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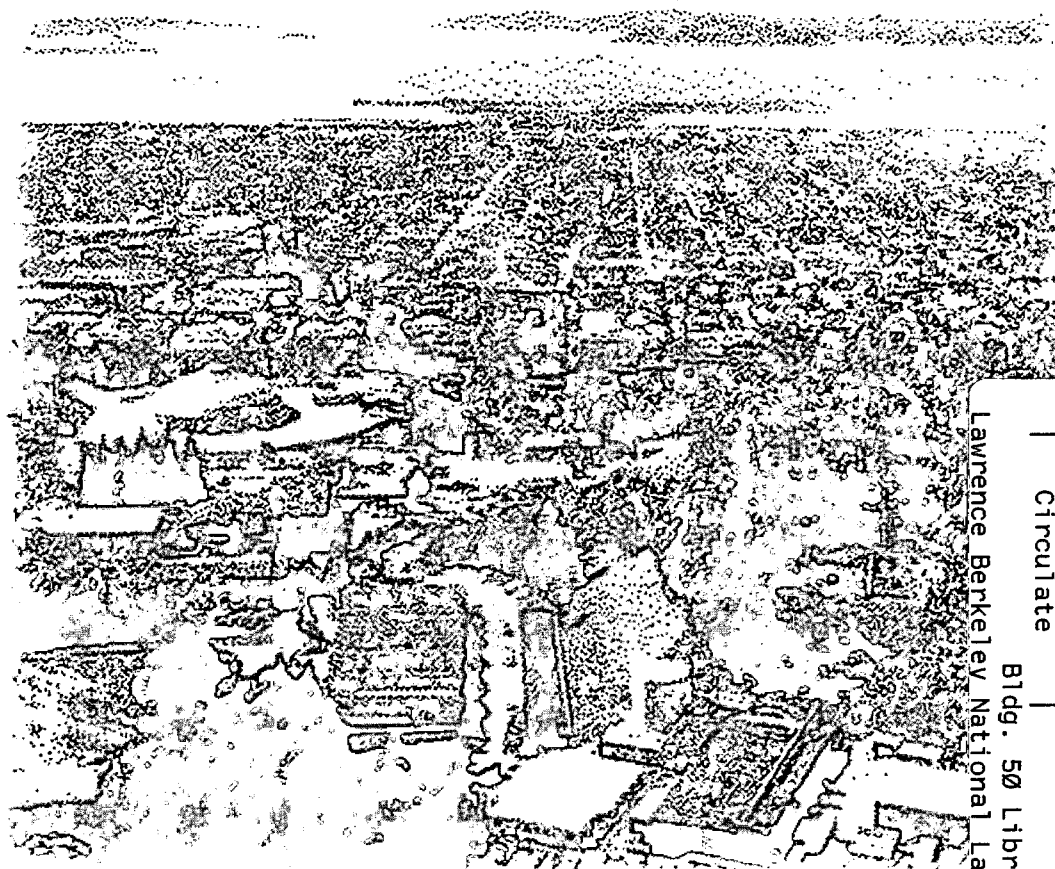1997-04-01

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Helmut E. Feustel and Corina Stetiu
**Environmental Energy
Technologies Division**

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ABSTRACT

Cooling of residential California buildings contributes significantly to electrical consumption and peak power demand mainly due to very poor load factors in milder climates. Thermal mass can be utilized to reduce the peak-power demand, downsize the cooling systems, and/or switch to low-energy cooling sources.

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.

Extended storage capacity obtained by using double PCM-wallboard is able to keep the room temperatures close to the upper comfort limits without using mechanical cooling.Simulation results for a living room with high internal loads and weather data for Sunnyvale, California, show significant reduction of room air temperature when heat can be stored in PCM-treated wallboards.

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NOMENCLATURE

β inclination [-]

ρ density [kg/m³]

τ width of the melting zone [K]

c_p specific heat [kJ/kg-K]

h specific enthalpy [kJ/kg]

h heat coefficient [W/m²-K]

k thermal conductivity [W/m-K]

T temperature [°C]

Indices

1   solid phase

2   liquid phase

r   radiative

c   convective

m   melting

o   operative

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 lightweight 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 for pure substances, their discharge is almost isothermal (Feustel et. al., 1992).

So far, only samples of PCM-treated wallboard exist. There are several approaches to treat wallboard with PCM material; however, none of these approaches has been tried in the industrial production process.

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 (E-Source, 1993). At the same time, it could help to moderate temperature

swings and improve thermal comfort in homes.

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 could 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.

THERMAL PERFORMANCE

Physical Properties of Treated Wallboard

Table 1 shows the physical properties for wallboard with a homogenous distribution of PCM material as measured by Oak Ridge National Laboratory (Tomlinson and Heberle, 1990). Unfortunately, the same data is not available for wallboard treated with PCM encapsulated in pellets.

Table 1: *PCM Wallboard[1] Characteristics*			
Wallboard	Density	Specific Heat	Conductivity	Latent Heat
	kg/m^3	kJ/kg-K	W/m-K	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

As all organic PCM will continue to burn in normal atmospheric conditions after igniting, 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 plasterboard with PCM, and with an insoluble fire retardant (Salyer and Sircar, 1990).[2]

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[1] The physical properties shown represent wallboard treated with PCM by means of post-manufacturing imbibing of liquid PCM into the pore space of the plasterboard. (Salyer and Sircar, 1993).

[2] However, no determination has been attempted with regards of fire codes and to the ability of phase change wallboard to be certified in relation to them.

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 wall boards showed that the best agreement was obtained if the specific heat as a function of temperature was modeled by the typical triangular-shaped curve.

Numerical Description of Phase Change Material

As the specific heat is taken as the temperature derivative of the specific enthalpy h, the specific heat as a function of temperature shows a discontinuity at the melting temperature T_m.

The specific heat can be described by:

$$c_p(T) = \frac{dh}{dT}$$

and the enthalpy by:

$$h = \int_0^T c_p(T) dT$$

At the melting point T_m, the specific heat shows very high positive values. The thermal diffusivity $\alpha (T)$ is constant at high and low temperature levels, where we find the linear temperature regimes. While crystalline substances and eutectics show a discontinuous transition, many materials (e.g., mixtures) show continuous enthalpy curves as a function of temperature. This leads to a "mushy region" between the solid and the liquid phase. In the mushy region, the thermal diffusivity decreases, with different derivatives on both sides of the melting point. Egolf and Manz (1993) formulated the following description for the specific enthalpy:

$$h(T) = c_{p1}T + \eta_1 \qquad\qquad T \le T_m$$

$$h(T) = c_{p1}T_m + (h_2 - h_1) + c_{p2}(T - T_m) - \eta_2 \quad T > T_m$$

with

$$\eta_n = \left(\frac{h_2 - h_1}{2}\right) e^{\left(-2\frac{|T-T_m|}{\tau_n}\right)} \qquad\qquad n \in [1,2]$$

The dynamic thermal building simulation model RADCOOL (Stetiu et al, 1995) used for the analysis imposes certain restrictions regarding the use of logical statements. It was therefore necessary to find not only a continuous equation for the enthalpy, but also a function which describes the enthalpy as a function of the temperature for the whole temperature range found in buildings.
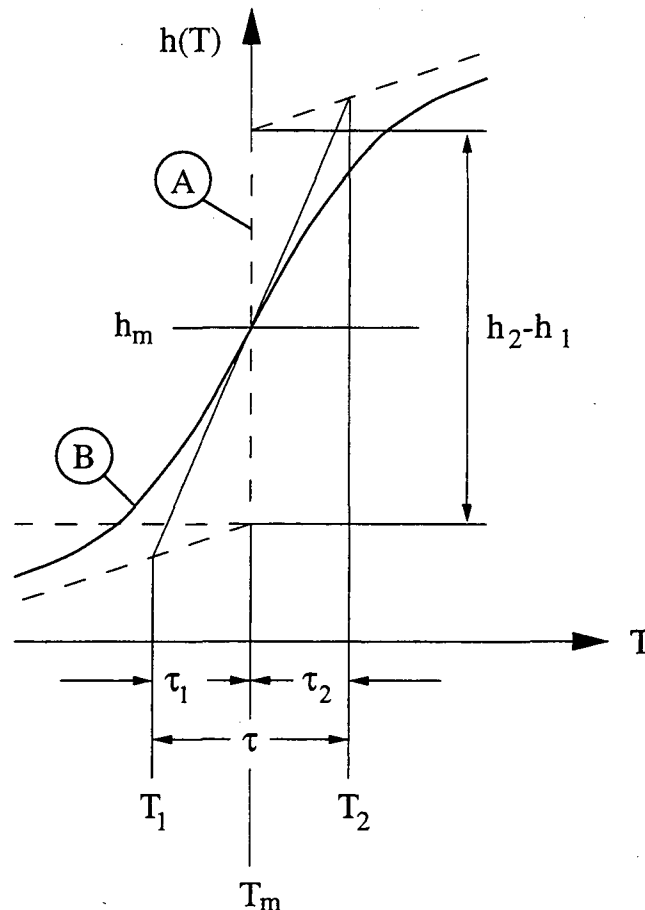

Figure 1: *Discontinuous (A) and Continuous (B) Functions for Specific Enthalpy [Egolf and Manz]*

For materials which show a symmetrical distribution of the specific heat for the melting region

$$\frac{\tau}{2} = \tau_1 = \tau_2$$

the hyperbolic tangent shows some similarity with the mushy region of the enthalpy curve. Feustel (1995) describes the simplifications which allow to describe the enthalpy and specific heat capacity as a hyperbolic function and its

derivative. The enthalpy can be described as:

$$h(T) = c_{p,const} T + \frac{h_2 - h_1}{2} \times \left\{ 1 + \tanh\left[\frac{2\beta}{\tau}(T - T_m) \right] \right\}$$

and, as the specific heat capacity is the first derivative of the specific enthalpy, we obtain:

$$c_p(T) = c_{p,const} + \frac{h_2 - h_1}{2} \times \frac{\dfrac{2\beta}{\tau}}{\cosh^2\left[\dfrac{2\beta}{\tau}(T - T_m) \right]}.$$

The functional description of the specific heat based on experimental data (see Table 1) was implemented into some of the wall modules available for RADCOOL, which is a thermal building simulation program based on the finite difference approach. RADCOOL was developed in the SPARK environment (Buhl et al, 1990) in order to achieve compatibility with the new family of simulation tools under development at the Lawrence Berkeley National Laboratory.

Tests were performed to determine the critical time-step as a function of the temperature change and the latent storage characteristics.

NUMERICAL STUDY

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 35m² 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%) is 20% of the exterior wall area. The opaque part of the walls has a U-value of 0.266 W/m²K (R-21), while the double-pane windows have a U-value of 0.95 W/m²-K (R-6). The ceiling insulation level amounts to a U-value of 0.17 W/m²-K (R-32). 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 τ = 4K. The interior walls are stud walls covered with treated gypsum board on both sides. 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 150 W (television) and also 100 W of electric lights for the last two hours of the occupied period. For more details on the simulation boundary conditions, please refer to the Appendix.

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. This and other parts of the Bay Area represent one of the California transition climates, where cooling of residential buildings is only necessary for a few days during the year.

Figure 2 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.
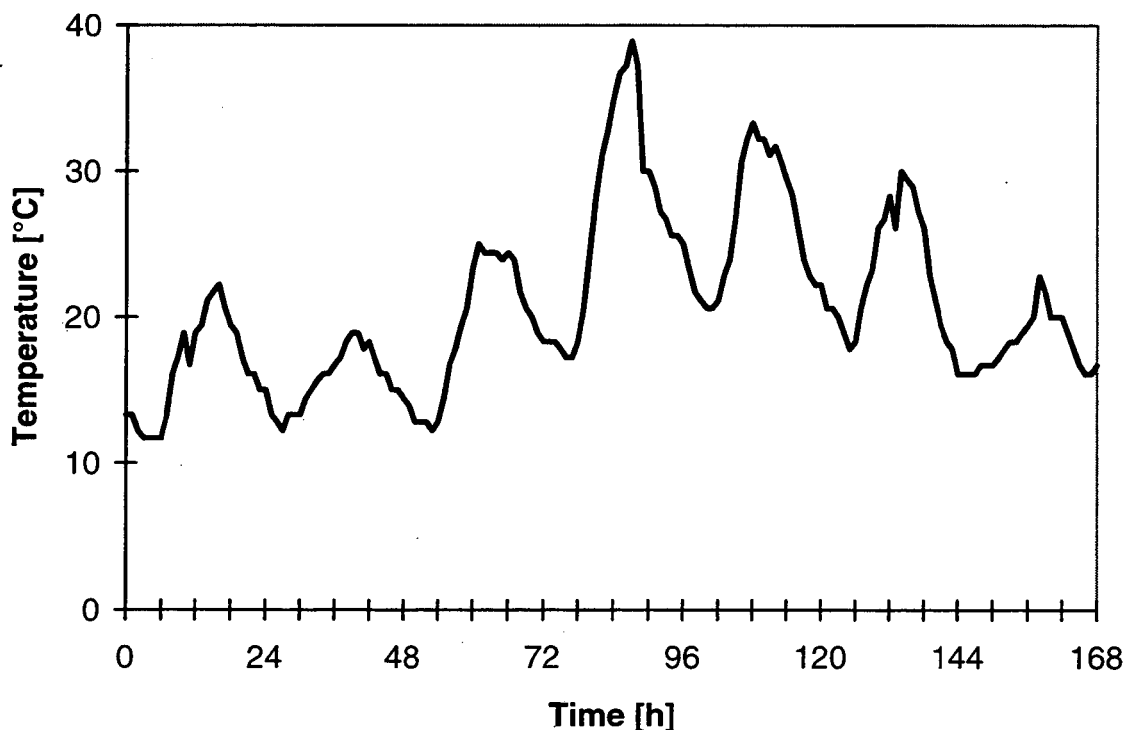

Figure 2: *Ambient Air Temperature Profile for the Period June 11 through 17*

Even though the ambient temperature profile shows a peak on the fourth day of the chosen period, the solar radiation obtained from the weather data is very stable for the 7-day period. **Figure 3** 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.
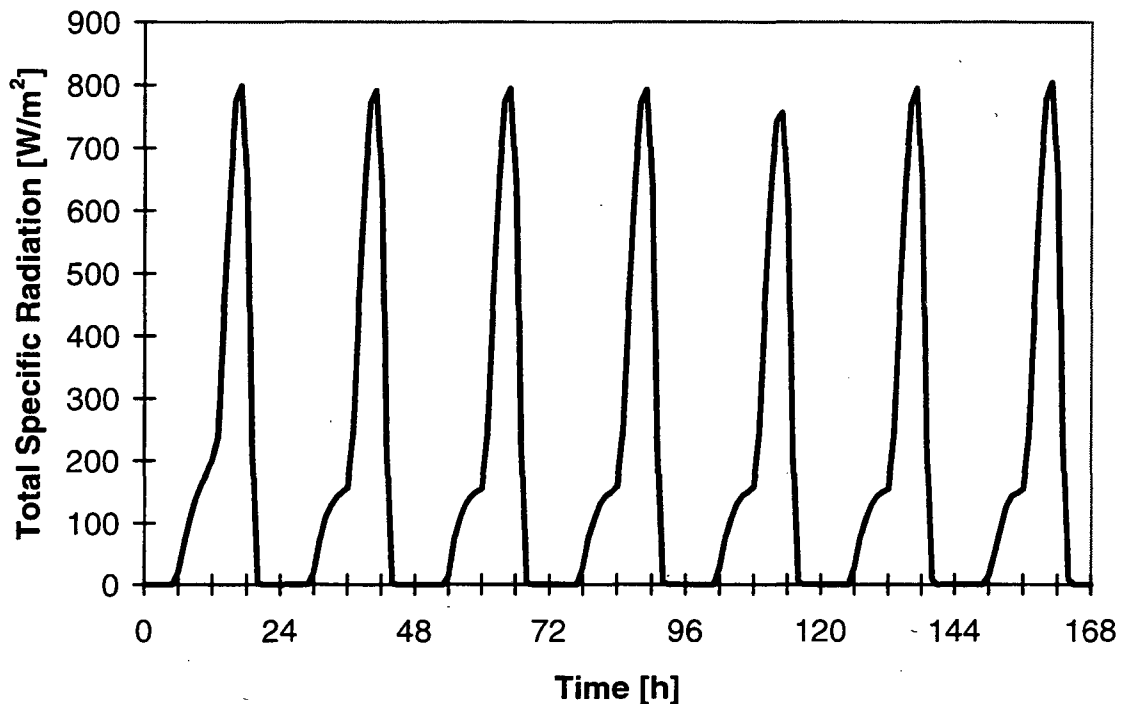

Figure 3: *Calculated Solar Energy received by the West Wall*

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 4 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 reduction 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.
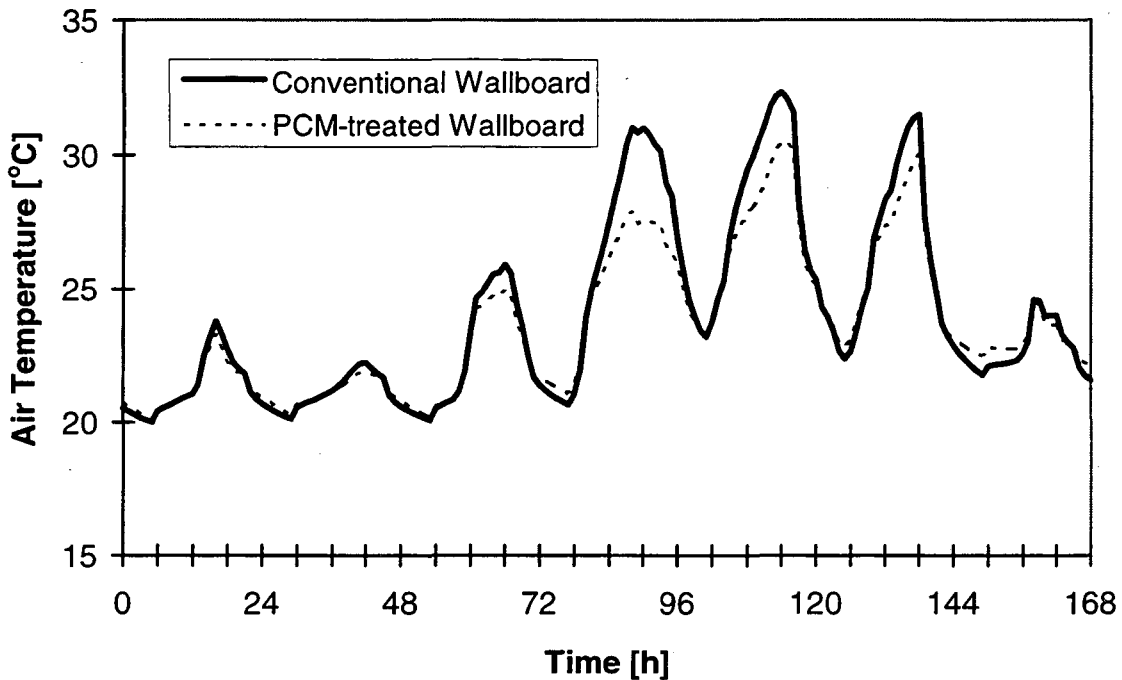
Figure 4: *Indoor Air Temperature Profile with Ventilative Cooling*

The temperature differences between the wall temperatures and the air temperature for conventional wallboard are shown in **Figure 5**. The differences range from -1 K to 4 K for the West wall and -0.7 K to 3 K for the interior walls. With the reduced cooling capability of the air, surface temperatures lower than the air temperature are experienced at peak temperatures. Highest temperature differences are 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 5** and **Figure 6**). This suggests that some of the energy transmitted through the exterior wall is being stored in the wall before reaching the interior surface.
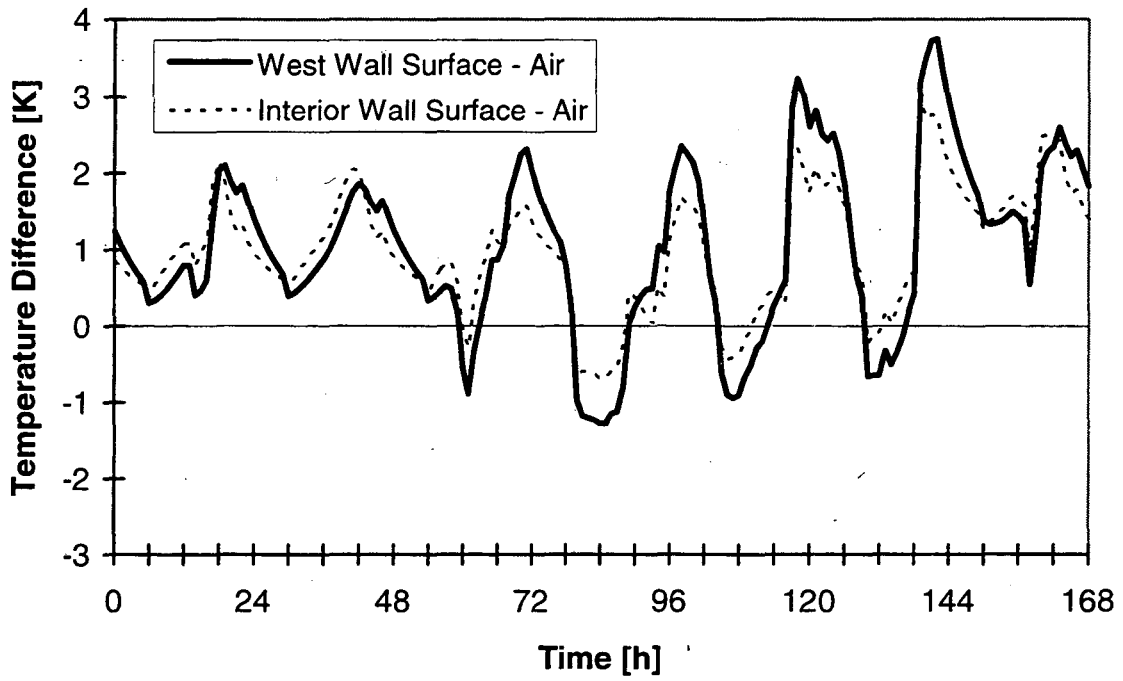
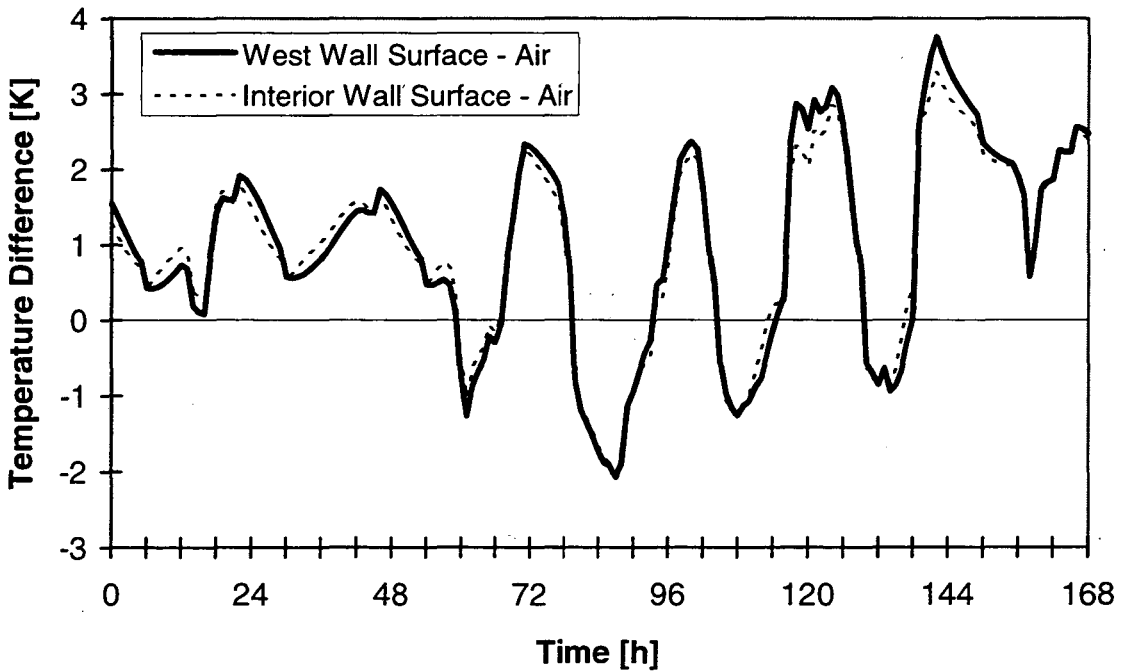**Figure 5:** *Temperature Difference between the Wall Surfaces and the Air for Conventional Wallboard*

Figure 6: *Temperature Difference between the Wall Surfaces and the Air for PCM-Treated Wallboard*

Surface temperatures of PCM-treated wallboard seem to be independent from their location (exterior walls vs. interior walls). Temperature differences between the wallboard surface and the air reach as low as -2 K during the peak hours (see **Figure 6**). One should keep in mind that the air temperatures for the PCM-treated wallboard are already lower than those for conventional 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).

$$T_0 = \frac{\left[h_r T_r + \bar{h}_c T_a\right]}{\left[h_r + \bar{h}_c\right]}$$

Figure 5 and **Figure 6** 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 that 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 7 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 8 shows the differences between the operative temperature and the air temperature. The differences for conventional wallboard and for PCM-treated wallboard follow each other very closely. The largest differences of up to 1.7 K can be observed in the late afternoon of the sixth day while negative values (operative temperature < air temperature) can be seen during the hours of peak temperature. Negative values of up to 0.9 K are calculated for the early afternoon of the fourth day.
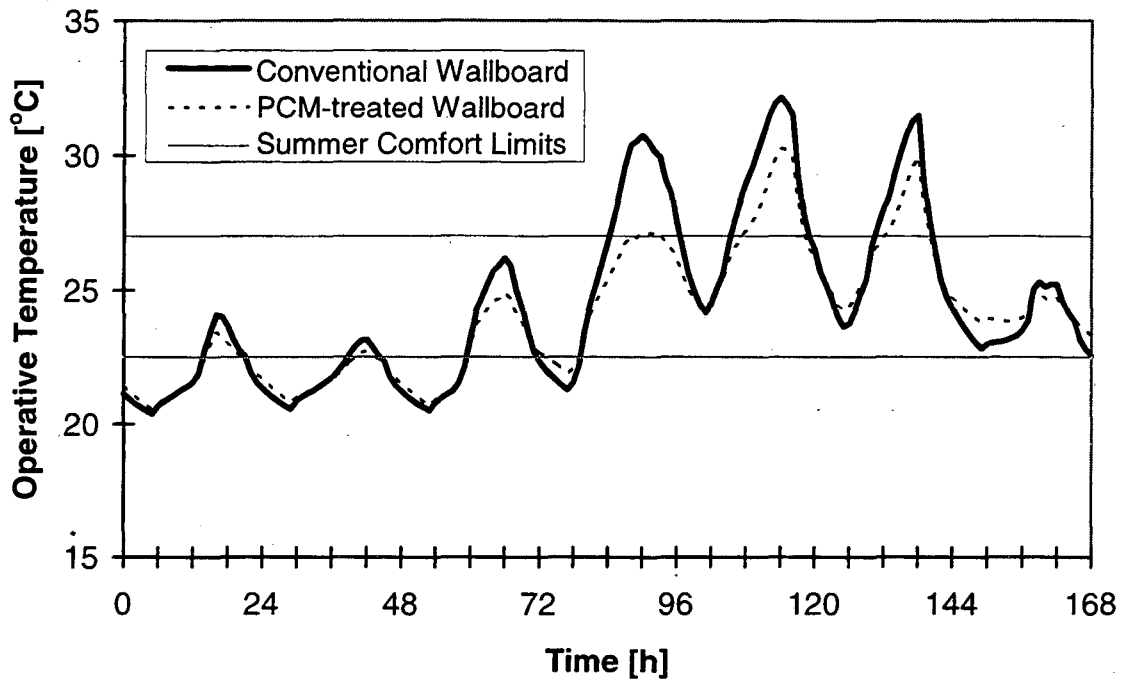
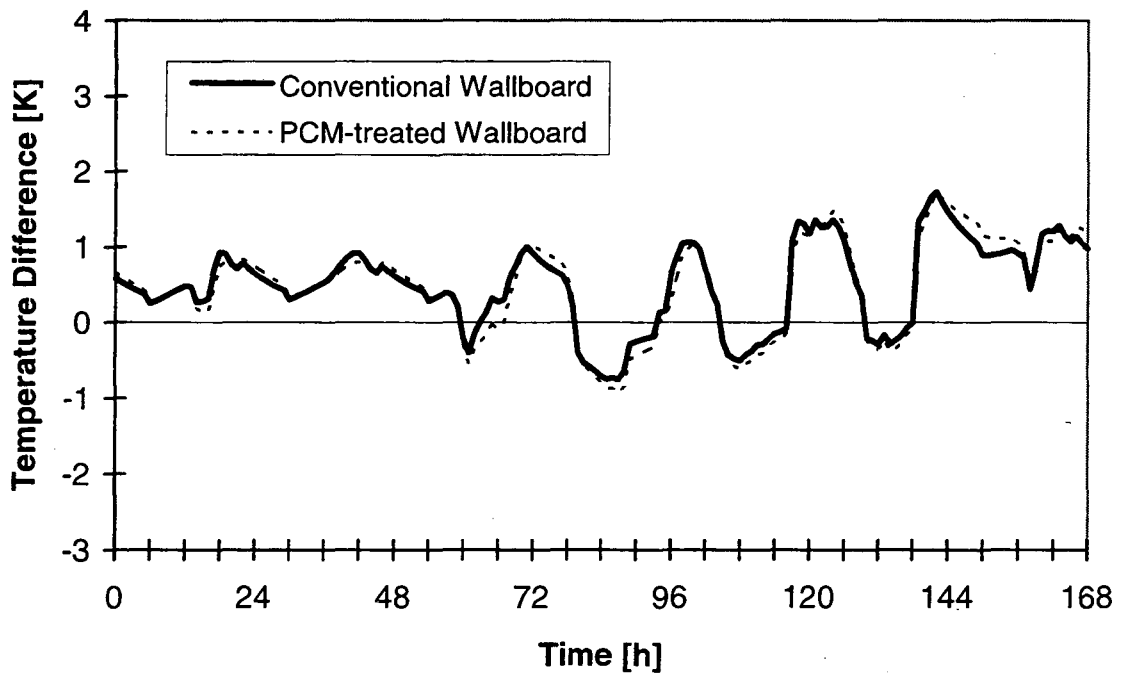**Figure 7:** *Operative Temperature Profile with Ventilative Cooling*

Figure 8: *Temperature Differences between Operative Temperature and Air Temperature with Ventilative Cooling*

Figure 9 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.

The higher specific sensible heat capacity for PCM-treated wallboard is due to the paraffin content. The specific enthalpy reaches 80 kJ/kg-K 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 days of the 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 is the high night-time indoor air temperatures. During the night between the fourth to 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 periods they occur, do not allow sufficient discharge of the PCM.
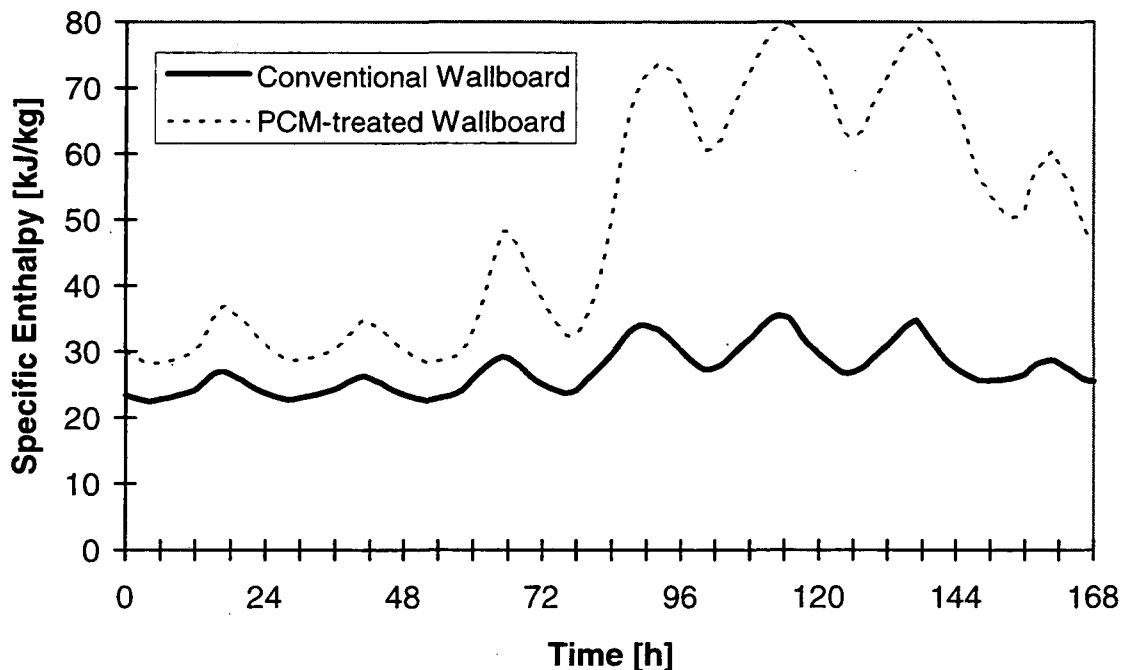
Figure 9: *Specific Enthalpy Variation for the Wallboard of the West Wall with Ventilative Cooling*

Figure 10 shows the specific heat capacity for the ventilative cooling case. Two times, in the late afternoons of the fifth and the sixth day, the specific heat

capacity reaches its minimum. During the last 18 hours of the investigated period, the heat capacity stays close to the maximum, indicating wallboard temperatures of about 25 °C.
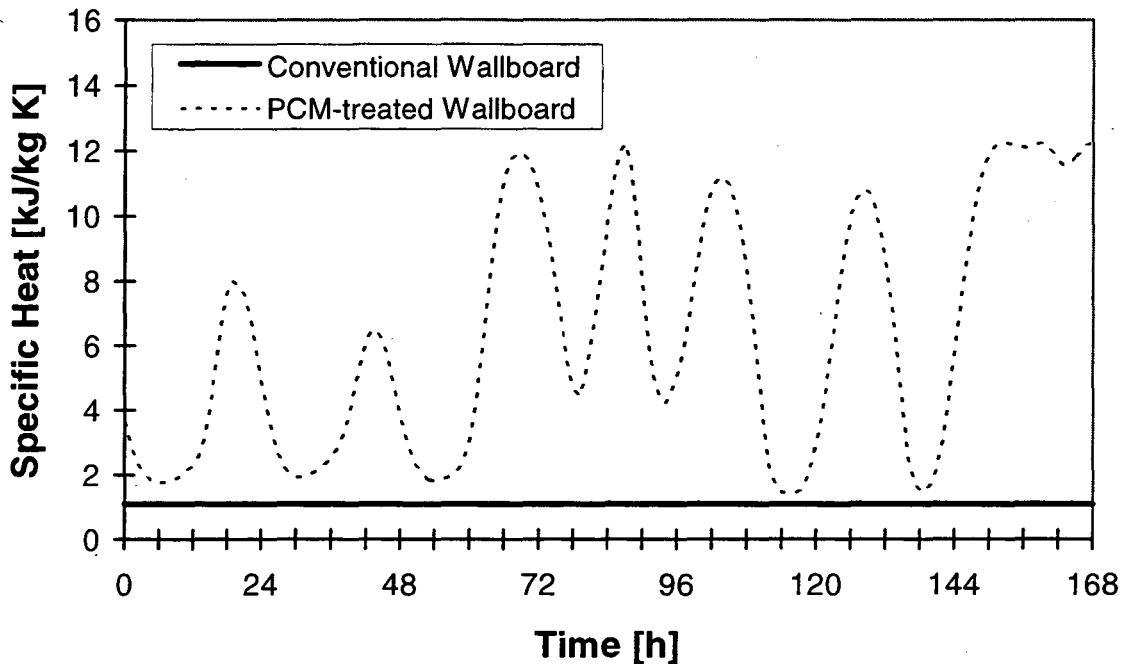

Figure 10: *Specific Heat Capacity Variation for the Wallboard of the West Wall with Ventilative Cooling*

Ventilative Cooling and Double Wallboard

In order to increase the thermal storage capacity of the structure, double thickness wallboard can be installed. **Figure 11** shows the indoor air temperature profiles for ventilative cooling, if double wallboard is installed. The temperature peaks for the case with conventional wallboard are only slightly lower than those shown in **Figure 4**. PCM-treated wallboard, however, performs much better. In this case we see significant reduction of the indoor air temperature for all three days of the heat wave.

Temperature differences between the surface temperature and the air temperature show slightly higher negative values for both conventional and PCM-treated wallboard (see **Figures 12 and 13**). For the PCM-treated wallboard, negative temperature differences of more than 2 K are calculated for the early afternoon of the fourth day. The two following days see temperature differences of up to -1.5 K and -1.2 K. When the ambient air temperature drops below 25 °C and ventilative cooling is provided, temperature differences of more than 3 K are calculated.
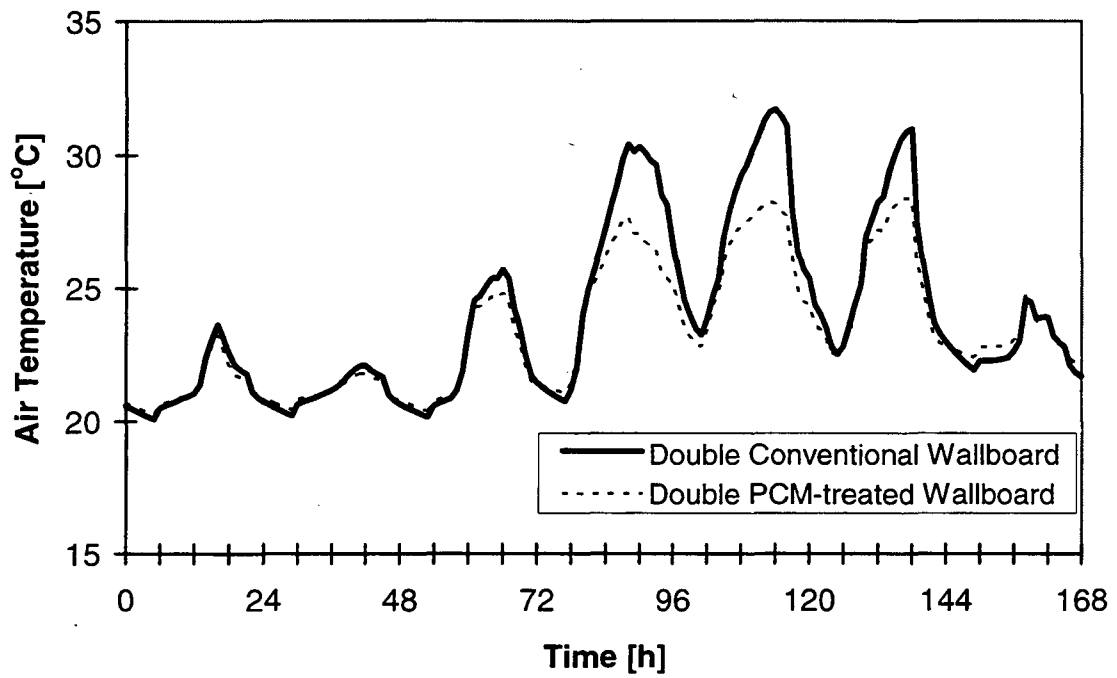
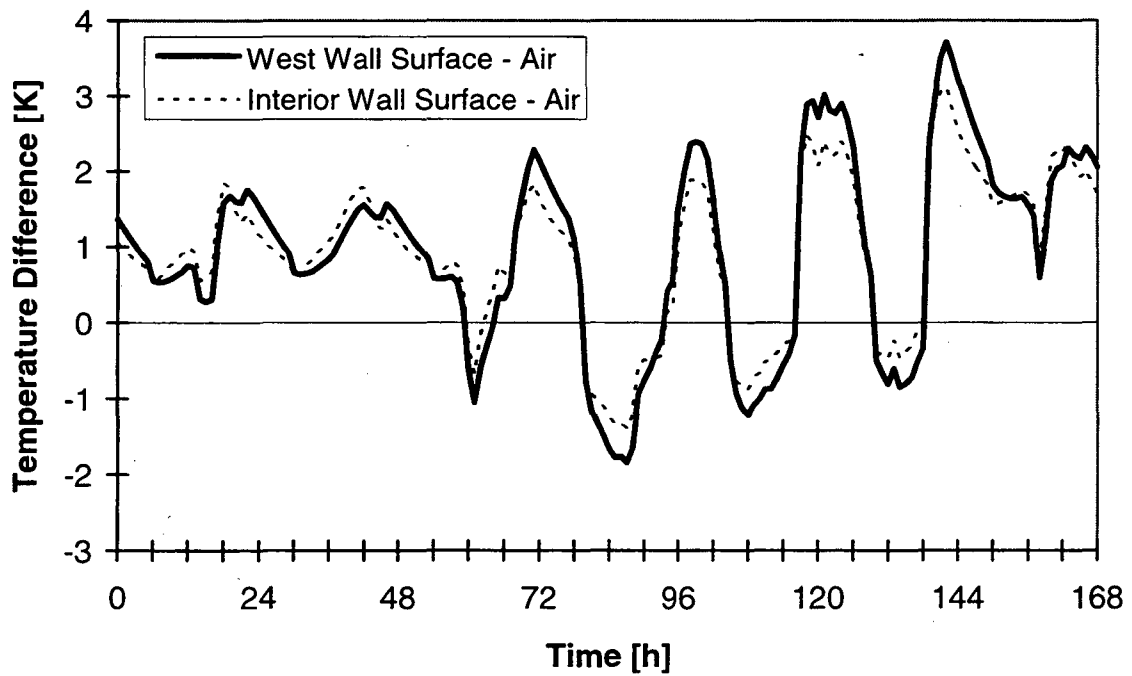**Figure 11:** *Indoor Air Temperature Profile with Ventilative Cooling*

Figure 12: *Temperature Difference between the Wall Surfaces and the Air for Conventional Wallboard*
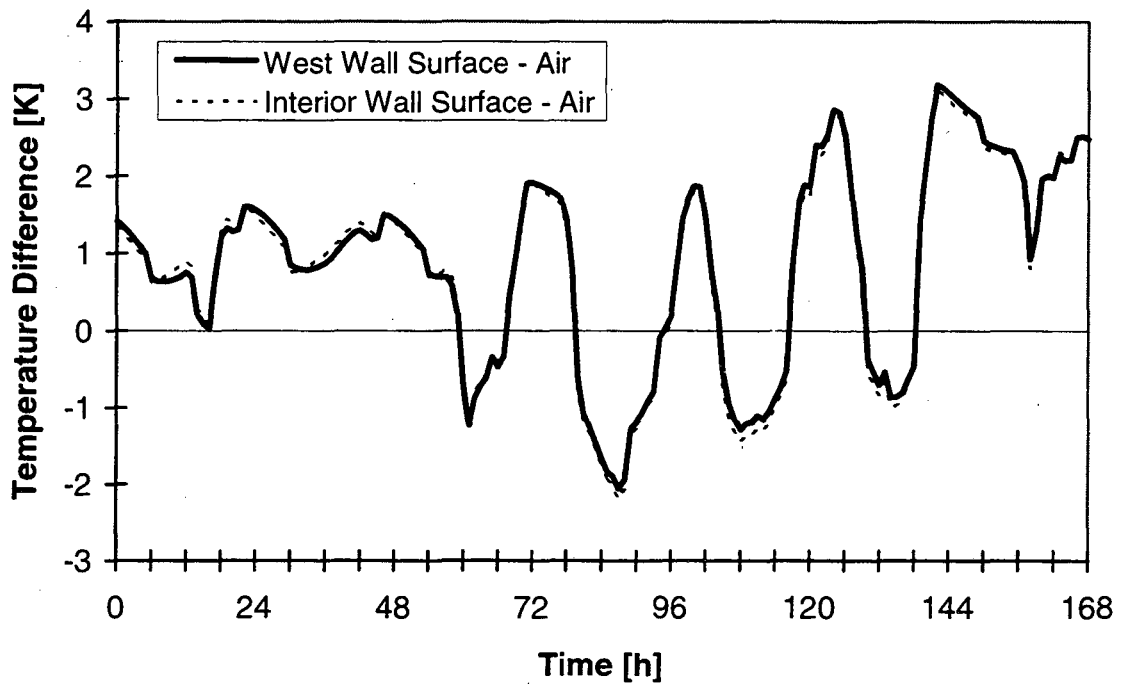
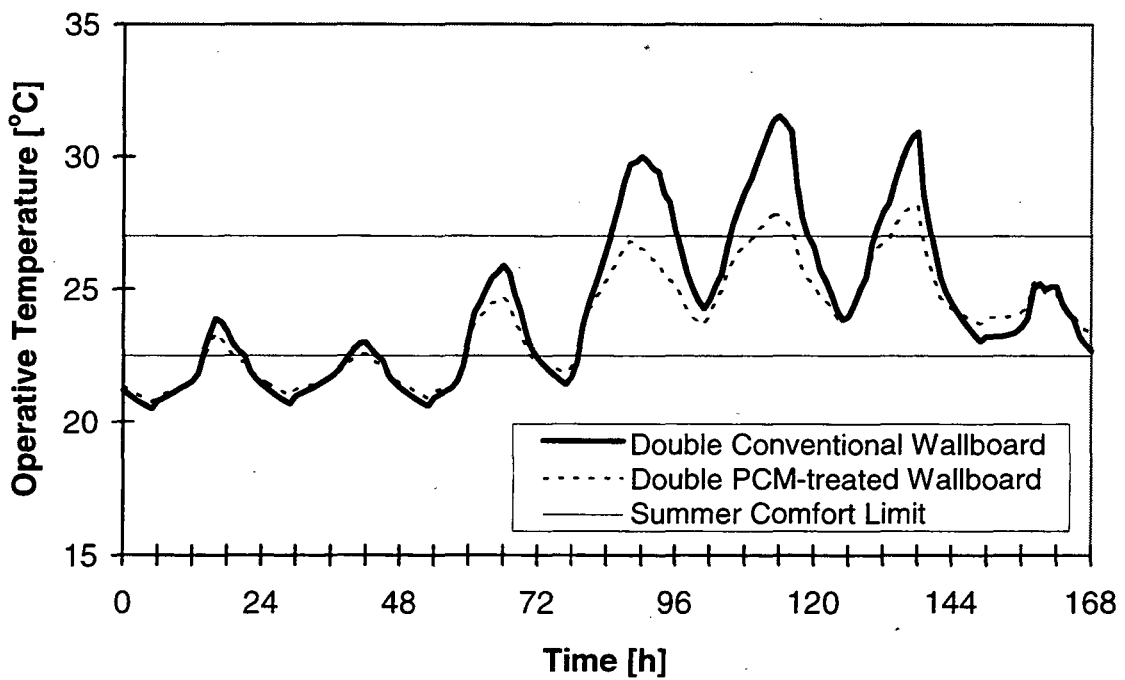**Figure 13:** *Temperature Difference between the Wall Surfaces and the Air for PCM-Treated Wallboard*

Figure 14: *Operative Temperature Profile with Ventilative Cooling*

The operative temperature profile for PCM-treated wallboard with double thickness **(Figure 14)** shows a significantly better performance than that for single sheets (shown in **Figure 7**). 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.

Differences between the operative temperature and the indoor air temperature are shown in **Figure 15**. For the first two days, differences remain in the range between 0 K and 1K; the third day brings temperature differences of up to -0.5 K. With increased indoor air temperature amplitudes, the amplitude of the differences also increases. At peak, the operative temperatures are lower. When ambient air temperatures drop below 25 °C and ventilative cooling starts, the differences show positive values.
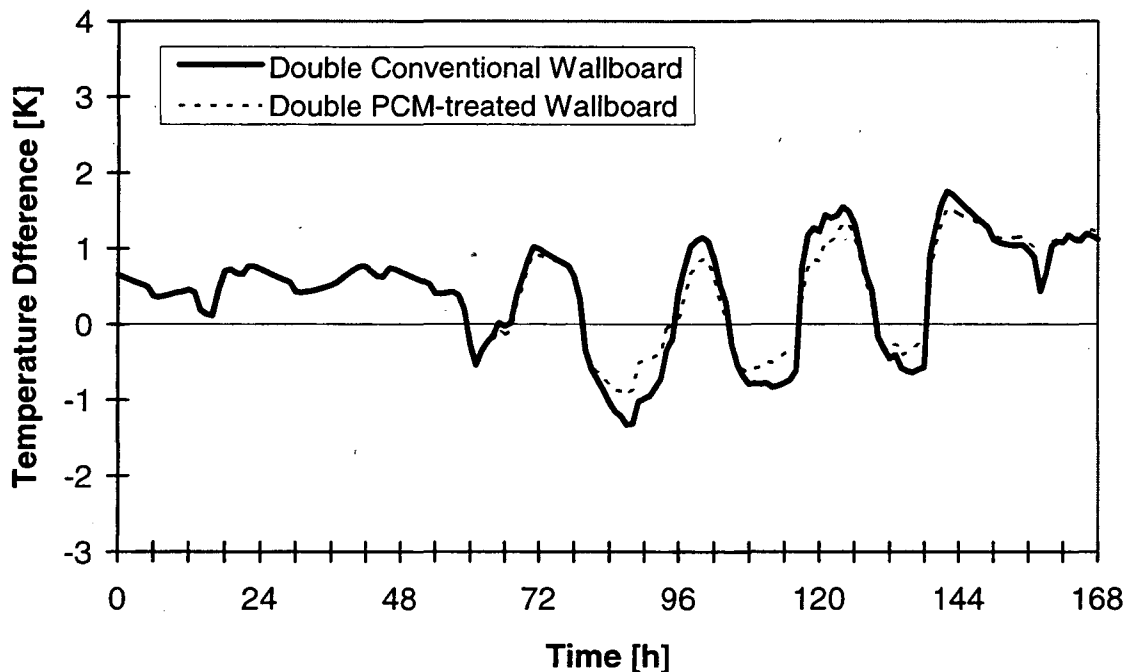

Figure 15: *Temperature Differences between Operative Temperature and Air Temperature with Ventilative Cooling*

When compared with the data shown in **Figure 9**, the specific enthalpy for the double-thick PCM-treated wallboard shows reduced values (see **Figure 16**). Peak values are reached with 73 kJ/kg on day five and 75 kJ/kg on day six. On the morning of day six, ventilative cooling is not able to reduce the specific
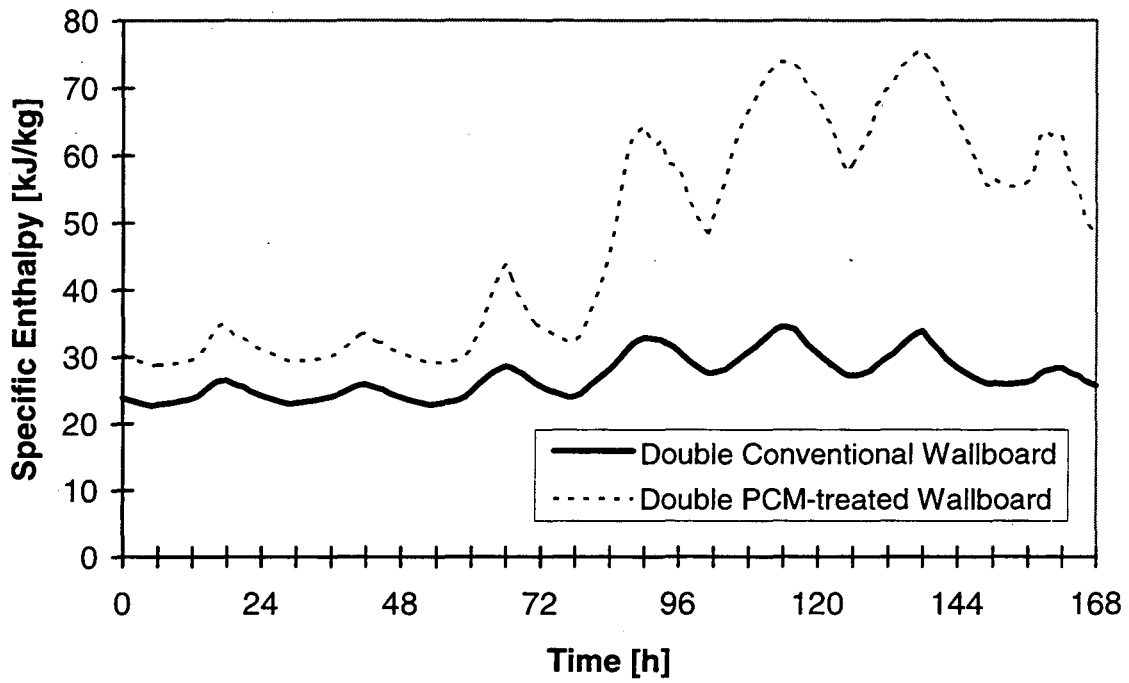
Figure 16: *Specific Enthalpy Variation for the Wallboard of the West Wall with Ventilative Cooling*
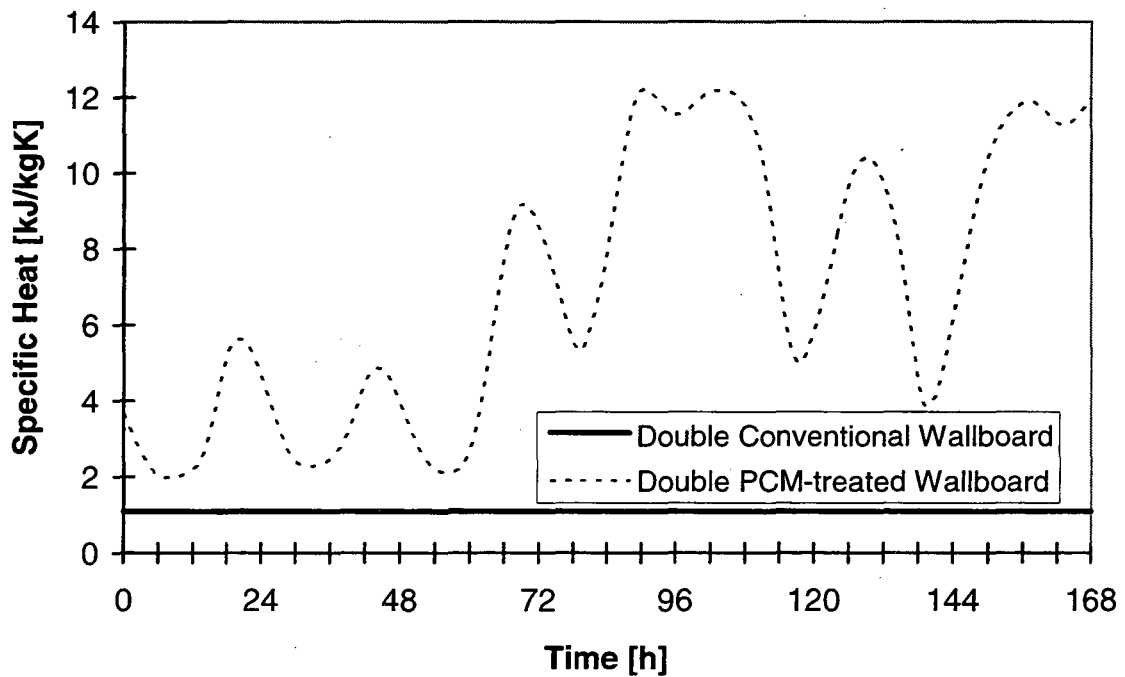

Figure 17: *Specific Heat Capacity Profile for the Wallboard of the West Wall with Ventilative Cooling*

enthalpy below 57 kJ/kg, and thus cannot force the wallboard temperature below the melting temperature of the paraffin.

The specific heat capacity, shown in **Figure 17**, reaches the peak on day four, when the specific enthalpy reaches its peak. Decreasing temperatures lead to decreasing enthalpy and specific heat capacity. The fifth day with his increase of specific enthalpy up to 73 kJ/kg sees decreasing values for the specific heat capacity. Approximately 5 kJ/kg-K correspond to the enthalpy peak. The sixth day starts with a slightly recovered specific heat capacity of 10.5 kJ/kg-K but almost reaches its minimum during the peak temperature on late afternoon.

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. 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.
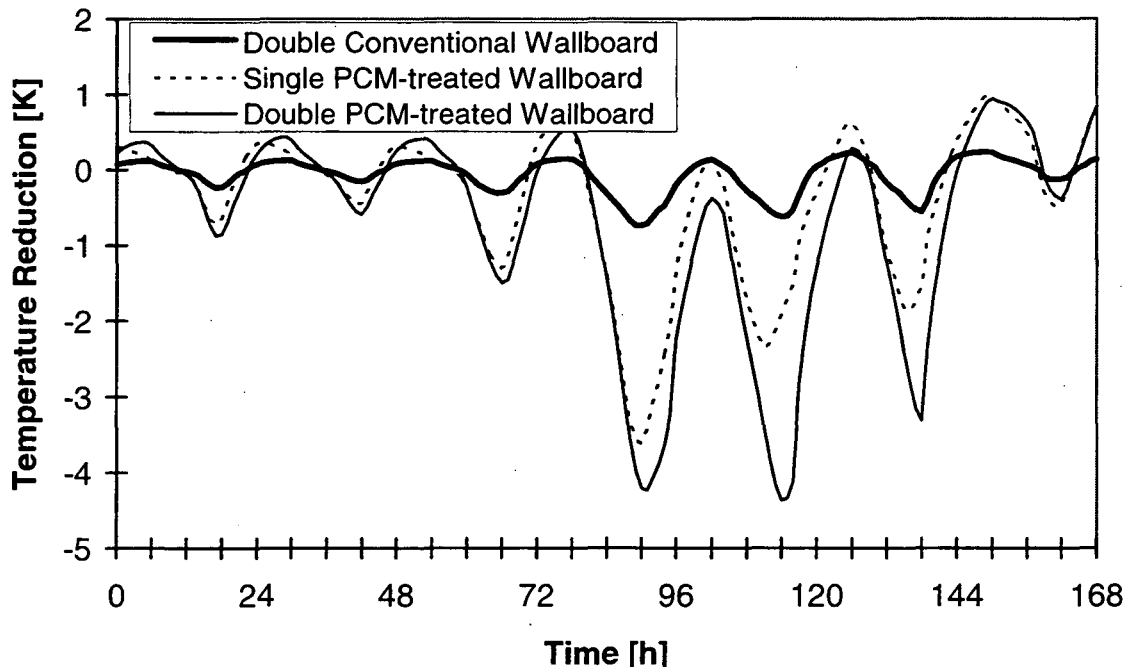

Figure 18: *Ventilative Cooling; Temperature Reduction of Operative Temperature for Double Conventional and Single- and Double PCM-treated Wallboard when compared with Single-Conventional Wallboard*

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 large diurnal swings, thermally heavy residences can be kept thermally comfortable by using night-time ventilation to discharge the latent storage of the wallboard. Therefore, mechanical cooling or evaporative cooling could be eliminated by applying PCM-treated 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 allows to provide the necessary storage in a relatively thin layer.

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 good heat exchange.

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. New 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

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Appendix

Boundary Conditions for Numerical Study:

Building Description:	
Floor Area	35 m²
Exterior Walls:	
West wall	
Length	7 m
Window area	20%
Shading factor for windows	55%
U-value for opaque part	0.266 W/m²K
U-value for windows	0.95 W/m²K
South wall	
Length	5 m
Window area	20%
Shading factor for windows	55%
U-value for opaque part	0.266 W/m²K
U-value for windows	0.95 W/m²K
Interior walls:	
Construction:	stud-frame wall with wallboard on both sides, adiabatic plane in the middle of the wall
Ceiling:	
U-value	0.17 W/m²/k
Attic	Vented, shielded by radiant barrier
Floor:	
Slab	Concrete, 0.1 m
Subslab	Sand, 1 m, temperature level below sand is kept constant at 20 °C

Wallboard:	
Conventional wallboard	
Thickness	0.015 m
Physical properties	see Table 1
PCM-treated wallboard	
Thickness	0.015 m
Physical properties	see Table 1 for 20% PCM
Modeling data	
Melting temperature	25 °C
Melting range	5 K
Inclination ß	1.4
Thermal loads	all loads 50% convective, 50% radiative
Occupants	
Number of occupants	4 Persons
Schedule	6 o'clock through 22 o'clock
Heat output per person	100 W
Lights	
Heat output of lights	100 W
Schedule	20 o'clock through 22 o'clock
Appliances	
TV	150 W
Schedule	6 o'clock through 22 o'clock

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