What are the Potential Benefits of Including Latent Storage in Common Wallboard?

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Previous work has shown that wallboard can be successfully manufactured to contain up to 30 percent phase-change material (PCM), or wax, thus enabling this common building material to serve as a thermal energy storage device. The PCM wallboard was analyzed for passive solar applications and found to save energy with a reasonable payback time period of five years. Further evaluations of the wallboard are reported in this paper. This analysis looks at potential applications of PCM wallboard as a load management device and as a comfort enhancer. Results show that the wallboard is ineffective in modifying the comfort level but can provide significant load management relief. In some applications the load management strategy also serves to save a small amount of energy, in others there is a small energy penalty.

Introduction

Increased utilization of passive solar energy for building heating requires that thermal energy be stored on a 24-hour basis. Existing sensible heat thermal storage systems in buildings are typically large, massive, and generally not well suited to stud wall construction—by far the dominant type of small building construction in the U.S. Research has shown that selected blends of paraffins that melt at room temperature can be incorporated into ordinary plasterboard so that the thermal capacity of the plasterboard is greatly enhanced through the latent heat capacity of the paraffin. Simple imbibing of conventional plasterboard with paraffin produces a PCM wallboard that contains up to 30 wt. percent of paraffin. Tests have shown that the paraffin, even in its melted state, adheres to the large surface area provided by the dendritic needles of calcium sulfate comprising the core of the wallboard. Prior economic analyses of a passive solar building indicate that the optimal PCM concentration is about ten percent by weight and that the payback resulting from annual energy savings in a building heated by an electric heat pump is three to five years (Tomlinson and Heberle, 1990). Other researchers have shown that paraffin can successfully be used as a wall component to damp out exterior temperature fluctuations (Lyons and Russell, 1977).

A main advantage of the PCM wallboard concept is elimination of the usual requirement of a system such as cans, bottles, or pouches to contain the PCM. With this new concept, containment is provided by the wallboard, an architectural building component. With almost two billion square meters of plasterboard produced annually in the U.S., the industrial infrastructure is in place and the changes in the manufacturing process needed for PCM wallboard manufacture are minimal. However, the passive solar market is considered too small to support large-scale production of the PCM wallboard. If the wallboard offered other benefits, it would become more marketable and could be produced in larger, more economic quantities. Two possible benefits in conventional, i.e., nonsolar buildings were therefore examined in this study: improved occupant comfort and utility load management. To provide load relief successfully, the storage device must allow customers to avoid using their air conditioner or heater during the utility's peak load hours. Such load shifting is only successful when a minimum level of occupant comfort is supplied throughout the on-peak period.

The analyses reported in this study indicate that the choice of PCM melting temperature is critical to the successful outcome of using PCM wallboard or ductboard as a load management tool. With many PCMs, particularly the salt hydrates where much prior development work has focused, the solid/liquid phase change temperature is a property fixed by the material itself. There are relatively few suitable pure salt hydrates, eutectics, and near eutectics with melting points near room temperature. Consequently, it would be highly unlikely that a phase-change temperature could be chosen (as in the proposed wallboard application) and a eutectic with this melting temperature found. If we consider that the desirable wallboard melting temperature depends on whether we are heating or cooling, climate, and thermostat control, it becomes obvious that PCMs whose melting temperature can be tailored to suit a particular application would be desired. Paraffins, as mixtures of several linear alkyl hydrocarbons, have this desired characteristic.

The paraffin PCM experimentally studied for the wallboard concept is a mixture of several components with the main constituent being n-octadecane ($C_{18}H_{38}$). This material has a melting point of about 23°C (73.4°F), which is in the room temperature range although somewhat higher than used in this analysis. As a mixture, the paraffin melting point can be adjusted by mixing homologues of the same series. To reach the lower melting temperatures used in this analysis, a mixture more rich in lighter hydrocarbons (e.g., $C_{16}H_{34}$) and less rich in octadecane should be selected, and it would be a straightforward process to produce this mixture. The fact that blends of near-neighbor linear hydrocarbons can be selected to obtain the required PCM melting temperature means that the same manufacturing process can be used to produce wallboard over a range of phase-change temperatures. Further, since wallboard is produced and sold on a regional basis to keep transportation costs down, PCM wallboard with phase-change temperature tailored for specific regions could easily be produced simply by adjusting proportions of the PCM mix.

Analysis Methods

The analysis was designed to determine if the PCM could provide improved occupant thermal comfort and/or load control with acceptable levels of occupant comfort. Thermostat management, both deadband width (the difference between the temperatures at which the heater turns on and off) and setpoint,

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Table 1 Weather data used for repetitive load management analysis

Month	Hour	Direct solar radiation[a] (kJ/m²)	Global solar radiation[b] (kJ/m²)	Temperature (°C)	Humidity ratio (×10⁴)	Wind velocity (m/s)	Wind direction[c] (°)
1	1	0	0	3.3	30	3	180
1	2	0	0	3.9	30	4	200
1	3	0	0	2.8	30	2	220
1	4	0	0	3.3	30	2	200
1	5	0	0	3.3	31	3	200
1	6	0	0	2.2	31	3	180
1	7	0	0	2.2	31	2	180
1	8	204	119	1.7	31	3	180
1	9	1175	602	3.9	31	2	200
1	10	2138	1116	6.1	33	2	200
1	11	2729	1533	8.9	33	3	240
1	12	2856	1758	11.1	34	3	220
1	13	2888	1779	12.2	33	3	240
1	14	2785	1573	13.3	36	4	240
1	15	2303	1151	13.9	34	4	180
1	16	1163	599	13.9	40	5	180
1	17	402	143	12.2	31	2	180
1	18	0	0	9.4	31	2	180
1	19	0	0	8.3	33	2	150
1	20	0	0	6.7	33	2	180
1	21	0	0	5.6	33	1	180
1	22	0	0	5.0	31	3	180
1	23	0	0	5.0	31	3	180
1	24	0	0	4.4	31	2	180

[a] direct solar radiation, integrated over previous hour
[b] global solar radiation on horizontal surface, integrated over previous hour
[c] wind direction expressed as 0 for wind from north, 90 for east, 180 for south, etc.

was a key variable. Other variables considered included the amount of PCM present (varied both by increasing the proportion of PCM in the walls and by increasing the amount of internal PCM wall surface area), the internal convection coefficient, and the PCM melt temperature. Results for a large number of tests, each covering a short test period of relatively cold weather, were compared. Statistical regression was then used to measure the relative effect of each analysis variable on the results. A small number of tests were also made to examine the most promising concepts on a seasonal basis.

A verified code, TRNSYS, was previously modified to incorporate a separately verified model of the PCM wallboard (Tomlinson and Heberle, 1990; TRNSYS, 1990). The TRNSYS code permits the explicit definition of each building component and a variety of control strategies. It iterates as necessary to perform an energy balance on the structure for each time step over the test period. Time steps varied for each test case and were generally less than 0.01 h (36 sec.). One very cold day from the Nashville typical meteorological year was chosen and duplicated so that the analysis could cover a one-to-two-week period of repetitive daily weather. The data for this day, with an average temperature of 6.8°C, is shown in Table 1. These long repetitive periods were necessary to avoid the distortions associated with the initial PCM state of charge/discharge. Seasonal test runs were made for a typical Boston winter and for Nashville and Miami summers.

The model consisted of a simple one-zone structure 17 m long by 13 m wide by 3 m high. The window and door area combined was 18 m^2 and was assumed to be opaque so that no credit was taken for passive solar gains. In this manner, the effects of solar gain through windows could be separated from effects of using room air heated by an auxiliary heating or cooling system in which thermal storage occurs through convective heat transfer between the room air and the interior surfaces of the building. The exterior walls had a total area of 162 m^2 and were constructed of PCM wallboard, insulation, and a facing with a solar absorbance of 0.5. These walls had an overall U-value of 0.314 $W/m^2-°C$ (1.13 $kJ/h-m^2-°C$). For some cases the ceiling, with an area of 221 m^2, was similarly constructed using PCM wallboard with a greater level of insulation for an overall U-value of 0.19 $W/m^2-°C$ (0.68 $kJ/h-m^2-°C$). For other cases the ceiling was modeled with the same overall U-value, but without PCM energy storage. The floor area of 221 m^2 was assumed to be over an unventilated crawl space, using an ASHRAE transfer function for this purpose included in the TRNSYS code. Interior partition walls with a total surface area ranging from 0 to 80 m^2 were also constructed using the PCM wallboard. No credit was taken for internal energy storage (furnishings, etc.) other than the wallboard itself and the capacitance of the air volume, 808 kJ/°C. Nor was there any effort to estimate the heat contributed by occupants. Infiltration was calculated as a function of the local wind speed using the correlation given in the TRNSYS code for medium construction levels and shown in Eq. (1).

$$\dot{m} = \rho \times V \times (0.1 + 0.17 \times |T_a - T_z| + 0.049 \times W) \quad (1)$$

where

$\dot{m}$ = mass flow rate of air infiltration,
ρ = density of room air,
V = volume of air in the zone
T_a = ambient temperature,
T_z = room temperature, and
W = wind speed.

The interior natural convection was driven by the temperature differences between the wall surfaces, the interior air, the colder window and door surfaces, and other interior objects. Typically natural convection coefficient correlations are based on experimental data for flat surfaces of relatively small dimensions. These empirical results predict relatively low rates of heat transfer and also show that the convective heat transfer for finite horizontal warm surfaces facing down is very small compared to vertical surfaces. However, these experiments do not properly represent the case of a room with large surfaces and where air currents are established by a mix of warm and cold surfaces. A study of natural convection for room size wall surfaces was made in 1983, using both numerical analysis and experimental techniques (Altmeyer et al., 1983). That study used small heated and cooled surfaces on the walls and showed definite circulation patterns established by these surfaces. The heat transfer coefficient for the wall surfaces near the heated regions in this study was measured to be 2.7 W/m^2–K. For the current investigation, a two-dimensional finite difference analysis was made for a room comprising about one fourth of the total house volume. This finite difference model used 35,000 cells in a space 1.5 m wide (half the room width, using a symmetry boundary condition in the center of the room) by 3 m tall. This numerical model included a window 0.33 m tall on each side wall and an insulated floor. The window temperature was set to 10°C and the walls and ceiling to 28.5°C. The results from this numerical model show the average heat transfer coefficient on the ceiling to be about 60 percent that of the wall/window surface. Considering both of these analyses, a base level of 2.7 W/m^2–K was used for the natural convection heat transfer coefficient for all surfaces, including both walls and ceilings. The air circulation patterns from the numerical model show that the convection conditions experienced by human occupants will vary slightly depending upon their position in the room. For this study, the convection coefficient for human comfort calculations was assumed to be the same as that used for the room surfaces. The convection coefficient was doubled and tripled to parametrically determine its influence on both comfort and energy storage availability.

For many of the analyses, the PCM wallboard was given a thickness of 0.019 m (nominal $\frac{3}{4}$ in.), typical of commercial fire-retardant dry wall. Other models were made assuming a wallboard thickness of 0.0127 m (nominal $\frac{1}{2}$ in.), typical of residential construction. The earlier investigation of solar applications showed that the optimal PCM content was ten percent. However, the applications considered here were based on a combination of convective and conductive heat transfer, with no solar radiant energy to warm the surface of the storage wall. Either convection or conduction could determine the availability of the stored latent energy. The convection conditions can be estimated as discussed above. However, the temperature profile across the medium, which drives the conductive heat transfer, is moderated by the presence of latent energy storage and the transient nature of the melting/freezing interface. Given this complexity, numerical methods were used to assess the overall interactions between the structure and the latent storage. PCM concentrations up to 30 percent were considered. The higher concentrations would place more PCM near the surface of the wall, which could be important if energy conduction through the wall was insufficient to make all the latent storage available. For analysis purposes, five nodes were used across the wallboard width. During each time step, the temperature, enthalpy, and phase were calculated for each node. One boundary condition for this calculation is the interior room temperature and convection coefficient. The second boundary condition is provided by the remainder of the wall structure and the ambient weather conditions. This wall structure, including insulation, framing materials, and exterior sheathing, is represented by the overall U-value and is not explicitly modeled. For interior partition walls, the second boundary condition is one of symmetry. The PCM wallboard properties are shown in Table 2. Experiments have shown that PCM wallboard can be made with a density, 696 kg/m^3, which is independent of the PCM content. Therefore, the density of the wallboard was assumed constant irrespective of the PCM concentration. Conductivities measured earlier, for wallboard samples that had been dipped in wax and therefore had densities that varied with the amount of PCM, were scaled to reflect the new volume fractions of the constant density PCM wallboard according to the Eucken equation for two-phase materials (see Eq. (2)) (Kedl, 1991; Eucken, 1932). When applying this equation, the continuous phase is the gypsum and the discontinuous phase is the PCM.

$$K_m = K_1 \frac{1 - f + f[3K_2/(2K_1 + K_2)]}{1 - f + f[3K_1/(2K_1 + K_2)]} \quad (2)$$

where

K_m = conductivity of the composite two phase material,
K_1 = conductivity of the continuous phase,
K_2 = conductivity of the discontinuous phase, and
f = volume fraction of the discontinuous phase.

The results of these numerical analyses show that the surface convection, rather than the internal conduction, limits the availability of the latent storage. For the climates and load cycles evaluated here, the ten percent weight fraction provides sufficient storage capacity at the lowest cost. Longer on-peak periods or more severe climates could require a higher PCM content.

The thermostat was modeled so that it would operate with a finite deadband in the same manner as most residential thermostats. When the house temperature was within the deadband region, the heater or air conditioner would remain either on or off, according to its status during the previous time step. During load management case studies, the heater was forced to remain off during the on-peak period. Some of the seasonal tests included a thermostat override feature to enable the heater or air conditioner to operate during the on-peak period if necessary to maintain a reasonable drybulb temperature within the room.

Based on the current price of the PCM, the wallboard is expected to cost ~\$1.30/m^2 more than conventional wallboard (Tomlinson and Heberle, 1990). For the small house used in our model, that corresponds to an incremental cost of about \$600. This is the only cost considered in the simple payback economic analysis reported in this paper. Since this system is only feasible for new construction, no installation costs were included, although there may be some additional installation cost associated with the plenum arrangement described later in this paper. Also, the thermostat cost was not explicitly considered, again because some form of control system would have been required without the PCM, and the incremental cost should be very small. For all estimates, the on-peak energy cost was assumed to be \$0.10/kWh and the off-peak cost was \$0.04/kWh. This cost structure is similar to the differential offered

Table 2 PCM wallboard properties

PCM content (wt. %)	PCM content (vol. %)	Composite conductivity (W/m-°C)	Latent heat (kJ/m²)		Specific heat (kJ/m²-°C)	
			0.0127 m wallboard	0.0191 m wallboard	0.0127 m wallboard	0.0191 m wallboard
0	0	0.173	0	0	9.63	14.5
10	9	0.186	171	257	10.7	16.0
16	14	0.190	273	410	11.5	17.2
20	18	0.198	343	515	11.8	17.8
30	27	0.218	514	771	13.0	19.5

by Boston Edison (Haas et al., 1987). All annual cost savings reported in this paper are based on this difference in on and off-peak energy cost. The on-peak period was defined to last from 8 a.m. to 2 p.m. during the winter and from 11 a.m. to 5 p.m. during the summer.

Comfort Effects

Published standards for thermal comfort of building occupants generally include a range of dry bulb temperatures that a majority of persons would find comfortable (ANSI/ASHRAE). To utilize the storage capacity of the PCM wallboard inside the building, the space interior temperature must cycle, and though the average temperature in the building might lie within a standardized comfort range through this cycling period, discomfort could exist. Our task in this analysis was to quantify comfort in a rational, consistent manner. The PCM wallboard was projected to increase comfort by decreasing the frequency of internal air temperature swings and maintaining the temperature closer to the desired temperature for a longer period of time. The PCM wallboard could also affect radiative exchange between occupants and the walls by holding the surrounding wall surfaces at a more constant, and more desirable, temperature. Existing comfort/discomfort indexes were all tightly linked to occupant clothing and activity level (ANSI/ASHRAE, and ASHRAE, 1985). We wished to disassociate this analysis from any assumptions of occupant behavior. Therefore, a discomfort index, I_{DC}, shown in Eq. (3), was defined to be the time-integrated absolute value of the difference between the desired temperature and the effective environmental temperature experienced by an occupant, shown in Eq. (4).

$$I_{DC} = \int_{24h} |T_d - T_0| \, dt \quad (3)$$

where

I_{DC} = discomfort index, °C–h/day,
T_d = desired temperature, and
T_0 = effective environmental temperature felt by occupant.

$$T_0 = \frac{(\overline{h}_r \overline{T}_r + \overline{h}_c T_a)}{(\overline{h}_r + \overline{h}_c)} \quad (4)$$

where

$\overline{h}_r$ = linearized radiation transfer coefficient,
$\overline{T}_r$ = mean radiant temperature,
$\overline{h}_c$ = mean convective transfer coefficient, and
$\overline{T}_a$ = indoor air temperature.

The mean radiant temperature is the average temperature of all surfaces, weighted by their respective areas. As described earlier, the mean convective heat transfer coefficient was varied from 2.7 to 8.1 W/m²–°C. The lower value is appropriate for a sedentary occupant wearing typical winter clothing in normal air movement (ANSI/ASHRAE). The higher value would require additional air movement. The linear radiation transfer coefficient used here follows the recommendation given in the TRNSYS literature, which is a slightly simplified version of that given by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (TRNSYS, 1990, and ANSI/ASHRAE).

$$\overline{h}_r = 4\sigma(Ti^3) \quad (5)$$

where

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m² – K⁴) and
Ti = initial room temperature, K.

The modeled discomfort index is effective at quantifying the magnitude and duration of temperature swings within the occupied area. This index was then used to judge whether the PCM storage improved comfort without load management and whether it maintained comfort during load management. Indoor humidity levels were also examined during the seasonal summer test cases.

More than 25 test cases were run for the selected cold winter day, varying the amount of PCM from 0 to 30 percent and the mean convective transfer coefficient while maintaining traditional thermostat management, i.e., no load management. The PCM wallboard was not shown to have any significant effect on occupant comfort. The PCM wallboard had only a small effect on the shape of the indoor temperature profile, and the total time at temperatures away from the desired temperature was unchanged. Increasing the convective transfer coefficient had the opposing effects of increasing the effective latent storage capacity but also decreasing the occupant's comfort by increasing the relative impact of air temperature fluctuations.

Load Management Effects

The initial tests of PCM wallboard as a load management device were made with a very simple arrangement. A PCM melt temperature was chosen equal to the thermostat set point (or T_d), the deadband and convection coefficient were selected, and the clock thermostat was set so that the heater could not come on during the on-peak period, regardless of the indoor air temperature. Results from these tests showed that load management was possible, but that modifications to the heater control strategy would be necessary. Some of these early tests are shown in Figs. 1 and 2. Figure 1 shows the interior air temperature while Fig. 2 shows the exterior wall's interior surface temperature. For some cases shown in the following figures, the interior air temperature appears to fluctuate within a very narrow range, instead of within the specified thermostat band width as expected. This appearance is caused by the use of 15-min. average temperatures in a house model with very little thermal storage except for that present in the PCM wallboard. For those cases discussed here in which the wallboard's latent storage was unused, the furnace was able to raise the air temperature

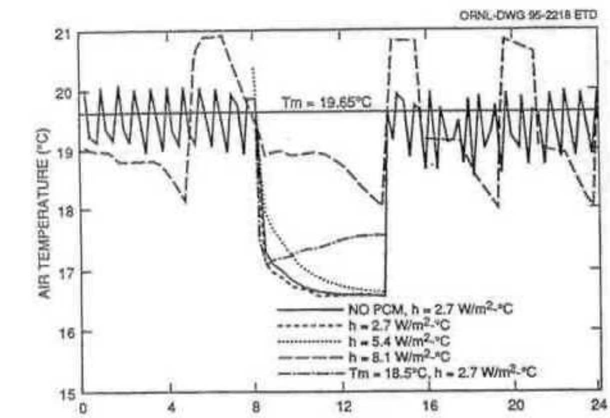

Fig. 1 Room air temperature during load management with ten percent PCM wallboard with a melting temperature of 19.5°C and varying convection coefficients

from the lower end of the dead band to the upper limit in a very short time, thus causing 15-min. average temperatures to remain very close to the thermostat setpoint.

The effect of increasing the air speed (thereby increasing the convection coefficient) is clearly shown in Fig. 1. Here, the desired air temperature, or thermostat deadband, is between 18 and 21.3°C and the on-peak time is chosen to be 8:00 a.m. to 2:00 p.m. A case without PCM and with the base level of 2.7 $W/m^2-°C$ convective heat transfer is shown for comparison. All other cases on these figures have ten percent PCM wallboard. Without thermal storage, the room air temperature falls to about 16.5°C, or 1.5°C lower than the desired minimum of 18°C, during the on-peak period. (All temperatures shown in these figures represent 15-min. averages.) Adding ten percent PCM at a melt temperature of 19.65°C (the middle of the desired temperature range) with the same level of convection has virtually no effect on the room air temperature. Doubling the convection coefficient from 2.7 to 5.4 $W/m^2-°C$ increases heat transfer between the wall and the room but is still insufficient to maintain the room air temperature in the desired range. As can be seen in Fig. 2, the PCM for these two cases never reaches the melt temperature and the latent storage capacity of the wall is unused. However, when the convection coefficient is increased to 8.1 $W/m^2-°C$, the room air temperature is maintained above 18°C throughout the on-peak period as can be seen in Fig. 1. Examination of this case (8.1 $W/m^2-°C$) on Fig. 2 shows the PCM at and above the melt temperature much of the time. When this curve rests on the melting temperature (shown by the line where $Tm = 19.65°C$), the PCM in the wall near the surface is either freezing or melting. The flat portions of this curve above the melting temperature on Fig. 2 represent times during which the internal nodes of the wall were melting (storing latent heat). The flat portions of this curve below the melting temperature on this same figure are times when the internal nodes were freezing (releasing latent heat).

In these initial tests, the latent storage capacity was utilized only at the highest convection coefficients. The increased convection enhances the exchange of energy between the wall and the air. However, occupants may be unwilling to accept such high air flows (although air ventilation distribution systems that throw air directly across wall or ceiling surfaces at high speeds are under development for cold air distribution and might be adaptable to the PCM wallboard system) (Int-Hout, 1992). Another way to increase the heat transfer between the air and the wallboard is to increase the temperature difference between the two. Another model was therefore run with a lower PCM melt temperature. This case is also shown on Figs. 1 and 2 and was based on ten percent PCM, convection at 2.7 $W/m^2-°C$, and a melt temperature of 18.5°C, near the bottom of the desired temperature range. This case showed an improvement, although the room temperature still dropped to nearly 17°C. Figure 2 *shows that the wall surface was at the melt temperature for* much of the time and that the PCM was releasing heat (freezing) during the on-peak time, as desired. The environmental (as felt by occupant) temperature was moderated by the surface temperatures so that the minimum temperature experienced by an occupant of the structure was approximately 0.3°C higher than the minimum desired air temperature.

Another interesting phenomenon found in the early tests, using repeating cold days, were instances of unfavorable interactions between the PCM latent storage and the thermostat operation. One example is found in the case of ten percent PCM with 1.9 cm ($\frac{3}{4}$ in.) wallboard, convection coefficient of 8.1 $W/m^2-°C$, thermostat deadband from 18 to 21.3°C, and a PCM melt temperature of 19.65°C. Figure 3 shows three days of wintertime load management temperature profiles for this case, including the room air, wall surface, and wall interior node temperatures. The on-peak periods during which heater operation was prohibited are also shown. The thermostat on/off signals shown are based on indoor air temperature and thermostat deadband, with clock control override for load management. This case, with a total latent storage capacity of about 120E6 J, exhibited three-day periodicity. On the first day of the cycle, the PCM latent storage was almost fully charged and the high convective coupling between the wall and the air maintained the desired temperature during the on-peak period without any heater operation. At the end of this first on-peak period, the

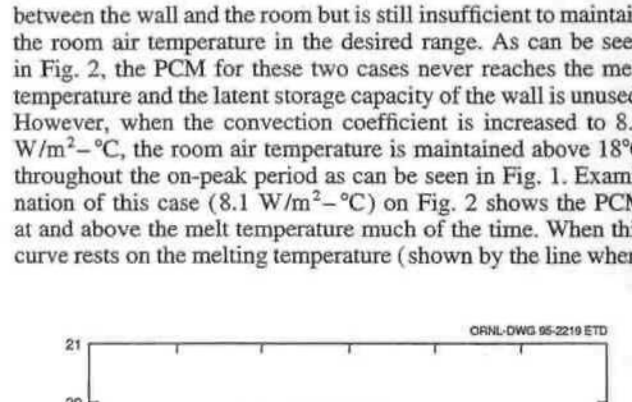

Fig. 2 Exterior wall indoor surface temperature during load management with ten percent PCM with a melting temperature of 19.65°C and varying convection coefficients

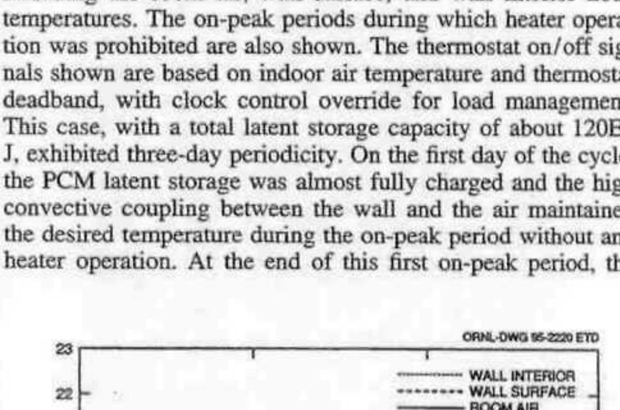

Fig. 3 Wall surface (facing the room), wallboard internal (away for the room), and room air temperatures with thermostat signals for ten percent PCM wallboard with 8.1 $W/m^2-°C$ convection

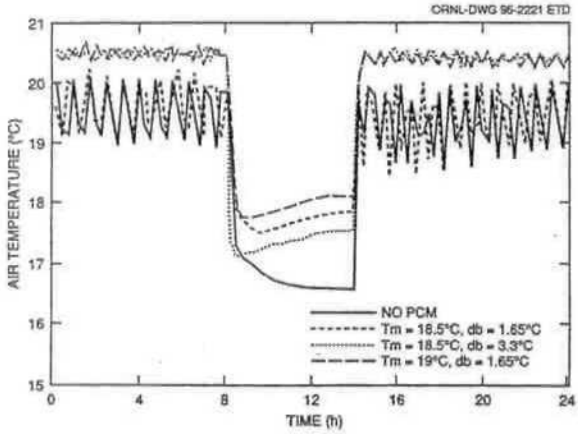

Fig. 4 Room air temperature with ten percent PCM wallboard, convection coefficient of 2.7 W/m^2–°C, two melting temperatures, two thermostat set points, and two thermostat deadbands

room temperature was near the bottom of the thermostat's deadband and the heater came on immediately and began to recharge the latent storage. However, the remaining charge continued to warm the room, leading to reduced heater operation, and therefore a reduction in the amount of storage available at the start of the next on-peak period. During this second on-peak period, the latent storage was exhausted early and the room air temperature fell far below the desired range. The heater came back on as soon as the on-peak period was over, charging the PCM walls so fully that at the end of the third on-peak period, the heater remained off for an additional hour until the room air temperature finally fell to the bottom of the thermostat's deadband. This cycle was found to repeat with a period of three days, producing unsatisfactory load management. Such cyclic behavior is due to the combined effects of the storage capacity, the total load on the house, and the shape of the outdoor weather profile.

Considering these preliminary results, we then explored new combinations of thermostat control and PCM melt temperature that could force the latent storage to always be in the fully charged state at the beginning of the on-peak period. All of these cases were examined using a convective coefficient of 2.7 W/m^2–°C and ten percent PCM wallboard. A new off-peak thermostat deadband from 19.65 to 21.3°C, consisting of the upper half of the one previously modeled, was chosen. This would affect the room temperature slightly, but would keep the air temperature above the PCM melt temperature throughout the off-peak charging period (thus avoiding the instabilities of Fig. 3). The PCM melt temperature was also varied to measure the effect of this parameter on the room temperature during both charging and discharging periods. The results are shown in Fig. 4. The no PCM case and one case with the original thermostat deadband width of 3.3°C are included in this figure for comparison. Figure 4 shows that both cases with the higher, narrower thermostat deadband from 19.65 to 21.3°C provided significant improvement in room air temperature during the on-peak period. Raising the melt temperature to 19°C also showed improvement over the 18.5°C case. Examination of the exterior wall interior surface temperatures showed that both cases with the smaller thermostat deadband were fully melted at the start of the on-peak period and held a nearly constant temperature throughout the entire on-peak time. After the heater came back on at 2:00 p.m., the 18.5°C material held steady at the melt temperature for about 2 hours, and then quickly rose. The 19°C material held steady at its melting temperature for about 5 hours before warming up further. This extended time at the melt temperature represents time during which the latent storage is being recharged, i.e., the PCM is melting. The longer time for the 19°C material showed that its latent storage was more fully discharged than the 18°C material. This trend was expected considering the relative sizes of the charging temperature differences for these two cases.

The most successful aspects of these preliminary studies were then examined over winter and summer seasons.

Seasonal Winter Savings Opportunities. In Boston, a comparison was made between a base case (Case 1) with no PCM energy storage and traditional thermostat management to two test cases. These cases are summarized in Table 3. The first test case (Case 2) used one PCM with a melting temperature slightly less than the desired room temperature. The second test case (Case 3) used two PCMs. The interior wall had a melt temperature equal to the desired room temperature and the exterior walls had a lower melt temperature. This two-PCM combination was developed with the goal of maximizing energy storage capacity while improving comfort and reducing energy loss through the walls. Both PCM test cases controlled the room temperature within the upper half of the acceptable temperature range (i.e., from 19.65 to 21.3°C) during the off-peak hours, thereby allowing the PCM to melt more fully. Both PCM test cases also had an override feature so that if the room temperature fell more than 0.5°C below the desired range (i.e., below 17.5°C) during the on-peak period, the furnace would override the clock-thermostat signal and heat the room. All three estimates of energy use cover a seven-month time period from Oct. 1 to Apr. 30. A shorter time period from Dec. 1 to Feb. 28 was also examined with similar results.

The results for the two-PCM case were improved over the single PCM case in all areas of consideration, total energy use, on-peak energy use, and resident comfort. However, the differences are slight and may not be significant. The energy storage/load management cases actually showed comfort increasing by about 30 percent, compared to traditional thermostat management without PCM walls. (Remember that PCM storage showed no comfort benefit with traditional thermostat management because the PCM never melted.) This result shows that load management can have an unexpected positive impact on occupant comfort in addition to energy management benefits. Also, both PCM energy storage/load management cases showed on-peak energy savings of 50 percent with almost no increase in the total energy use. It is significant that this form of energy storage produced no overall increase in energy use, because most forms of load management involve some degree of energy penalty. The location of the storage medium within the occupied area, the lack of intermediate heat transfer mechanisms (such as heat exchangers, fans, or pumps), and the modification to the thermostat controls all contribute to this improvement over other thermal energy storage methods.

The annual cost savings is about $190 for the small house modeled so the PCM load management installation would have a simple payback of about three years.

Seasonal Summer Savings Opportunities. In Miami, a comparison was made between Case 4, a base case with no PCM energy storage, no load control, and traditional thermostat management (setpoint of 23.9°C with a dead band of 2.2°C) to four test cases, summarized in Table 3. Case 5 used a single PCM with a melting temperature of 24.5°C, slightly greater than the desired room temperature of 23.9°C for all the walls and the ceiling. Case 6 used two PCMs, with the interior wall at a melt temperature equal to the desired room temperature, 23.9°C and the exterior walls at a higher temperature of 24.5°C. Both Case 5 and Case 6 controlled the room temperature within the lower half (22.8 to 23.9°C) of the acceptable temperature range (22.8 to 25°C) during the off-peak hours, thereby allowing the PCM to freeze more fully.

The other two test cases were based on an arrangement where the air is routed from the air conditioner through internal wall cavities before it is introduced into the conditioned space. In other words, the PCM wallboard is used to form a supply air

Table 3 Summary of seasonal load management case studies

Case Description	Results
Seasonal winter saving opportunities - 7-month period from October 1 to April 30 in Boston	
Case 1: Base case, no PCM, thermostat deadband from 18 to 21.3 °C	Total energy use=28,300 kWh On-peak energy use=6,400 kWh Discomfort index=4,290 °C-h
Case 2: One PCM in ceiling and walls, total latent storage capacity=33 kWh, Tm =19.0°C, thermostat deadband from 19.65 to 21.3 °C during off-peak hours, thermostat override permitted	Total energy use=28,500 kWh On-peak energy use=3,200 kWh Discomfort index=2,990 °C-h
Case 3: Two PCMs, interior wall Tm=19.65°C, exterior wall and ceiling Tm =18.5°C, total latent storage capacity=33 kWh, thermostat deadband from 19.65 to 21.3 °C during off-peak hours, thermostat override permitted	Total energy use=28,500 kWh On-peak energy use=3,200 kWh Discomfort index=2,950 °C-h
Seasonal summer savings opportunities - 3-month period from June 1 to August 31 in Miami	
Case 4: Base case, no PCM, thermostat deadband from 22.8 to 25 °C	Total energy use=1330 kWh, On-peak energy use=540 kWh
Case 5: single PCM Tm =24.5°C for all walls and ceilings, total latent storage capacity=33 kWh, thermostat deadband from 22.8 to 23.9 °C during off-peak hours	Total energy use=1440 kWh, On-peak energy use=35 kWh
Case 6: two PCMs, interior wall Tm=23.9°C, exterior walls tm=24.5°C, thermostat deadband from 22.8 to 23.9 °C during off-peak hours	Total energy use=1440 kWh, On-peak energy use=35 kWh
Case 7: interior wall cavities used as supply air plenum, base case with no PCM, thermostat deadband from 22.8 to 25 °C	Total energy use=1240 kWh, On-peak energy use=630 kWh
Case 8: interior wall cavities used as supply air plenum, interior wall Tm=21.1°C, exterior walls and ceiling Tm=18.5°C, total latent storage =31 kWh, load management time clock and separate fan-control thermostat, thermostat deadband from 22.8 to 25 °C	Total energy use=1100 kWh, On-peak energy use=0 kWh
Seasonal summer saving opportunities - 3-month period from June 1 to August 31 in Nashville, TN	
Case 9: interior wall cavities used as supply air plenum, base case with no PCM, thermostat deadband from 22.8 to 25 °C	Total energy use=630 kWh, On-peak energy use=400 kWh
Case 10: interior wall cavities used as supply air plenum, interior wall Tm=21.1, exterior walls and ceiling Tm=18.5, total latent storage =31 kWh, load management time clock and separate fan-control thermostat, thermostat deadband from 22.8 to 25 °C	Total energy use=540 kWh, On-peak energy use=0 kWh

plenum. Current house construction techniques often use such spaces for return air plenums, so this is a reasonable assumption. This arrangement offers two significant advantages: (1) the air speed within the interior cavities, and therefore at the interior wall surfaces, is very high, allowing improved convective heat transfer without uncomfortable drafts around the occupants and (2) the temperature difference between the supply air and the melt temperature is increased, again improving the overall heat transfer. In all the plenum cases, the interior walls were given a melt temperature of 21.1°C, between the desired heating and cooling temperature ranges. The exterior walls were given a melt temperature of 18.5°C, near the bottom of the wintertime temperature band. This could offer significant winter savings and possibly permit the use of cool night temperatures to freeze the PCM during summer nights. Controlled use of nighttime exterior ventilation air was not examined for Miami's humid climate, but would be appropriate for drier climates.

Test Case 7 is a base case for the plenum arrangement with no latent storage and uses traditional thermostat management, with a setpoint of 23.9°C and a deadband of 2.2°C. Test Case 8 is the load management plenum arrangement and modifies the thermostat control with the addition of a time-clock and a separate fan-control thermostat. The fan-control thermostat permits air circulation through the plenum region when the air conditioner is not operating during on-peak hours. (Fan energy consumption was not calculated, but would be much less than that used by the air conditioner compressor.) For the plenum arrangement, 80 m^2 of .0127 m thick wallboard was used for the interior walls. The exterior walls and ceiling were constructed from 0.0191 m wallboard and all the wallboard contained ten percent PCM, for a total latent storage capacity of 31 kWh. All estimates of energy use cover a three-month time period from June 1 to Aug. 31.

For all summer simulations the air conditioner's total cooling capacity, sensible cooling capacity, and power requirements were calculated as a function of indoor drybulb temperature, outdoor drybulb temperature, and the indoor wetbulb temperature. The power requirements are less (and the cooling capacity greater) during cooler nighttime hours. Thus, these calculations include the load-management savings that occur when air conditioner efficiency is improved due to the shift in use from on-peak daytime hours to off-peak nighttime hours.

The first two PCM tests, Cases 5 and 6, showed nearly identical energy use over the three-month period. The on-peak energy use was reduced by 95 percent but the total energy use was about ten percent greater than the base Case 4. The increase in the total energy use is probably attributable to the lower off-peak room air temperatures necessary to charge the PCM. The relative humidity was unaffected, based on an examination of the average, maximum, and hourly distribution of this variable. Although these two tests did not include a clock thermostat override feature, the room temperature exceeded the desired range only four hours, or 0.2 percent during the entire summer test period and the overall discomfort was cut in half. Case 6, with two PCMs showed slightly better comfort results than the Case 5 with one PCM. Because of the increase in overall energy use, these first two load management cases only resulted in an annual saving of \$30, giving a simple payback of 20 years. In summary, the summertime application of the two-PCM/thermostat control strategy provides successful load management but is not economically viable under the economic assumptions used here.

The plenum tests offered quite different results. The plenum arrangement without load control and no PCM energy storage (i.e., Case 7) used 7 percent less total energy than Case 4, the traditional base case, although there was a slight increase in the on-peak energy consumption. The comfort level of these two cases was very similar. The plenum arrangement showed a slight advantage in the drybulb temperature, but was more humid, with 15 percent of the time spent at relative humidity values greater than 70 percent, compared to only three percent of the time for the base case. Case 8, the plenum test case with storage and load management, showed improved humidity control but with unacceptably high drybulb temperatures 14 percent of the time. Case 8 showed a 20 percent energy savings, probably because of these higher interior temperatures. Case 8 was reexamined with a clock thermostat override feature because of the large amount of time at elevated temperatures. The override feature reduced the drybulb temperatures, but the relative humidity was still elevated and the energy and cost savings were small. The plenum arrangement for hot, humid climates therefore appears unsuccessful under both technical and economic criteria.

A similar comparison (Cases 9 and 10) was then made for Nashville's milder summer climate to evaluate the plenum load management arrangement. Here, the drybulb temperature exceeded the desirable range 11 percent of the time, but was within 1°C of the desirable range 99 percent of the time. Therefore, the thermostat override feature was not implemented. The load management of Case 10 showed total energy savings of 15 percent, with 100 percent of the on-peak energy use shifted to off-peak periods compared to Case 9 in Nashville. The relative humidity was only slightly affected, with the load management case showing a small improvement over the base case. The arrangement therefore was a technical success when applied to a moderately hot climate. However, the total annual savings amounted to only \$30. Further examination of wintertime load management saving for the same house (since the PCM temperatures chosen for this arrangement suit both seasons) could increase the savings to an economically justifiable level.

Conclusions

The use of phase-change energy storage within wallboards shows significant load management potential. These conclusions are made under conservative assumptions without any allowance for passive solar gains that will serve to improve the wintertime economics in actual applications. Success depends on the critical interactions between the thermostat control strategy, PCM melting temperatures, and PCM placement. For every case, the thermostat control strategy must focus on providing fully charged energy storage at the start of the on-peak period. Using two different melting temperatures within one structure can improve comfort, overall energy savings, and permit possible year-round applications with seasonal variations in temperature requirements. The melting-temperature customization is facilitated by the state of the art of wax manufacturing and mixing methods and by the localized nature of wallboard production.

Thermal storage in wallboard did not improve occupant comfort with traditional thermostat controls. However, it should still be considered for regions without current load management programs because there is essentially no energy penalty associated with its use, and the incremental cost is relatively small for new construction. Also, the long lifetime of houses should be recognized when considering future energy supply uncertainties that could necessitate load management programs in the near future.

The possible combinations of PCM placement, melting temperatures, and thermostat control strategies are endless and those presented here have not undergone any kind of formal optimization. However, they do represent the results of reasonable engineering assumptions and analysis. Future work should focus on carefully defining the most appropriate relationships between PCM melt temperature, PCM location (interior vs exterior walls), and occupant comfort for various climates.

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