Use of PCM-Enhanced Insulations in the Building Envelope

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ABSTRACT

A phase change material (PCM) alters the heat flow across the building envelope by absorbing and releasing heat in response to cycling ambient temperatures. The benefit of a PCM is reduction in heating and cooling loads and in many cases a shift in peak-load demands and the time of day of the peak load.

Ambient or interior temperature cycling past the phase change temperature range is necessary for the PCM to function. The design of a PCM application requires selection of material, identification of PCM location and bounding thermal resistances, and specification of the amount of PCM to be used. PCM can be distributed in an insulation or building material or packaged for localized application. This paper describes small-scale laboratory testing, large- scale laboratory testing, and field studies undertaken to evaluate the energy savings potential for PCM in the building envelope.

INTRODUCTION

A PCM with a phase change temperature near the temperature of the conditioned space results in a small temperature difference between the PCM and the interior air during the phase change. The heat flow in or out of the conditioned space depends on the thermal resistance between the PCM and the interior air. A reduction in the temperature difference translates to a reduction of heat flow. Heat retained by the PCM is returned to the ambient during the "discharge" part of the diurnal cycle. This discharge is controlled by the thermal resistance between the PCM and the inside air and the level of thermal resistance between the PCM and the outside. The design of a PCM application must address these factors.

Energy and thermal comfort benefits of conventional massive walls, floors, or slabs, have been well known for centuries. PCM-enhanced building materials have been utilized for at least 40 years as lightweight alternatives for conventional massive systems.

Many PCMs have been considered for building applications, including inorganic salt hydrates, organic fatty acids and eutectic mixtures, fatty alcohols, neopentyl glycol, and paraffinic hydrocarbons. In the US, there were several moderately successful attempts in the 1970s and 1980s to use different types of organic and inorganic PCMs to reduce peak loads and heating and cooling energy consumption (Balcomb 1983). Previous investigations focused on impregnating concrete, gypsum, or ceramic masonry with salt hydrates or paraffinic hydrocarbons. Most of these studies found that PCMs improved building energy performance by reducing peak-hour cooling loads and by shifting peak-demand time.

In past studies, non-encapsulated paraffinic hydrocarbons generally performed well (Tomlinson et al. 1992), but they sometimes compromised the fire resistance of the building envelope. Kissock et al. (1998) reported that wallboard including a paraffin mixture made up mostly of n-octadecane, which has a mean melting temperature of 75°F and a latent heat of fusion of 65 Btu/lb, "was easy to handle and did not possess a waxy or slick surface. It scored and fractured in a manner similar to regular wallboard. Its unpainted color changed from white to gray. The drywall with PCM required no special surface preparation for painting." In addition, Salyer and Sircar (1989) reported that during tests of 4×8 ft sheets of wallboard with PCM, there was insignificant loss of PCM after three months of exposure to continuously cycled 100°F 38˚C) air.

The ability of PCMs to reduce peak loads is also well documented. For example, Zhang, et al. (2005) found peak cooling load reductions of 35 to 40 percent in side-by-side testing of conditioned small houses with and without paraffinic PCM inside the walls. Similarly, Kissock et al. (1998) measured peak temperature reductions of up to 10°C in side-by-side testing of unconditioned experimental houses with and without paraffinic PCM

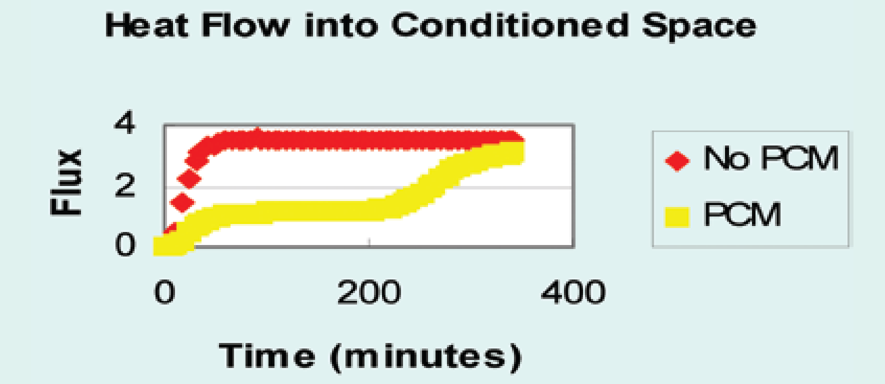
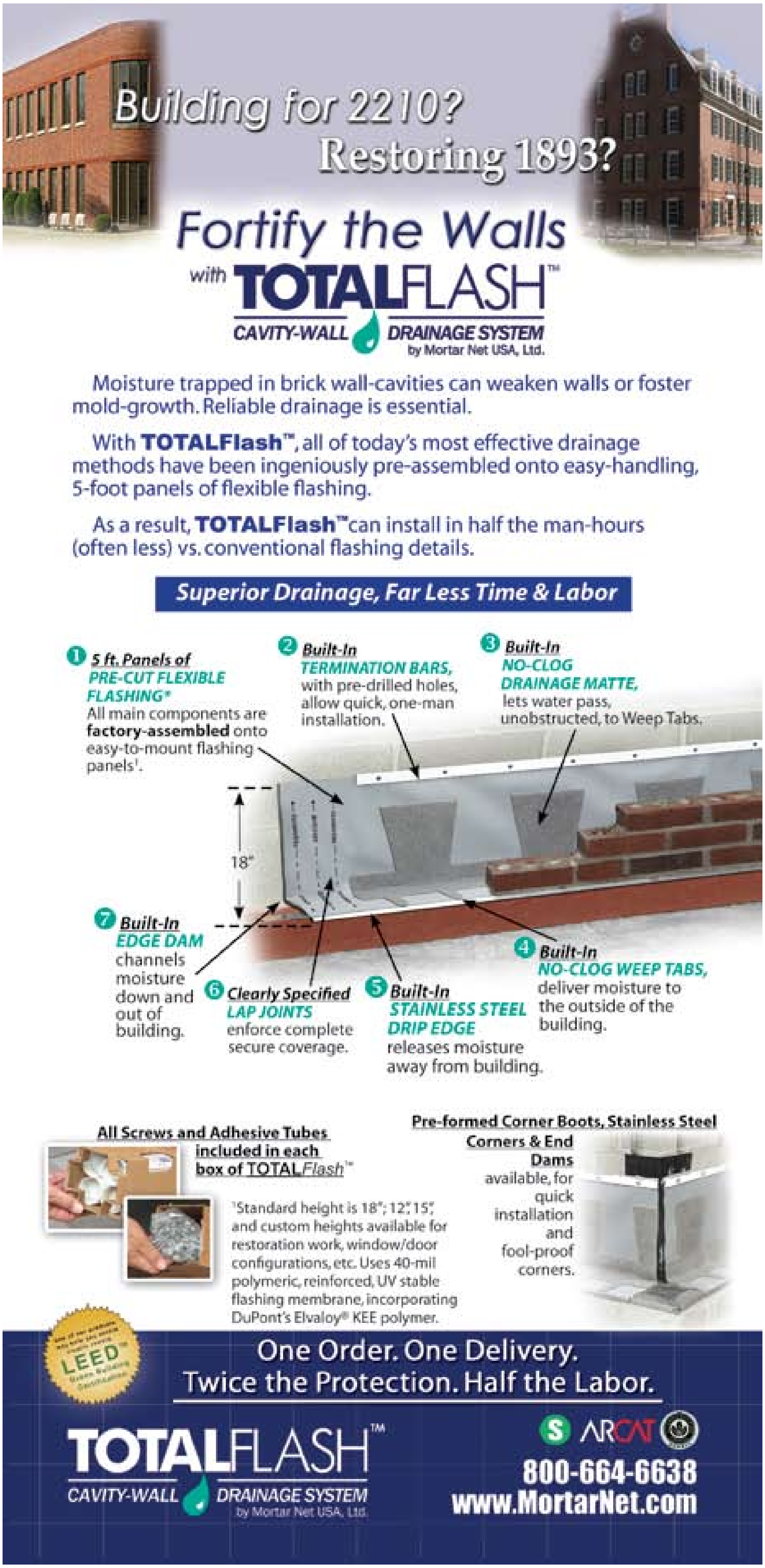


Figure 1. Small-scale test of a localized PCM showing heat flux (Btu/ft2·hr).



wallboard. Kosny (2006) reported that PCM-enhanced cellulose insulation can reduce wall-generated peak-hour cooling loads by about 40 percent .

SMALL-SCALE LABORATORY TESTS

The use of a heat-flow meter appartaus to study transient heat flow has been discussed (Kosny et al. 2007) and (Alderman 2007). Both distributed and localized PCM applications have been evaluated by comparing insulation with PCM and insulation without PCM subjected to the same thermal cycling. **Figure 1** is an example of transient heat flux data that show the difference between an insulation containing a localized PCM and the same insulation without PCM. The area between the curves is a measure of the reduction of heat flow to the cold side of the test.

The overall saving requires an additional step of determining how much of the heat contained in the PCM is returned to the ambinet during the "discharge" part of the cycle. The time required to "charge" the PCM shown by the horizontal part of the curve for the material with PCM is controlled by the amount of PCM and the level of thermal resistance between the PCM and the elevated temperature. In this example there was a termal resistance of 9 ft2·h·°F/Btu (R 9) between the PCM and the warm side of the test specimen and 5 ft2·h·°F/Btu (R 5) between the PCM and the cold side of the specimen.

The time scale starts with the specimen at constant temperature and no heat flow across the boundaries. **Figure 2** summarizes data obtained with a heat-flow meter and insulation containing distributed PCM. The results in **Figure 2** illustrates how the performance depends on the amount of PCM present. A 70 percent reduction in cumulative heat flow is shown for the test specimen with 30 wt. percent PCM. This overall savings depends on the efficiency with which the heat absorbed by the PCM can be discharged to the ambient.

LARGE-SCALE LABORATORY TESTING OF WALLS CONTAINING INSULATION WITH DISTRIBUTED PCM

During 2002-2004 PCM-enhanced fiber insulations were tested for their effectiveness as wall-cavity insulation.

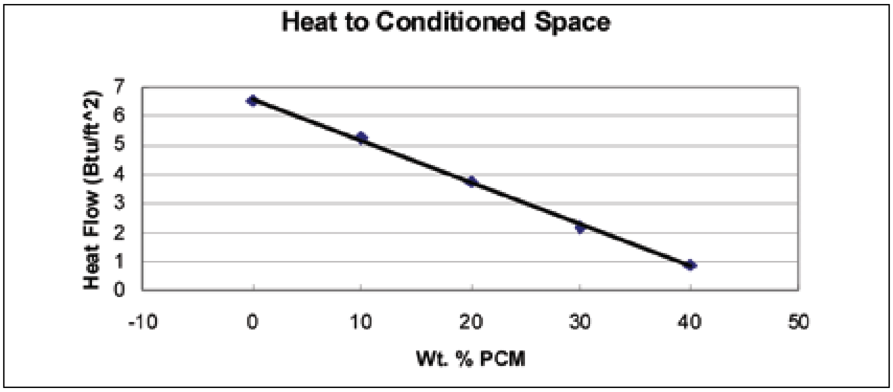


Figure 2. Small-scale determination of the effect of increasing PCM loading.

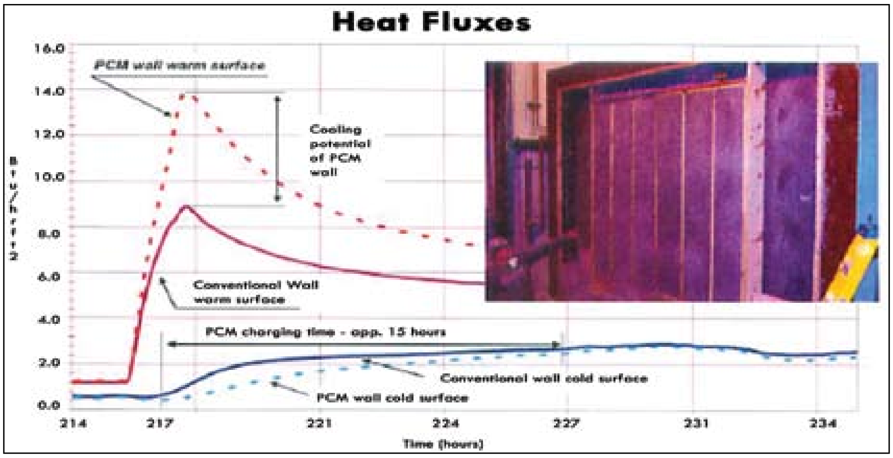


Figure 3. Heat flux measured during a dynamic hot-box measurement in a 2x6 wood-frame wall containing PCM-enhanced cellulose insulation.

Small amounts of different cellulose–PCM blends were made using a pilot-scale production line (Kosny 2006). In this project, microencapsulated paraffinic PCM was used. The PCM microcapsules were between 2 and 20 micrometers in diameter with melting point 78.5°F (25.8°C). This PCM is produced with the use of a microencapsulation technology that holds wax droplets inside hard acrylic shells. Since production of cellulose insulation includes the addition of dry chemicals, the addition of a dry PCM component does not require significant changes in the manufacturing or packaging processes.

A series of steady-state heat flow apparatus thermal conductivity measurements were conducted on the two- inch thick samples of PCM-enhanced cellulose insulation. These tests showed that the addition of up to 30 percent of the microencapsulated PCM does not increase the thermal conductivity of the cellulose insulation (Kosny 2006).

A nominal 8×8 ft wood-frame wall specimen was used for transient hot-box testing of a PCM–cellulose blend. The test wall was constructed with 2×6 in. wood framing installed 16-in. OC. Three wall cavities were insulated with cellulose insulation with density 2.6 lb/ft3. Three remaining wall cavities were insulated with a cellulose–PCM blend at a density of 2.6 lb/ft3 containing 22 wt percent PCM. It is estimated that about 38lb of PCM-enhanced cellulose insulation (containing 8lb of PCM) was used for this experiment.

At the beginning of the hot-box measurement, temperatures on both surfaces of the specimen were stabilized at about 65°F (18.3°C) on the cold side and 72°F (22°C) on the warm side. The temperature of the warm side was rapidly increased to 110°F (43.3°C). After about 120h, the hot-box heaters were turned down and the temperature of the warm side of the wall was reduced by natural cooling to 65°F (18.3°C). **Figure 3** shows the heat fluxes for both sides of the wall recorded during the rapid warm-up period.

It took 15 hours to charge the PCM material in the wall. Heat fluxes on both sides of the wall were measured and compared. For three five-hour time intervals, heat fluxes were integrated for each surface. Comparisons of measured heat flow rates on the wall surface, which was opposite the thermal excitation, enabled an estimate of the potential thermal load reduction generated by the PCM. In reality, most daily thermal excitations generated by solar irradiance are no longer than five hours (peak-hour time). Heat flux was measured during the first five hours after the thermal ramp.

The PCM-enhanced cellulose material reduced the total heat flow through the wall by over 40 percent . The load reduction for the entire 15h of the PCM charging time was close to 20 percent . Surface temperatures on the PCM part of the test wall specimen were approximately 2°F (16.6°C) lower during the time of the thermal ramp (cooling effect).

FIELD TESTING OF INSULATION WITH PCM

Two small-scale field tests were performed on 2×6 in. wood-frame walls insulated with PCM-enhanced cellulose

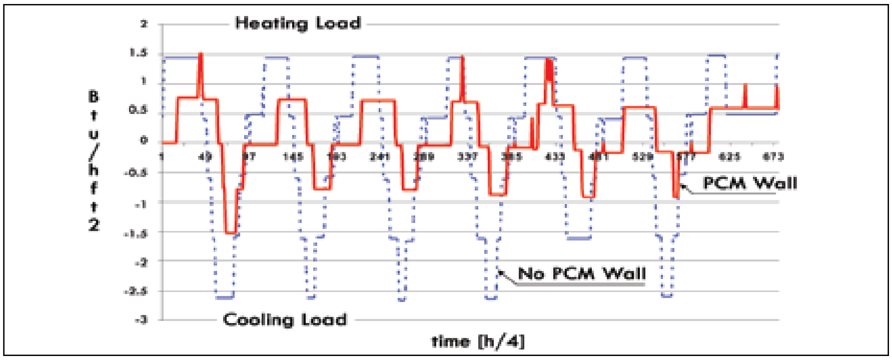


Figure 4. Comparison of surface heat fluxes recorded during field experiment which took place during a sunny week in April.

insulation. Test walls were located in Oak Ridge, TN and Charleston, SC. In both cases, PCM walls were located next to identical wood-frame walls containing cellulose insulation with no PCM. To estimate the effect of direct solar radiation, the walls tested in Oak Ridge faced south and the walls tested in Charleston faced northwest.

Figure 4 shows heat fluxes recorded in Tennessee on test walls during a sunny week in late April 2006. Exterior surface temperatures on the Oak Ridge walls were cycling between 120°F (48.8°C) during the days and 55°F (12.7°C) during most nights. Field test data demonstrated that the PCM wall was more thermally stable than the conventional wall. Significantly lower heat fluxes were observed in the PCM wall: peak-hour heat flux was reduced by at least 30 percent compared with the conventional wall without PCM. In addition, a shift of about two h in the peak-hour load was observed in the PCM wall.

Analysis of the temperatures in the tested walls showed that the PCM was going through full charging and discharging processes during the 24-h time period.

Recorded temperature profiles in **Figure 5** show that the PCM thermally stabilized the core of the wall as a result of its heat storage capacity. Temperature peaks were notably shifted inside the PCM wall. Significantly lower temperatures were observed during the night in the wall cavities where no PCM was used. The conventional wall (with no PCM) was warming up and cooling down more quickly than the wall with PCM.

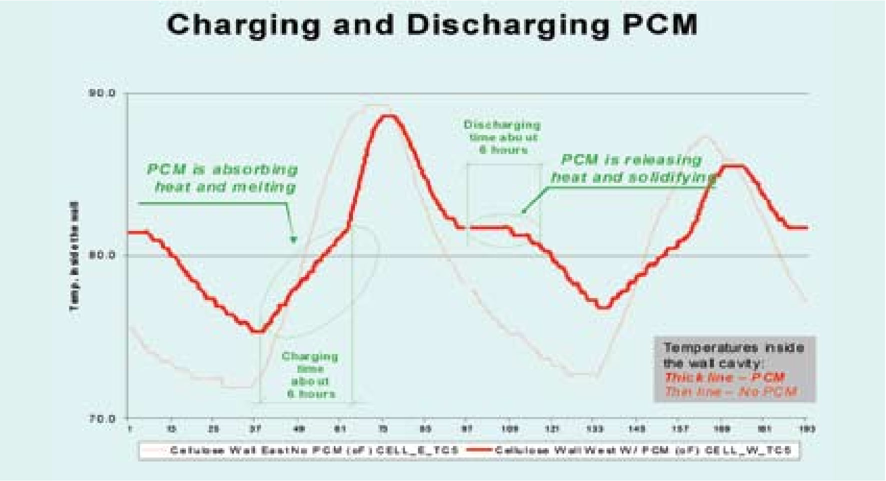


Figure 5. Temperature profiles inside the wall cavities of the south-facing test walls (no-PCM wall located on the east side, PCM wall located on the west side), during a sunny week in late April in Oak Ridge, TN.

Figure 6. Test attic module used for testing of PCM-enhanced cellulose.

ANALYSIS OF THE PCM DISCHARGE TIME: DYNAMIC TESTS OF THE RESIDENTIAL ATTAC CONTAINING PCM-ENHANCED PCM

One of the most important design criteria for building assemblies containing PCM is the charging and discharging times, which has to be less than 24 hours. If PCM is not fully discharged before the start of the next cycle, then the full thermal storage potential will not be available. In order to investigate the total charging-discharging times for a full-scale attic assembly, dynamic hot-box experiments were performed in the residential attic module shown in **Figure 6**.

The attic module was tested under periodic temperature changes in the Large Scale Climate Simulator (LSCS) at the Oak Ridge National Laboratory. Two concentrations of microencapsulated PCM were tested (5 percent and 20 percent by weight). The main focus of the attic tests was discharging time of the PCM, since dynamic hot-box testing of the wall had already proved the good thermal performance of the PCM-enhanced cellulose insulation. Charging is not a problem in attics because of the intensive fluctuations of the attic air temperature during sunny days (a rapid increase in temperature caused by the sun). However, the attic cooling process is significantly slower.

In a well-designed PCM application, 100 percent of the PCM material should be able to fully discharge before the beginning of the next cycle.

During the dynamic LSCS tests, the model of a residential attic was subjected to periodic changes of temperature (65°F [18.3°C] for about 16 h, rapid temperature ramp to 120°F [48.8°C] and exposure to 120° F [48.8°C] for about 4 h, followed by natural cooling back to 65°F [18.3°C]). An array of thermocouples installed at one inch intervals was used to monitor the temperature distribution across the attic insulation.

One of the interesting findings from the analysis of temperature data was that only layers of insulation located higher than four inches from the bottom of the attic were involved in the phase change process. An analysis of the temperature profiles demonstrated charging and discharging of the PCM (similar to those presented in **Figure 3** for PCM wall) even in attic insulation containing only five percent PCM. It took about six to eight hours to fully discharge the energy stored in these layers. No forced ventilation was needed to discharge the PCM.

CONCLUSION

Several applications of PCM-enhanced building insulations have been tested and analyzed over the past four years.

Two forms of PCM application were

considered: dispersed PCM in cellulose wall insulation, and PCM application with fiberous insulations as a part of an attic insulation system.

1. Laboratory-scale testing has demonstrated the potential for energy savings with PCMs.
2. A dynamic hot-box test that included a 40°F (4.4°C) thermal ramp, performed on a 2×6 wood frame wall, demonstrated about 40 percent reduction of the surface heat flow as a result of the use of PCM. This finding was confirmed by the field tests.
3. A dynamic hot-box test performed on the attic containing PCM-enhanced cellulose insulation proved that PCM can be fully discharged without the use of additional forced ventilation of the attic.

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David Yarbrough is a member of the research staff of the Building Technology Center at the Oak Ridge National Laboratory and a Principal at R&D Services, Inc. Dr. Yarbrough has been active in thermal insulation research for over 25 years.

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