PHASE-CHANGE FRAME WALLS (PCFWS) FOR PEAK DEMAND REDUCTION, LOAD SHIFTING, ENERGY CONSERVATION, AND COMFORT

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ABSTRACT

This paper presents results of side-by-side experimental testing of a technology, referred to as Phase Change Frame Wall (PCFW), whose primary purpose is to increase building thermal mass by the application of phase change materials (PCMs) for lowering peak heat transfer rates across walls of residential and small commercial buildings. A PCFW is a typical wall in which phase change materials (PCMs) have been incorporated via macroencapsulation to enhance the energy storage capabilities of the wall via the high latent heats of the PCMs. The main goal of this study was to determine the feasibility of using PCFWs for peak air conditioning demand reduction, thermal load shifting, energy conservation, and thermal comfort. The results showed that the PCFWs offer the potential to reduce wall peak heat transfer rates by an average of approximately 27 percent. The results also indicate that interior surface temperatures and wall temperature fluctuations (wall temperature swing) could both be reduced by about 2.6 ^{o}F. The PCM used in this research was a commercially available mixture whose main component was calcium chloride hexahydrate.

INTRODUCTION

The technology presented in this paper is referred to as Phase Change Frame Wall (PCFW). A PCFW is a typical wall in which phase change materials (PCMs) have been incorporated via macroencapsulation to enhance the energy storage capabilities of the wall via the high latent heats of the PCMs. The schematic of the PCFW is shown in Figure 1. In building applications, PCMs (e.g., hydrated salt, paraffins, and/or fatty acids) change from solid to liquid and back to solid as a function of wall temperature. During these processes significant amounts of heat are absorbed, stored, and released. In a summer daily cycle, the absorption of heat, its storage, and release by the PCFW make it possible for the peak air conditioning demand from walls and ceilings to be reduced and a portion of the thermal load to be time shifted (forward) to other times of the day, all while the wall temperature remains relatively stable, and at relatively lower temperatures (2 – 3 ^{o}F) than a standard wall. This helps increase occupant comfort and equipment operating life. During the wintertime, heat from the furnace is stored in the PCFW, which is later released back to the heated space, thus reducing heat losses from the conditioned space and furnace cycling, which in turn could increase its efficiency.

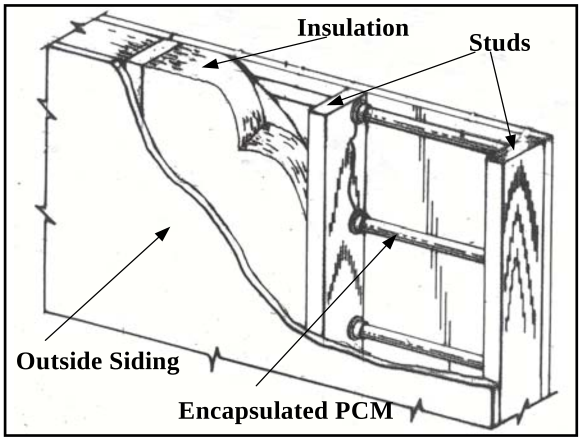

Figure 1. Section of Phase Change Frame Wall (PCFW)

The use of PCFWs targets the problem of elevated on-peak demand from air conditioning use during summers. This technology offers the potential to significantly reduce the impact of energy demand problems, improve extremely poor load factors from this sector, and make residential air conditioning a more cost-effective load to serve. In addition, this technology represents another step in the efforts to further develop energy-efficient home designs that will help lower compressor-based space conditioning and would also improve space comfort systems efficiencies by reducing their current short-cycle operation.

The concept of the phase-change frame walls presented in this paper is an improvement from previous attempts made to integrate PCMs into frame walls. In the past, the attempts to enhance the energy efficiency of walls by the application of thermal mass using the heat storage available during the phase-change process were met with mixed results (Salyer and Sircar, 1989). Various PCMs were utilized for this purpose, which were mostly integrated by imbibing them into gypsum boards. This system demonstrated many advantages in energy savings; however, four main problems limited their potential application. These were (1) durability of PCM-impregnated gypsum boards, (2) low water permeability of the walls, (3) low fire rating, and (4) issues of contact between PCM and people and/or PCM and wall coatings and/or wallpapers (Banu et al, 1998). In the system presented in this paper, a macrocapsule containment method (MCM) rather than an imbibing method (IM) was used. The MCM is safer and more stable than the IM because PCMs are first encapsulated in pipes, which are then capped at both ends to prevent leakage. In addition, the pipes are assembled within the wall and held in place by light metal "ladder type" frames, which are then fastened to the studs. Thus, no holes are drilled across the studs, which otherwise could reduce their structural properties. Figure 2 shows these frames. In the IM, the PCM was infused into the gypsum board. The MCM eliminates PCM dripping (if any) and contact issues, eliminates moisture transfer problem across the envelope, and reduces the flammability of the wall. In addition, because the pipes are never completely filled with PCM, problems associated with PCM volume changes during the phase change process are eliminated.

Figure 2. Light Metal "Ladder Type" Frame Holding PCM Pipes for PCFWs and Details

The main goal of this project was to determine the feasibility of using phase change frame walls (PCFWs) for peak air conditioning demand reduction, thermal load shifting, energy conservation, and comfort during the summertime. The results are expected to apply in particular to buildings located in predominantly cooling dominated climate zones, which are subjected to high electric demand.

The PCM used in this research was a hydrated salt PCM with melting and freezing points in the 82 – 86 ^{o}F range. The main component of this PCM was calcium chloride hexahydrate. The argument for using this type of PCM, as opposed to paraffin-based PCM, was its non-flammability. PCFW performance in which the PCMs were paraffin based is found in Zhang et al. (2005). Performance for phase change structural insulated panels is found in Medina et al. (2008).

FABRICATION OF THE TEST WALLS AND PCFWs

Two sets of walls were fabricated. One set of walls was composed of standard frame walls, which were used as control walls. The second set was made of PCFWs. The walls had dimensions of 6 ft x 4 ft and were made of plywood board, 7/16" thick, as the outside siding, fiberglass insulation (R-11), 2" by 4" studs, and 1/2" thick wallboard. In the PCFW's the PCM was encapsulated in 1-in diameter thin-walled cylindrical copper pipes, 15-in in lengths, which were sealed with caps at both ends to prevent leakage. The pipes were placed horizontally and were attached to the studs via light metal "ladder type" frames for the purpose of easing the integration of the PCM. The number of pipes in each wall depended on the PCM concentration being tested. PCM concentrations of 10 percent and 20 percent were tested in this research. Concentration refers to the weight of PCM in relation to the weight of the interior sheetrock.

PROTOTYPE TESTING

<u>Pre-Retrofit Thermal Performance Verification of the Test Houses</u>

The location of the testing facility was Lawrence, Kansas, where the average summer climate (including the swing season) is made up of mean daily temperatures ranging from the mid 60's to the mid 80's. That is, the average monthly mean high is in the low 80's and the average monthly mean low is in the low 60's. The average median precipitation for the same periods is about 3.8 inches of rain per month. The test houses were identical, were independently metered, and each was space cooled using a chilled water system. The houses are shown in Figure 3.

It was necessary to perform calibration tests before every retrofit. The thermal performance of the two houses was compared and recorded as a reference. Indoor air temperatures of the test houses, surface heat fluxes, and average wall temperatures were measured and compared to verify the similarity of thermal capacity for both houses. During the calibration period, the indoor air temperatures were controlled to a 0.1 °F difference between both test houses. That is, the control house was kept at an average indoor air temperature of 75.5 °F, while the retrofit house was kept at an average temperature of 75.6 °F. Figure 4 is presented as a sample of how close the heat transfer rates compared in the west-facing walls during the verification, or calibration, period. The data shown in Figure 4 set a baseline of how the heat transfer rates compared before the PCMs were added to the PCFWs. Also, in Figure 4, and in all subsequent figures, the darker solid lines represent data of the control house. The lighter solid lines with the symbols (dots) represent the data of the house retrofitted with the PCFWs.

The heat flux sensors were installed on the inside surface of each wall. For each sensor that was installed in one location in one house, another was installed, at the same location, in the other house. Furthermore, each line in the graphs represents weighted averages of several (typically four) heat flux sensors. Some HFMs were installed in heat transfer paths that included only insulation, others in paths that included pipes, and others in paths that included stud. The west walls, being the one that received the most solar radiation in the hottest periods of the afternoons were of special interest for this research.

Figure 3. Test Houses (PCFW Walls Were Installed in the West House)

Table 1 shows the type of sensors used, their operating range, and their accuracy.

Table 1. Sensors and Their Accuracy

Sensor	Range	Accuracy (% Deviation)
Heat Flux Meter	0-10^5 Btu/hr-ft^2	2%
Type T Thermocouple	0 - 200 °F	1 °F
Water Flow Meter	0 - 3 Gal/min	1 %
Pyranometer	0 - 500 Btu/ft^2	3%
Rel. Hum. Transducer	10 - 95%	3%
Digital Thermostats	59 - 86 °F	0.3 °F

From the trend depicted in Figure 4, it was shown that the thermal responses of both test houses were nearly identical. The average difference in peak heat transfer rate was approximately 0.5%. The installation of the "ladder bracket" did not affect the insulation thickness and/or its compactness in a significant manner.

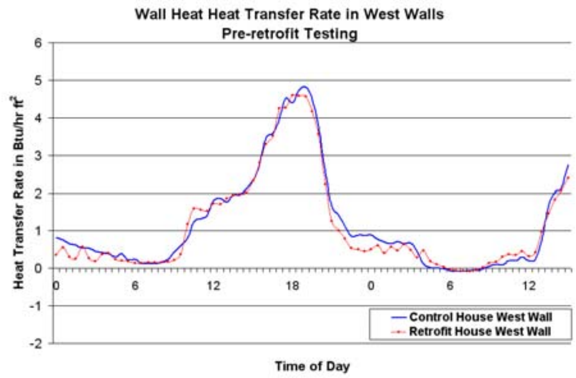

Figure 4. Wall Heat Transfer Rate in West Walls (Pre-Retrofit Tests)

Field Testing – Retrofit West Test House with PCFW at 10 Percent Concentration

The impact of the PCFWs on the thermal performance of walls was significant. While the peak heat transfer rates during the pre-retrofit tests were nearly identical, the difference in peak heat transfer rates between the control walls and the PCFWs was approximately 27 percent. The average reduction in peak heat transfer rates when using the PCFW in the north wall was 33.7 percent. For the south, east, and west walls the reductions were 25.6 percent, 24.3 percent, and 24.6 percent, respectively. In fact, the data shown in Figure 5 correspond to the same walls shown in Figure 1 (west facing walls). Data for all the walls are found in Medina (2007). The average indoor air temperature between both test houses during the experiments that produced the data of Figure 5 differed by approximately 0.4 °F. That is, the control house had an average indoor air temperature of 73.7 °F while the retrofit house had an average indoor temperature of 74.1 °F.

Table 2 summarizes the reductions in peak heat transfer rates in each of the walls.

In terms of surface temperatures, Figure 6 depicts how the PCFW was able to keep a more constant indoor surface wall temperature and a narrower temperature swing than the standard wall.

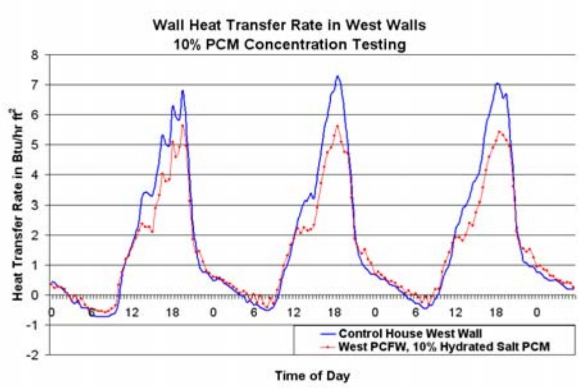

Figure 5. Wall Heat Transfer Rate in West Walls (10% PCM Concentration Tests)

Table 2. Peak Heat Transfer Rate Reductions as a Result of Using FCFWs at 10 % PCM Concentration

Wall Orientation	**Peak Heat Transfer Rate Reduction From Using PCFWs at 10 Percent PCM Concentration (Percent)**
North	33.7
South	25.6
East	24.3
West	24.6
Average	**27.1**

For each wall represented in Figure 6, two segments are depicted. The segment in the left represents the data of the pre-retrofit period, while the segment in the right represents the data of indoor surface temperature for a PCFW and for the equivalent standard wall. For example, for the north walls in Figure 6, the indoor surface temperature of the control house was on average 74.5 ^{o}F while the surface of the PCFW was 72.5^{o}F.

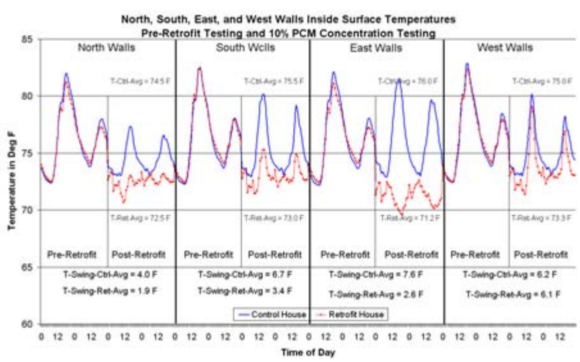

Figure 6. North, South, East, and West Walls Inside Surface Temperatures (Pre- and Retrofit Tests – 10 % PCM Concentration)

The temperature swing in the standard wall was 4.0^{o}F while it was 1.9 ^{o}F for the PCFW.

Table 3 summarizes the findings related to the reductions in indoor wall surface temperatures and in daily temperature swings. Thus, it was clear that the PCFWs, as a result of containing a phase change material, were able to not only lower the inside surface temperature of the walls, in this case by 2.6 ^{o}F on average, but their daily temperature fluctuations, also by an average of 2.6 ^{o}F, which as stated previously, could translate into human comfort and into an increment of the life of comfort equipment.

One other key parameter that affects the comfort level of occupants is relative humidity (RH). Figure 7 shows RH for the pre-retrofit period and for the period after the application of the PCFWs. A major concern emphasized on whether the use of the PCFWs would increase the indoor air RH dramatically. The results indicated that indoor air relative humidity was not affected by the retrofit in a significant way. The increase in relative humidity as a result of the retrofits was less than 5 percent. Table 4 summarizes the results.

Table 3. Reductions in Indoor Wall Surface Temperatures and Reductions in Temperature Fluctuations as a Result of Using PCFWs at 10 % PCM Concentration

Wall Orientation	Average Surface Temperature		Diff	Average Daily Temperature Swing		Diff
	Control	Retrofit		Control	Retrofit	
North	74.5	72.5	2.0	4.0	1.9	2.1
South	75.3	73.0	2.3	6.7	3.4	3.3
East	76.0	71.2	4.8	7.6	2.6	5.0
West	75.0	73.3	1.3	6.2	6.1	0.1
Average	75.2	72.6	2.6	6.1	3.5	2.6

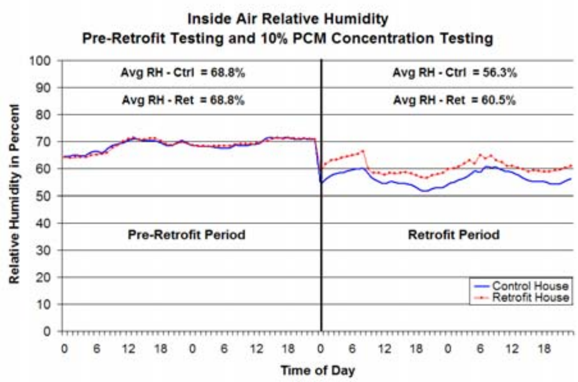

Figure 7. Indoor Air Relative Humidity (Pre- and Retrofit Tests – 10% PCM Concentration)

Table 4. Changes in Indoor Air Relative Humidity as a Result of Using PCFWs at 10% PCM Concentration

	Control House	Retrofit House	Diff
Calibration	68.0 %	68.0 %	0.0 %
10 % PCM Tests	56.3 %	60.5 %	4.2 %

Field Testing – Retrofit West Test House with PCFW at 20 Percent Concentration

The same analyses that were performed for the 10 percent PCM concentration were performed for a concentration of 20 percent.

From Table 5, and except from the north-facing wall, it was seen that doubling the quantity of PCM in the PCFWs improved the performance by 3.6, 1.4, and 2.6 percentage points for the south, east, and west orientations, respectively. The data of Figure 8 correspond to the walls of Figures 4 and 5, except that in Figure 8 the PCFWs carried a PCM concentration of 20 percent.

Table 5. Peak Heat Transfer Rate Reductions as a Result of Using FCFWs at 20% PCM Concentration

Wall Orientation	Peak Heat Transfer Rate Reduction From Using PCFWs at 10 Percent PCM Concentration (Percent)
North	27.1
South	29.2
East	25.7
West	27.2
Average	27.3

The process of solidification of the PCM in the PCFWs was more noticeable for the 20 percent PCM concentration than for the 10 percent. The values of heat transfer rates during the PCM solidification were higher than those of the control wall because the PCMs were releasing the heat that had been stored during the previous hours.

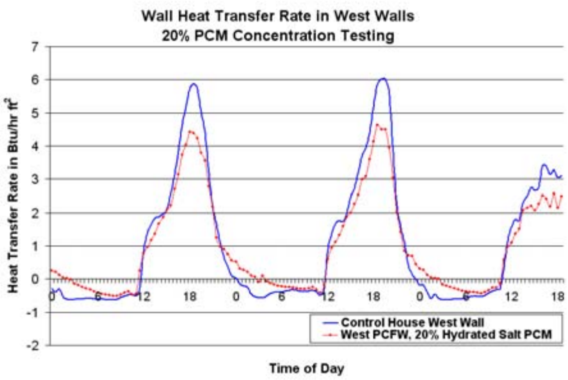

Figure 8. Wall Heat Transfer Rate in West Walls (20% PCM Concentration Tests)

Table 6 shows that indoor surface temperatures in the control and PCFW walls responded in a similar manner to Table 3. The average indoor surface temperature of the four control walls was 75.0 ^{o}F while the indoor surface temperatures in the PCFWs were 72.3 ^{o}F, or a 2.7 ^{o}F reduction. Also, the temperature of the surface of the PCFW was more constant than the control walls. The average temperature fluctuation (swing) in the control walls was 5.7 ^{o}F while it was 3.1 ^{o}F in the PCFW, or a 2.6 ^{o}F swing reduction; which represent the same values obtained for the PCFWs with 10 percent PCM concentration.

Table 6. Reductions in Indoor Wall Surface Temperatures and Reductions in Temperature Fluctuations as a Result of as a Result of Using PCFWs at 20% PCM Concentration

Wall Orientation	Average Surface Temperature		Diff	Average Daily Temperature Swing		Diff
	Control	Retrofit		Control	Retrofit	
North	74.5	72.2	2.3	3.9	1.5	2.4
South	75.5	72.8	2.7	7.5	3.7	3.8
East	75.3	71.1	4.2	5.9	1.9	4.0
West	74.8	73.2	1.6	5.4	5.3	0.1
Average	75.0	72.3	2.7	5.7	3.1	2.6

In the case of the 20 percent PCM concentration the relative humidity of both houses remained virtually the same at about 64 percent. This is shown Table 7.

In summary, doubling the amount of PCM did not produce significantly different values from those that had already been obtained when using only 10 percent PCM concentration in the PCFWs.

Table 7. Changes in Indoor Air Relative Humidity as a Result of Using PCFWs at 20% PCM Concentration

	Control House	Retrofit House	Diff
Calibration	68.0 %	68.0 %	0.0 %
20 % PCM Tests	64.0 %	64.4 %	0.4 %

PUBLIC BENEFITS

The proposed technology offers the potential for energy, environmental, and economic benefits. The technology also offers the potential to reduce electric energy demand and electric consumption from space cooling, as well as space heating energy. The primary environmental benefits from the proposed technology would be air pollution emission reductions from the energy savings. In addition, this technology constitutes another step in the nation's efforts to develop energy-efficient home designs that will allow space cooling and space heating systems to achieve their intended efficiencies by reducing current short-cycle operation, which may reduce energy resource use and ultimately decrease emissions of greenhouse gases.

In summary, the general benefits of the proposed technology include the potential to: (1) Save energy and cost savings. (2) Shift electricity usage from peak to off-peak times. Peak electric demand typically occurs in the early to mid afternoon. If PCM-enhanced insulation were used, building cooling peak demand could potentially be shifted by a few hours, thus allowing power producers to keep operating costs, and subsequently, consumer energy bills low. (3) Increase the efficiency of air conditioners, chillers, furnaces and heat pumps and/or to reduce their sizes. Space cooling devices run at optimum conditions when longer on-times are allowed. This will reduce energy consumption. This also helps in maintaining the indoor humidity at acceptable levels. (4) Expand geographic regions in which the-more-efficient heat pumps are practical for heating in winter. (5) Reduce air pollution emissions.

SUMMMARY AND CONCLUSIONS

The purpose of this research was to evaluate a thermally enhanced residential frame wall, which was referred to as phase change frame wall – PCFW, for possible application in residential and small commercial buildings. A PCFW is a typical residential frame wall, consisting of outside siding, thermal insulation, studs, and inside sheathing, in which phase change materials (PCMs) are incorporated, to enhance the energy storage capabilities of the wall, and thus thermal mass of the building, via the high latent heat of fusion of the PCMs. PCMs are substances (e.g., hydrated salts, paraffins, and/or fatty acids) that change from solid to liquid and back to solid as a function of wall temperature.

For the experimental evaluation, two wood-framed test houses of identical dimensions, equipped with space conditioning systems, were used in which a monitoring system was installed to measure and collect thermal performance parameters including surface and air temperatures, heat transfer rates, relative humidities and weather parameters. A hydrated salt PCM with melting/solidification points in the range between 82 and 86 °F was used. The PCM was integrated into the PCFW via macroencapsulation using copper pipes, which were held in place in the wall by a light-weight metal "ladder type" frame attached to the studs and located just behind the interior sheathing layer. PCFWs with PCM concentrations of 10 percent and 20 percent were tested and evaluated. Concentrations of PCM were defined in terms of the weight of the PCM to the weight of the interior wallboard.

Before the testing of the PCFWs a pre-retrofit tests (calibration and/or verification tests) were carried out to establish a baseline and to demonstrate that the thermal performance of the test houses was nearly identical. During the pre-retrofit testing the indoor air temperatures of both test houses were maintained at differences of less than 0.1 ^{o}F and on average the peak heat transfer rates of equivalent walls (i.e., north wall in the would-be-control house vs. the north wall of the would-be-retrofit houses) were less than 3 percent.

The peak heat transfer rates through the PCFWs were substantially reduced when compared to those across a standard wall facing the same orientation. For the north facing walls, the reduction in peak heat transfer rate as a result of using the PCFW with a PCM concentration of 10 percent was 33.7 percent. Similarly, for the south, east, and west walls the reductions were 25.6 percent, 24.3 percent, and 24.6 percent, respectively. Therefore, when all the wall orientations were considered, the average peak heat transfer rates across the PCFW vs. those of the standard wall were reduced by approximately 27.0 percent. During these tests, the indoor air temperature between both houses differed by less than 0.4 ^{o}F on average.

In terms of surface temperatures, it was found that the use of the PCFWs reduced the wall temperature by an average of 2.6 ^{o}F. Similarly, the temperature fluctuations of the interior surface of the PCFW were reduced by an average value of also 2.6 ^{o}F. As for load shifting, it was observed that the "shift" was about one hour. The relative humidity in the retrofit house was about 4 percent higher than that of the control house.

For 20 percent PCM concentration PCFWs the average reduction in peak heat transfer rate was 27.3 percent when all orientations were considered. For the north, south, east, and west, the percent reductions in peak heat transfer rates were 27.1 percent, 29.2 percent, 25.7 percent, and 27.2 percent, respectively. The interior surface temperatures were reduced by 2.7 ^{o}F and the temperature fluctuations by 2.6 ^{o}F. No increase in indoor air relative humidity was observed. These experiments were also well controlled. The average difference in indoor air temperatures was also less than 0.5 ^{o}F.

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