a hydronic loop. Combining continuous discharge and phase change material allows the discharge of thermal energy storage without releasing the energy back into the conditioned space.

PHYSICAL PROPERTIES OF TREATED WALLBOARD

As all organic PCM will continue to burn in normal atmospheric conditions after it has been ignited, potentially severe fire-hazards related to PCM-treated wallboard exist. Two tested methods have shown promising results in eliminating the fire hazard for treated wallboards: limiting the amount of PCM to 20%, and sequentially treating the wallboard with PCM, and with an insoluble fire retardant.

Table 1 shows the physical properties for wallboard as measured by Oak Ridge National Laboratory (Tomlinson and Heberle 1990). The physical properties shown represent wallboard treated with PCM by means of post-manufacturing imbibing of liquid PCM into the pore space of the wallboard (Salyer and Sircar 1993).

Only ultra-pure paraffins melt and freeze sharply at a given temperature (Salyer and Sircar, 1990). Mixtures of PCM show a region of temperatures where melting takes place (Egolf and Manz 1994). Results from experimental studies and simulation exercises showed clearly that the treated wallboard does not act like an ideal storage material, which would melt and freeze at a specific temperature. Comparison between measured data and simulation results for the dynamic behavior of a stack of wallboards showed that the best agreement was obtained if the specific heat as a function of temperature was modeled by the typical triangular-shaped curve (Salyer and Sircar 1993).

NUMERICAL STUDY

The dynamic thermal performance of PCM-treated wallboard was studied in a residential building in Sunnyvale, California.

Building Description

The thermal building simulation model used in this study is the single-zone model RADCOOL (Stetiu et al, 1995). The model is based on the finite difference approach; each wall is divided in several layers, which allows the modeling of multi-layer walls. The zone being modeled is a living room with 35m^2 floor area and two exterior walls. The longer of the exterior walls (7 m) is facing West; the shorter (5 m) is facing South. The window area (shading factor 55% (as defined by ASHRAE 1993)) is 20% of the exterior wall area. The opaque part of the walls has a U-value of 0.266

Table 1. *PCM Wallboard Characteristics*

Wallboard (% in weight)	Density kg/m^3	Specific Heat Capacity kJ/kg-K	Conductivity W/m-K	Latent Heat Capacity kJ/kg
Conventional	696	1.089	0.173	0
10% PCM	720	1.215	0.187	19.3
16% PCM	760	1.299	0.192	31.0
20% PCM	800	1.341	0.204	38.9
30% PCM	998	1.467	0.232	58.3

W/m^2K (R-21), while the double-pane windows have a U-value of 0.95 W/m^2-K (R-6). The ceiling U-value is 0.17 W/m^2-K (R-32 for insulation). The attic is vented and well shielded by means of a radiant barrier. The floor is made of a 0.1 m concrete slab above 1.0 m of sand. The temperature below the sand is assumed to be constant at 20° C.

All the walls and the ceiling are covered with PCM-treated wallboard (0.015 m) containing 20% paraffin with a melting temperature of 25° C and a melting range of $\tau = 4K$. To simplify the boundary conditions, we assumed that no heat is being transferred to the adjacent rooms. The interior walls are therefore treated as adiabatic in the center of the wall.

The living room is occupied by four persons from 6:00 in the morning until 22:00 hours at night. During the time of occupancy there is a constant additional load of 150W (television) and also 100 W of electric lights for the last two hours of the occupied period.

The thermal storage is being discharged by means of ventilation.

Weather Data

The climatic conditions chosen represent Sunnyvale, California (see California Energy Commission, 1991, climate zone ctz04c). Sunnyvale is located at the southern tip of the San Francisco Bay.

Figure 1 shows the ambient temperature profile for the period of June 11 through 17. While the first three days of the period chosen are relatively mild, on day 4, outdoor temperatures reach almost 40 °C.

Even though the ambient temperature profile shows a peak on the fourth day of the chosen period, the solar radiation is surprisingly stable for the 7-day period. Figure 2 shows the calculated solar energy received by the West wall.

The peak solar radiation on the West wall reaches 750 to 800 W/m^2 on each of the days during the considered period.

Ventilative Cooling

In this example, the supply air is not being cooled. Ten air changes per hour (ACH) of outside air provide ventilative cooling if the ambient air is below 25 °C. Above 25 °C, the ventilation rate is being reduced to 1.5 ACH. In case the outside air temperature is below 19 °C, outside air is mixed with recirculation air in order to keep the supply air temperature at the 19 °C level.

Figure 3 shows the development of the indoor air temperature for the chosen period. On days four through six, air temperatures reach well above 30 °C, if the room is equipped with conventional wallboard. With PCM-treated wallboard, the fourth day shows a significant decrease of the peak temperature from 31 to 28 °C, while the temperature drop for the following two days is much smaller. The shape of the temperature curves for PCM-treated wallboard signal the saturation of the latent storage capacity.

The temperature differences between the wall temperatures and the air temperature for conventional wallboard are shown in Figure 4. The differences range from -1 K to 4 K for the West wall and -0.7 K to 3 K for the interior wall. With the reduced cooling capability of the air, surface temperatures lower than the air temperature are experienced at peak temperatures. Highest temperature differences are

Figure 1. *Ambient Air Temperature Profile for the Period June 11 through 17*

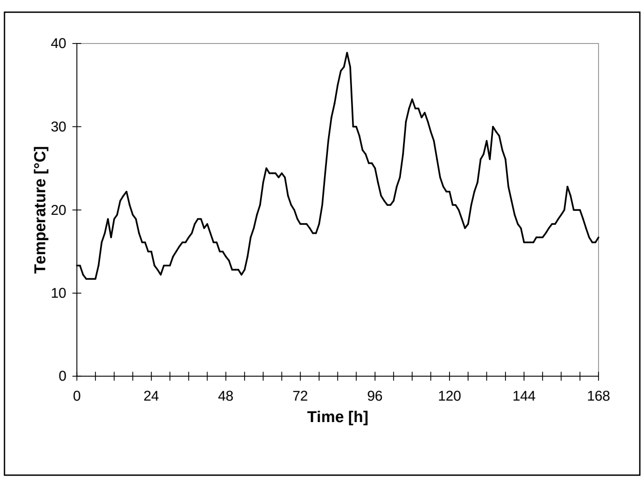


Figure 2. *Calculated Solar Energy received by the West Wall*

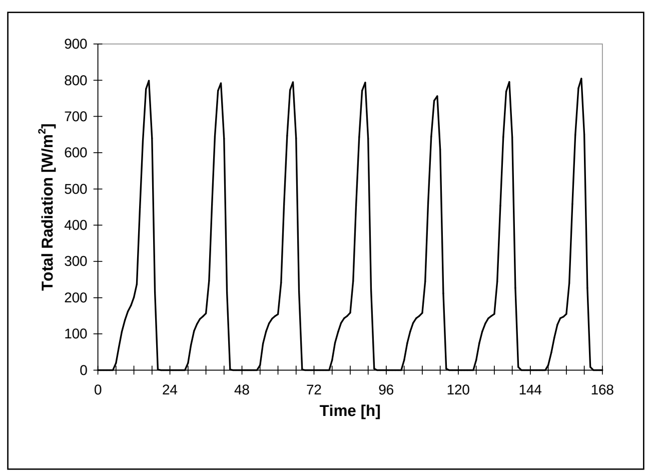


Figure 3. *Indoor Air Temperature Profile with Ventilative Cooling*

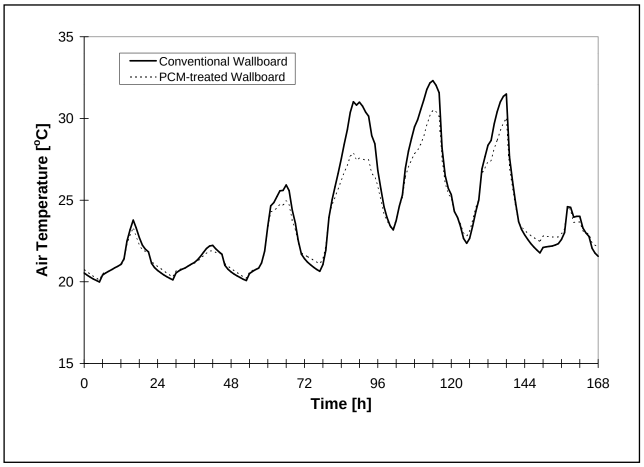
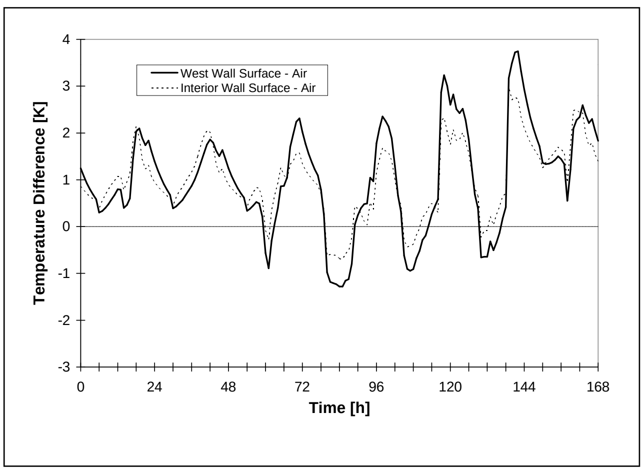


Figure 4. *Temperature Difference between the Wall Surfaces and the Air for Conventional Wallboard*

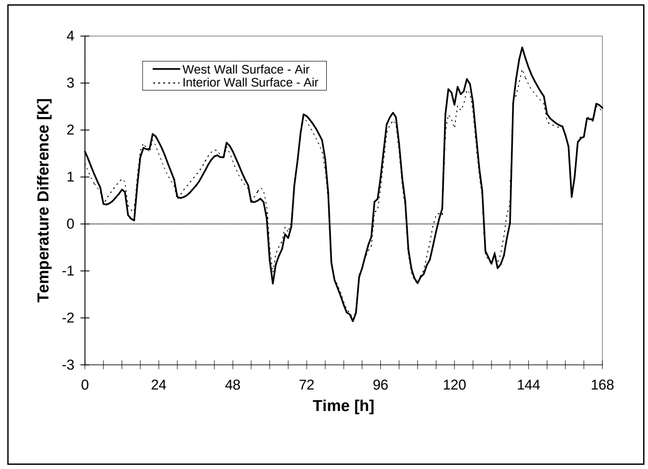


observed when the ventilative cooling starts in the late afternoon.

As long as there is latent storage capacity available, the surface temperatures of the PCM-treated wallboard are closer to the air temperature at peak than the surface temperatures of conventional wallboard. It should be mentioned that the temperature differences for the surfaces of the interior and exterior walls are much smaller for PCM-treated wallboard than those of conventional wallboard (compare Figure 4 and Figure 5). This suggests that some of the energy transmitted through the exterior wall is being stored in the wall before reaching the interior surface.

Surface temperatures of PCM-treated wallboard seem to be independent of their location. Temperature differences reach as low as -2 K during the peak hours. One should keep in mind that the air temperatures for the PCM-treated wallboard are already lower than those for conventional wallboard (see Figure 5).

Figure 5. *Temperature Difference between the Wall Surfaces and the Air for PCM-Treated Wallboard*



The surface temperature is very important for the perceived comfort. The operative temperature, T_o, which is the perceived temperature, is the uniform temperature of an imaginary enclosure with which a person exchanges the same sensible heat by radiation and convection as in the actual environment (ASHRAE, 1985).

Figure 4 and Figure 5 show the danger of using only the air temperature as a comfort criterion instead of the operative temperature. Sensing only air temperature might lead to uncomfortable conditions or might provoke thermostat settings which might create increased energy consumption. Many thermal building simulation models do not calculate surface temperatures and therefore are not able to determine the operative temperature. For all-air systems, this might result in undersized equipment and lower predictions of energy consumption.

Figure 6 shows that operative temperatures of 27.3 °C are obtained on the fourth day, and that, due to saturation of the latent storage, peak temperatures of 30 °C are reached on day five.

Figure 7 shows the variation of the specific enthalpy with time. When comparing the values for conventional wallboard with those for the PCM-treated wallboard, one has to keep in mind that the absolute values of the specific enthalpy are not important. The ability to store heat at an increase of temperature, as expressed by the specific heat capacity, is more important than the value of the enthalpy itself.

Figure 6. *Operative Temperature Profile with Ventilative Cooling*

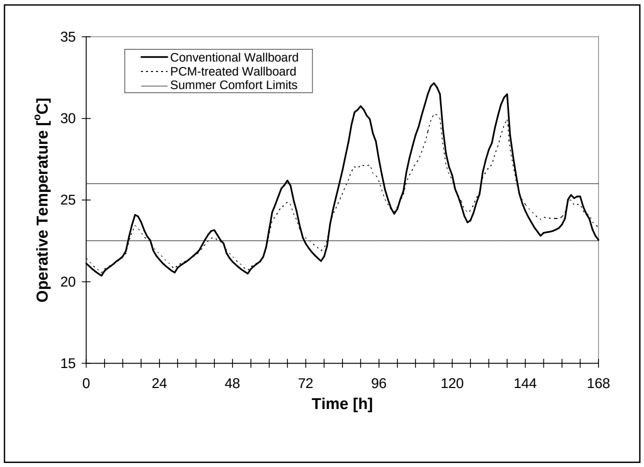
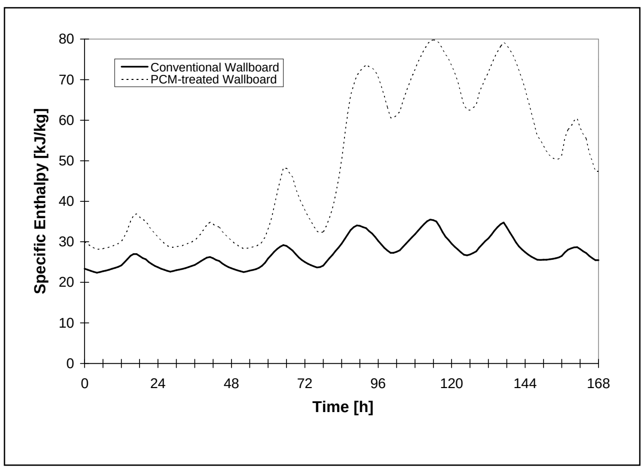


Figure 7. *Specific Enthalpy Variation for the Wallboard of the West Wall with Ventilative Cooling*



The higher specific sensible heat capacity for PCM-treated wallboard is due to the paraffin content. The specific enthalpy reaches 80 kJ/kg on days five and six, which shows that the end of the mushy region is reached. The graph clearly shows that the latent storage capacity is being exhausted during the three day hot spell. After the fourth day, PCM-treated wallboard already contains a specific enthalpy of 60 kJ/kg. And even at the end of the seventh day, the latent storage is not being fully discharged.

The reason for the high enthalpy values are the high night-time indoor air temperatures. During the night between the fourth and the fifth day, night-time air temperatures do not fall below 23 °C, and in the following night, temperatures are still above 22 °C. These air temperatures, and the short period during which they occur, do not allow sufficient discharge of the PCM.

Ventilative Cooling and Double Wallboard

In order to increase the thermal storage capacity of the structure, double thickness wallboard can be installed. The operative temperature profile for PCM-treated wallboard with double thickness (Figure 8) shows the significantly better performance than that for single sheets (shown in Figure 6). Particularly for the fifth and sixth day, significant temperature reductions are being reached when compared to double conventional wallboard. On the sixth day, the highest operative temperature for PCM-treated double wallboard is reached at 28.2 °C, while the peak temperature for double conventional wallboard occurs at 31.5 °C on day five. Again, the performance for the PCM-treated wallboard could be enhanced if the possibility to discharge the latent storage was available.

Comparison of Thermal Storage Potential

When compared with single-conventional wallboard, doubling the thickness of the wallboard only provides minimal reduction of the peak operative temperatures (see Figure 9). Maximum reduction values are below 1 K. The use of PCM-treated wallboard provides a good temperature reduction for the first day of the heat spell, but saturation of the latent storage diminishes the reduction potential. Doubling PCM-treated wallboard shows a significant improvement for the temperature reduction potential. After two days of reducing the operative temperature by more than 4 K, the third day of the heat wave still sees a temperature reduction of 3.3 K.

CONCLUSIONS

PCM-treated wallboard has the potential to convert light buildings, as often found in earthquake-prone areas, into thermally heavy constructions. In Californian climates with

Figure 8. *Operative Temperature Profile with Ventilative Cooling*

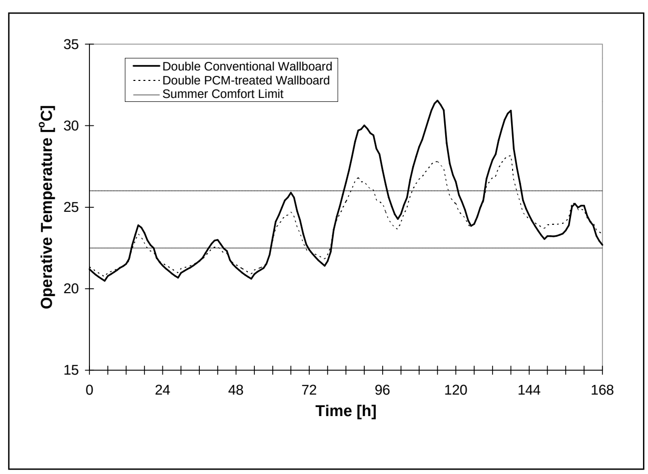
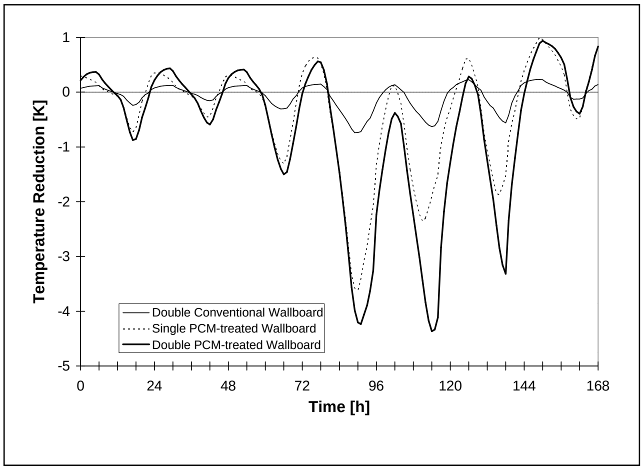


Figure 9. *Ventilative Cooling; Temperature Reduction of Operative Temperature for Double Conventional and Single- and Double PCM-treated Wallboard when compared with Single-Conventional Wallboard*



large diurnal swings thermally heavy residences can be kept comfortable for most of the year without applying mechanical cooling or evaporative cooling, by using night-time ventilation to discharge the latent storage of the wallboard. The high surface-to-volume ratio of the wallboard helps to utilize the storage capacity over a short cycle (24 hours). Compared to strictly sensible thermal storage, the storage density of PCM-treated wallboard is much higher, which provides the necessary storage in a relatively thin layer.

The examples show. that longer cycles between charge and discharge can be mastered with higher thermal storage capacity. The additional storage capacity can be provided by multiple layers or thicker layers of treated wallboard.

Cooling the envelope of a room by means of air transport through the room provides a very inefficient way of heat transfer. Air movement close to the walls, which determines the amount of heat being transferred, is relatively small. Particularly in periods of relatively high ambient temperatures during the night, it would be beneficial to force the supply air along the wall surfaces to facilitate a good heat exchange.

The results suggest that in dry transition climates, houses with internal loads smaller than being proposed for this paper, could be cooled by a combination of PCM-treated wallboard and ventilative cooling.

FUTURE WORK

In order to determine the amount of thermal latent storage that would keep the operative temperature within the comfort zone for different California climates, a parametric study, taking internal loads and weather parameters into account, will be performed.

The limited discharge capacity of ventilative cooling during heat spells calls either for increased storage capacity or can cause the thermal storage to fail. Alternative ways to discharge the latent storage have to be investigated. Coupling latent thermal storage with the ground by means of a hydronic loop is on the research agenda.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies of the US Department of Energy under Contract No. DE-AC03-76SF00098 in cooperation with the Alternatives to the Compressor Cooling Project sponsored by the California Institute for Energy Efficiency.

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