PCM-Enhanced Building Envelopes in Current ORNL Research Projects

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ABSTRACT

This paper summarizes the results of experimental and theoretical analysis performed at ORNL during 2003–2006 on organic Phase Change Materials (PCMs) used in building thermal envelopes. PCMs have been tested as a thermal mass component in buildings for at least 40 years, and most studies have found that PCMs enhance building energy performance. However, problems such as high initial cost, loss of phase-change capability, corrosion, and PCM leaking have hampered widespread adoption. Paraffinic hydrocarbon PCMs generally performed well, but they increased the flammability of the building envelope. Traditionally, PCMs were used to stabilize interior building temperature. Thus the best locations for PCM were interior building surfaces—walls, ceilings, or floors. In research under way at Oak Ridge National Laboratory (ORNL), PCM is used as an integral part of the building thermal envelope. Microencapsulated paraffinic PCM is positioned in the wall cavity or installed as a part of the attic insulation system.

INTRODUCTION

The authors anticipate that new type of PCM-enhanced building components could have a high potential for successful adoption in U.S. buildings because of their ability to reduce energy consumption for space conditioning and reduce peak loads. Other anticipated advantages of PCMs are improvement of occupant comfort, compatibility with traditional wood and steel framing technologies, and potential for application in retrofit projects. Most current studies (Feustel 1995, Tomlinson 1992, Kosny 2001) demonstrate that the use of thermal mass in well-insulated buildings can generate heating and cooling energy savings of up to 25% in U.S. residential buildings. Considering that new PCM-enhanced building envelope components are installed in about 10% of U.S. homes, the potential for energy savings is between 0.2 and 0.5 quad/year (including an additional 10% of U.S. residential buildings that can be retrofitted using PCM-enhanced materials).

The main goal of this project was experimental validation of several theoretical concepts developed earlier by the ORNL research team. This paper presents results from dynamic hot-box tests and small-scale field experiments performed using new types of PCM-enhanced materials. The ORNL team is working on both inorganic and organic PCMs; only paraffinic PCMs are discussed in this paper.

PCMs have been used in buildings for at least 40 years. Many potential PCMs were tested for building applications, including inorganic salt hydrates, organic fatty acids and eutectic mixtures, fatty alcohols, neopentyl glycol, and paraffinic hydrocarbons. 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). Historically, performance 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.

Paraffinic hydrocarbon PCMs generally performed well, but they 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 24°C (75°F) and a latent heat of fusion of 143 kJ/kg (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 1.22×2.44 m (4×8 ft) wallboard with PCM, there was insignificant loss of PCM after 3 months of exposure to continuously cycled 37°C (100°F) air.

The capability of PCMs to reduce peak loads is also well documented. For example, Zhang, Medina, and King (2005) found peak cooling load reductions of 35 to 40% 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 (18°F) in side-by-side testing of unconditioned experimental houses with and without paraffinic PCM wallboard. Kosny (2006) reported that PCM-enhanced cellulose insulation can reduce wall-generated peak-hour cooling loads by about 40%.

In former applications, the chosen locations for flammable paraffinic PCMs were the interior surfaces of the wall, ceiling, or floor. In this work, the PCM-enhanced materials were positioned inside the wall cavity or installed as a part of the attic insulation system. Placement in these locations is expected to significantly reduce flammability issues that were common in earlier applications of the technology. Also, detailed optimizations performed for PCM applications showed a significant reduction of initial costs with a corresponding reduction in payback time.

Dynamic Hot box Tests of Wood Frame Wall Insulated with Fiberglass Batts and PCM-Enhanced Foam

During last two decades, numerous wall assemblies containing convetional thermal mass and PCM components have been studied at ORNL (Tomlinson et.al. 1992; Stovall and Tomlinson 1995). New material configurations were developed and theoretically optimized using transient heat condution simulations (Kossecka and Kosny 2001; Kosny 2006). Experimental validation has been performed with the use of dynamic hot-box testing. One of the first tested material configurations was gypsum-based stucco containing 20% by weight of microencapsulated PCM. A test wood frame wall containing about 35 lb (15.9 kg) of PCM (in a ¾ in. or 1.9-cm. thick layer of stucco) was constructed and tested in the hot box. This simple dynamic hot-box test, very similar to previous experiments performed on PCM-impregnated gypsum boards, enabled estimation of charging and discharging times for PCM (the time has to be less than 24 hours). It also aided in validating the transient computer models and enabled development of a special thermal ramp procedure for testing of wall assemblies containing PCMs.

FIGURE 1. Six-cavity 2x4 wood-frame wall in hot-box frame.

A nominal 2×4 wood frame wall insulated with novel dynamic reflective insulation (DRI) containing PCM-enhanced open-cell polyurethane foam was avaulated. In total, the DRI contained about 0.1 lb of PCM per ft^2 (0.49 kg/m^2) of the surface area. The melting point of this PCM was 78°F (25.5°C), and the maximum enthalpy was about 60 Btu/lb (140 J/g). As shown in Figure 1, this wall had six identical cavities (2×4 wood studs were installed at 16-in. on center [o.c.], and the cavities were insulated with unfaced R-13 fiberglasss batts). In three of these cavities, a novel batt insulation facing (DRI) was installed (see Figure 2).

All cavities used conventional ½ in. thick (1.3-cm.) oriented strand board sheathing on one wall side. On the opposite side, ½ in. thick (1.3-cm.) gypsum board was installed.

During dynamic hot-box testing, side-by-side thermal performance was compared for two wall options:

1. Three conventional 2×4 wall cavities insulated with R-13 fiberglass batts

2. Three 2×4 wall cavities insulated with R-13 fiberglass batts and DRI containing PCM-enhanced foam. This part of the wall surface area, 32 ft^2 (6 m^2), had a total heat storage capacity of about 192 Btu (202.6 KJ).

Dynamic hot-box testing was initiated with about 60 h of steady-state heat flow in the wall and a temperature difference across the test specimen of 47°F. Next, the temperature on the cold side was increased to 66°F and the temperature of the warm side was slightly increased to 78°F. After the assembly reached steady-state heat transfer condition, a rapid temperature excitation was introduced on the warm side of the wall (temperature was increased to 95°F). Next, after almost 80 h, the hot-box heaters were turned down and the temperature of the warm side of the wall was reduced by natural cooling to 68°F. Table 1 shows the temperature profiles used for the dynamic hot-box test.
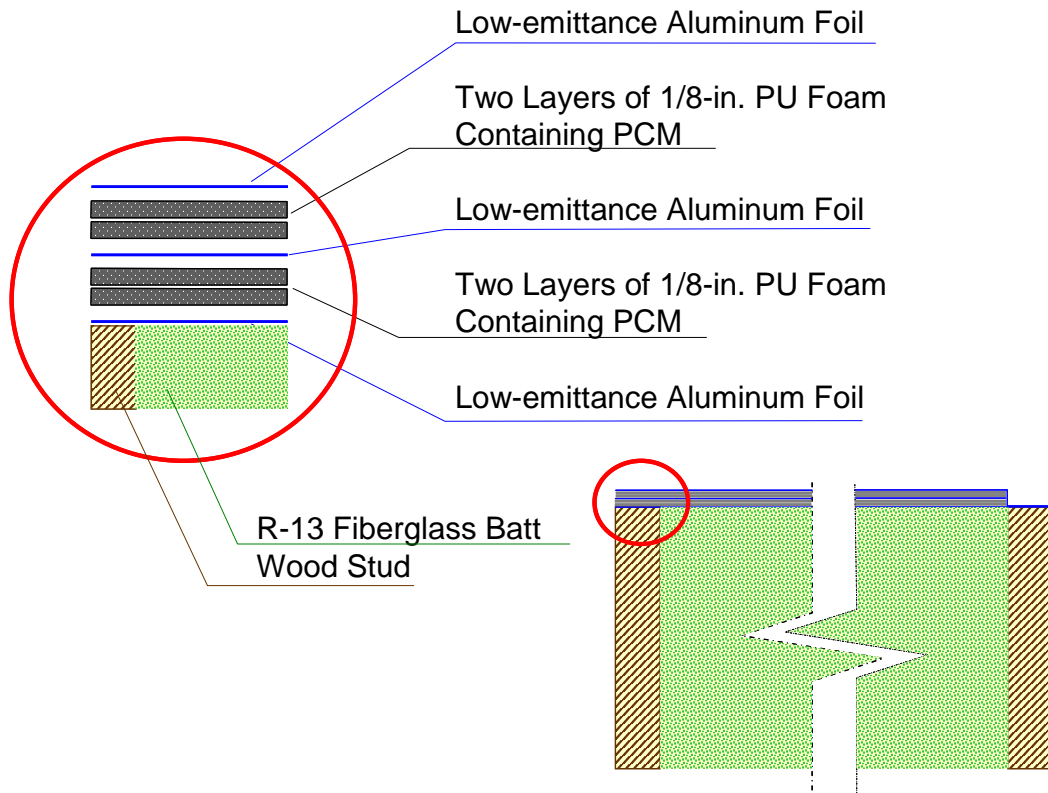
FIGURE 2. Schematic of Dynamic Radiant Insulation (DRI) containing PCM-enhanced foam.

Table 1. Temperature profiles of the dynamic hot-box test of the wood frame test wall containing DRI and traditional fiberglass batt insulation

	Initial steady-state period	Ramp on the cold side	Rapid warm-up ramp	Cool-down ramp
Warm side	73°F (23°C)	78°F (26°C)	95°F (35°C)	68°F (20°C)
Cold side	20°F (-6.6°C)	66°F (19°C)	68°F (20°C)	66°F (19°C)

A side-by-side thermal performance comparison of the PCM wall containing DRI and a traditional 2×4 wood frame wall demonstrated a potential for steady-state and dynamic energy savings resulting from application of a multilayer dynamically working batt facing containing PCM-enhanced foam and low-e surfaces.
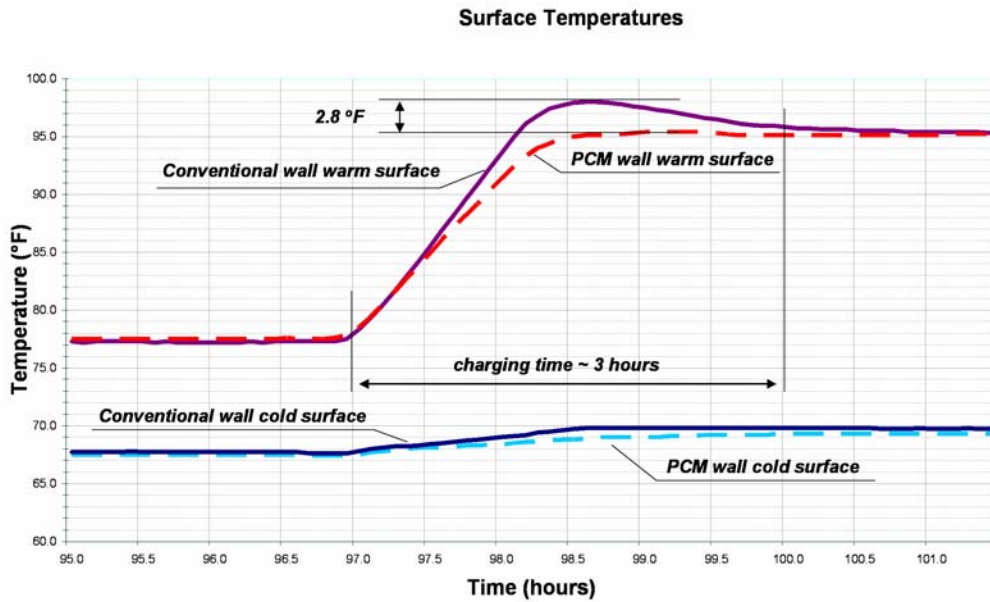
FIGURE 3. Surface temperatures during dynamic hot-box test of the PCM wall containing DRI and conventional 2x4 wood framing.

As shown in Figure 3, it took about 3 h to fully charge the PCM in the test wall after a 17°F (22.8°C) thermal ramp. Analysis of the wall surface temperatures showed that the PCM demonstrated significant cooling and temperature stabilizing potential—there was a difference of almost 3°F (1.6°C) between the conventional and the PCM wall on the side of the thermal excitation. Since the PCM wall warmed much more slowly than the conventional wall (cooling effect), the temperature difference between the hot-box meter side air and the surface of the PCM wall was higher compared with the conventional wall. Therefore, the heat flux on the warm side of the PCM wall was significantly higher as well. This difference in heat fluxes is shown in Figure 4 as "*Cooling potential of the PCM wall*."
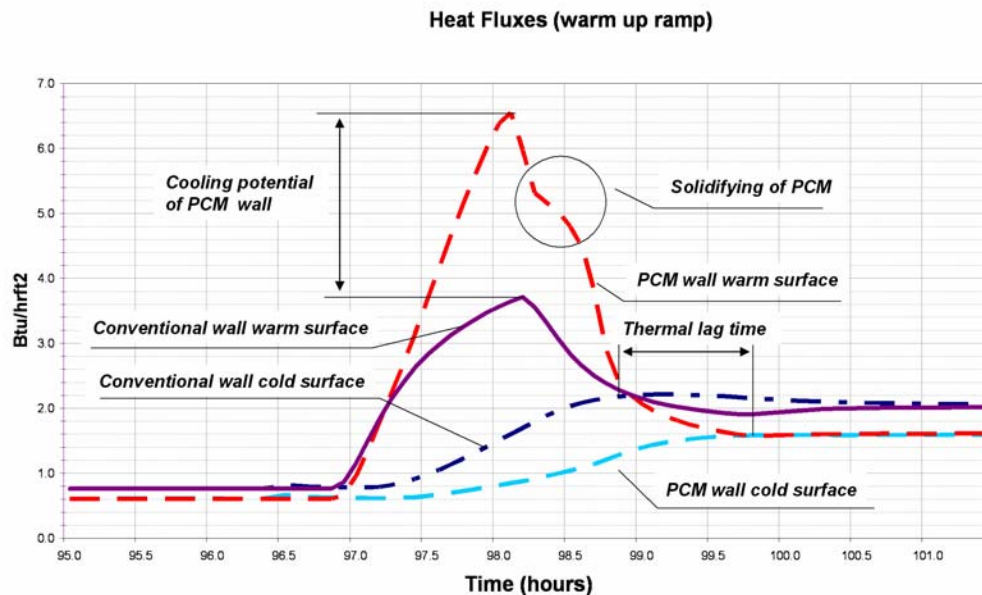
Heat Fluxes (warm up ramp)

FIGURE 4. Heat fluxes during the time of thermal excitation of the PCM wall containing DRI and conventional 2x4 wood-framed wall.

Comparisons of heat fluxes measured on the cold side of the wall during the time just after the thermal excitation (heat fluxes were integrated over the time) demonstrated a difference of about 40%. This value translates directly to a potential 40% reduction in the wall-generated peak-hour cooling load. A thermal lag time of about 1 h can also be observed on the cold surface of the PCM wall. For the same wall configuration, the discharge time for the PCM during the cool-down ramp was about 12 h.

Measurements of heat fluxes during periods of time with a steady-state heat flow enabled comparisons of the R-values of both parts of the test wall. Since the heat flux differences were over 20%, the R-value difference was between R-3 and R-4. This difference in R-value has to be attributed to the additional thermal resistance provided by the DRI.

TESTING OF RESIDENTIAL ATTIC USING CONCENTRATED PCM THERMAL STORAGE

A prototype residential roof using a cool-roof surface, natural subventing, and DRI containing a PCM was designed and field tested. The ORNL team used a multilayer configuration of PCM-enhanced polyurethane foams, PCM-impregnated fabrics, and highly reflective aluminum foil. Loading of PCM was about 0.08 lb per ft^2 of the surface area (0.39 kg/m^2). Two types of PCMs were used. Their melting temperatures were around 78 and 90°F (26 and 32°C). The total storage capacity of the DRI was about 4.8 Btu per ft^2 (54 kJ/m^2) of the roof area.
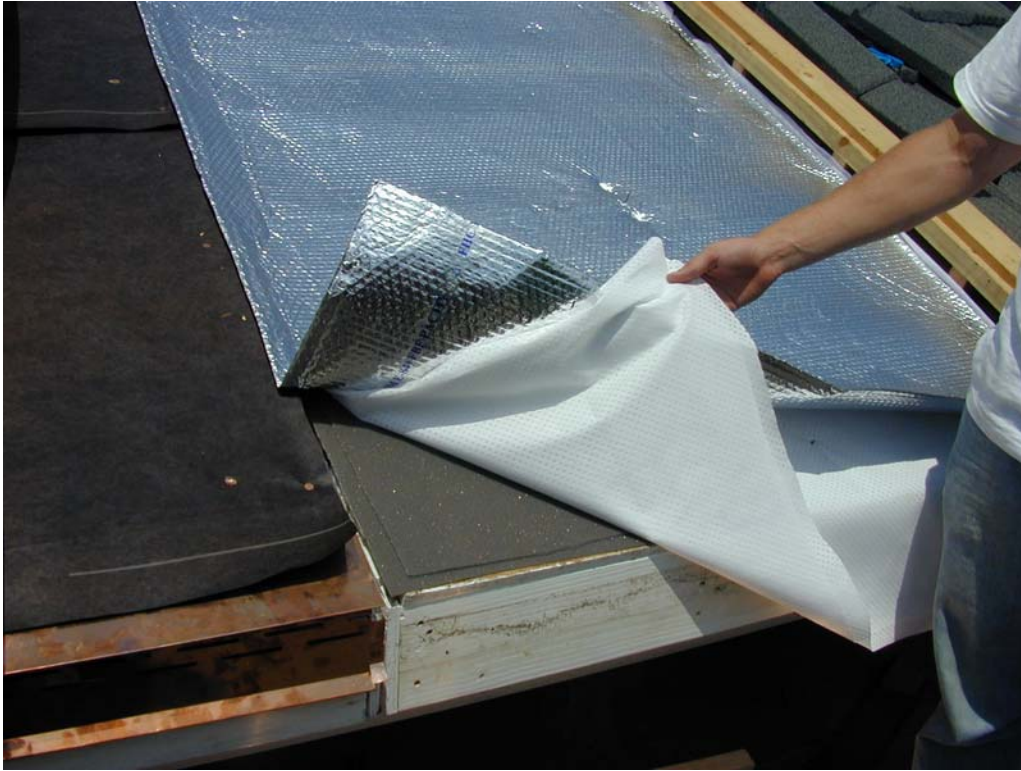
FIGURE 5. Installation of the residential attic containing Dynamic Reflective Insulation.

As shown in Figure 5, the PCM roof also used 4 in. (10-cm.) air channels to exhaust excess heat during peak irradiance (subventing). Two low-emittance membranes were placed above the roof sheathing boards with the low-emittance surfaces facing each other across the 4 in. air gap (description is greatly simplified). PCM storage was placed above the roof deck but below the reflective foil. Standing seam cool-painted metal roofing was used for this test assembly. Thus the thermal performance of this roof assembly represents the combined effects of reduced thermal bridging, reflective insulation, cool-roof pigments, PCM, and an attic subventing system.

An assembly of three steep-slope attics with shed-type roofs was constructed for a side-by-side field test performance comparison between novel metal roof assemblies and a conventional asphalt shingle roof. Two standing seam metal roofs used cool-roof pigments, reflective insulation, and natural subventing channels. One of the metal roof assemblies also contained DRI with PCM. All roofs were equipped with ridge and soffitt vents for ventilating the attic; the vent opening to the attic floor area was 1 to 300.

The conventional asphalt shingle roof had solar reflectance of 0.093 and thermal emittance of 0.89. A metal roof (standing seam metal with solar reflectance of 0.28 and thermal emittance of 0.81) was used for installation of the DRI and subventing air channels. Examples of the roof heat fluxes are presented in Figure 6 for two sunny summer days in 2006. During these days, for the asphalt shingle roof, the peak attic air temperature was close to 110°F (43.3°C) and roof surface temperature was about 160°F (71.1°C) (during peak hours). In comparison, the attic air peak temperature was only around 90°F (32.2°C) for the roof containing DRI and subventing channels.
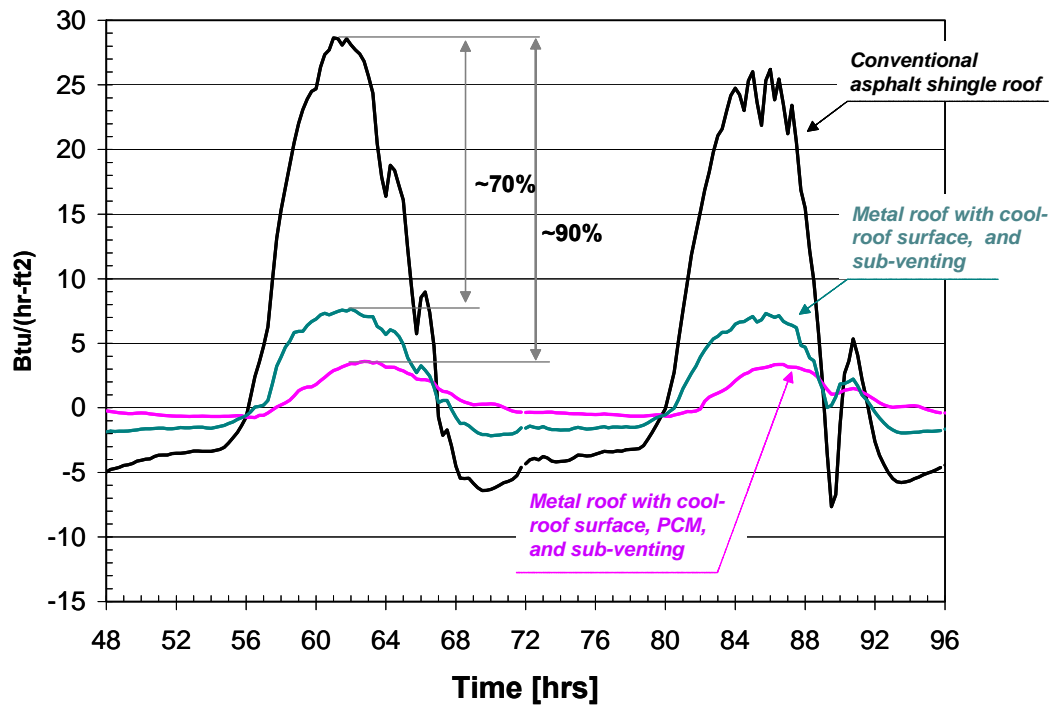
FIGURE 6. Heat transfer penetrating the roofs of a direct nailed asphalt shingle, standing seam metal roof (containing, cool roof pigments, reflective insulation, and sub-venting air channels), and similar metal roof containing Dynamic Reflective Insulation with PCM.

As shown in Figure 6, the conventional asphalt shingle roof had a heat flux of about 30 Btu/h·ft^2 (94.6 W/m^2) penetrating the roof deck during peak solar irradiance. At the same time, on the metal roof with cool-roof pigments, reflective insulation, and subventing air channels, the heat flux was about 8 Btu/h·ft^2 (25 W/m^2). On a similar roof containing PCM, the heat flux was less than 4 Btu/h·ft^2 (12.6 W/m^2). The results show that for the metal roof assembly using cool-roof pigments, reflective insulation, and subventing air channels, the summertime peak heat flow crossing the roof deck was reduced by about 70% compared with the heat flow penetrating the conventional shingle roof. Installation of the DIR containing the PCM generated an additional 20% reduction in the peak-hour heat flow, bringing the total reduction to 90%! Additionally, the PCM energy storage eliminated the overnight subcooling effect. This finding is important for applications of cool roofs in northern areas of the United States, where overnight subcooling compromises the energy performance of cool roofs.

The heat flow reduction demonstrated in these experiments is very dramatic, and the results are leading ORNL researchers toward development and validation of energy-efficient roof systems that support zero-energy building initiatives spearheaded by the DOE Building Technologies program. In November 2006, the ORNL team filed a patent application for a roof configuration using findings from this experiment.

APPLICATION OF DISPERSED PCM—DYNAMIC TESTING OF WOOD FRAME WALLS AND ATTICS

A new PCM-enhanced thermal insulation was developed to generate a thermal mass effects in building envelope. Small amounts of different cellulose–PCM blends were produced with the use of 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, and their melting point was 78.5°F. This PCM is produced with the use of a new microencapsulation technology that holds microscopic wax

droplets inside hard acrylic polymer shells. Since production of cellulose insulation already includes the addition of dry chemicals, the addition of a dry PCM component did not require significant changes in the manufacturing or packaging processes.

As shown in Figure 7, the amount of PCM in the cellulose was monitored with the use of a scanning electron microscope. It was observed that in PCM amounts higher than 10%, the PCM formed clusters of pellets between cellulose fibers. The fiber structure of the cellulose insulation was able to support the addition of up to 40% by weight of PCM microcapsules without segregation.

A series of steady-state heat flow apparatus thermal conductivity measurements were conducted on the 2 in. (5 cm.) thick samples of PCM-enhanced cellulose insulation. These tests showed that the addition of up to 30% of the microencapsulated PCM does not increase the thermal conductivity of the cellulose insulation (Kosny 2006).
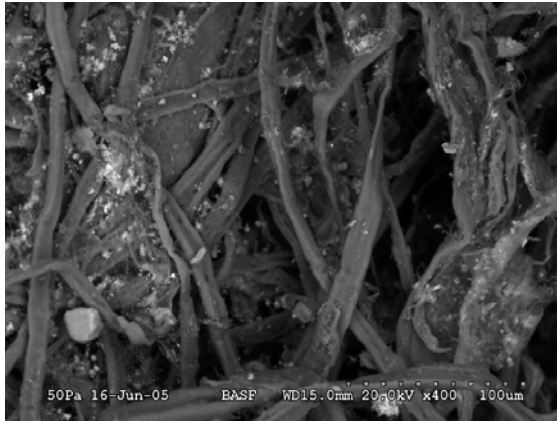
Cellulose without PCM - visible
fire-retardant chemicals.
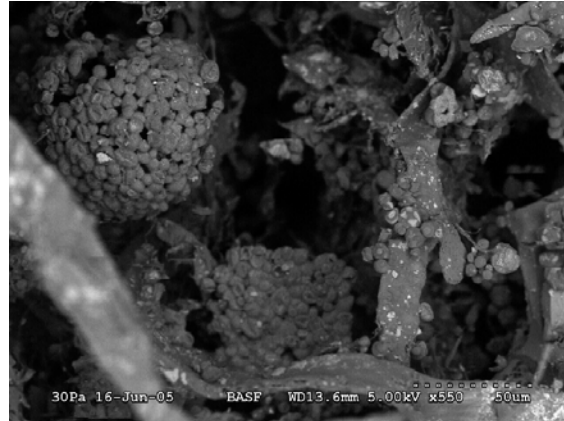
Cellulose with 30% PCM - visible
clusters of PCM pellets.

FIGURE 7. Scanning Electron Microscope images of PCM-cellulose blend.

A nominal 8×8 ft (2.4×2.4 m) wood-frame wall specimen was used for dynamic hot-box testing of a PCM–cellulose blend. The test wall was constructed with 2×6 in. (6×15.2 cm) wood framing installed 16-in. o.c. (40 cm). Three wall cavities were insulated with plain cellulose of a density about 2.6 lb/ft^3 (42 kg/m^3). Three remaining wall cavities were insulated with a cellulose–PCM blend of a density of about 2.6 lb/ft^3 (42 kg/m^3) and containing about 22% by weight of PCM. It is estimated that about 38 lb (17 kg) of PCM-enhanced cellulose insulation (containing 8 lb or 3.6 kg of PCM) was used for this dynamic 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 (22.2°C) on the warm side. Next, the temperature of the warm side was rapidly increased to 110°F (43.3°C). Next, after about 120 h, 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 8 depicts test-generated heat fluxes for both parts of the wall, recorded during the rapid warm-up excitation.
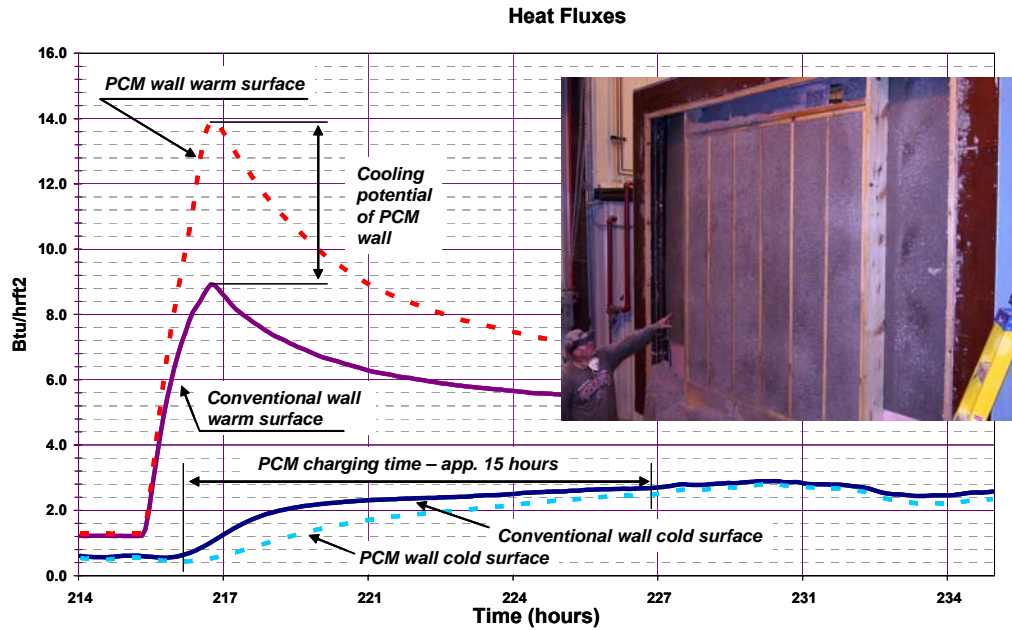
FIGURE 8. Heat flux measured during the dynamic hot-box experiment performed on the 2x6 wood stud wall containing PCM-enhanced cellulose insulation.

It took 15 h to charge the PCM material within the wall. Heat fluxes on both sides of the wall were measured and compared. For three 5-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 5 h (peak-hour time). Heat flux was measured during the first 5 h after the thermal ramp. The PCM-enhanced cellulose material reduced the total heat flow through the wall by over 40%. The load reduction for the entire 15 h of the PCM charging time was close to 20%. Surface temperatures on the PCM part of the test wall specimen were approximately 2°F (1°C) lower during the time of the thermal ramp (cooling effect).
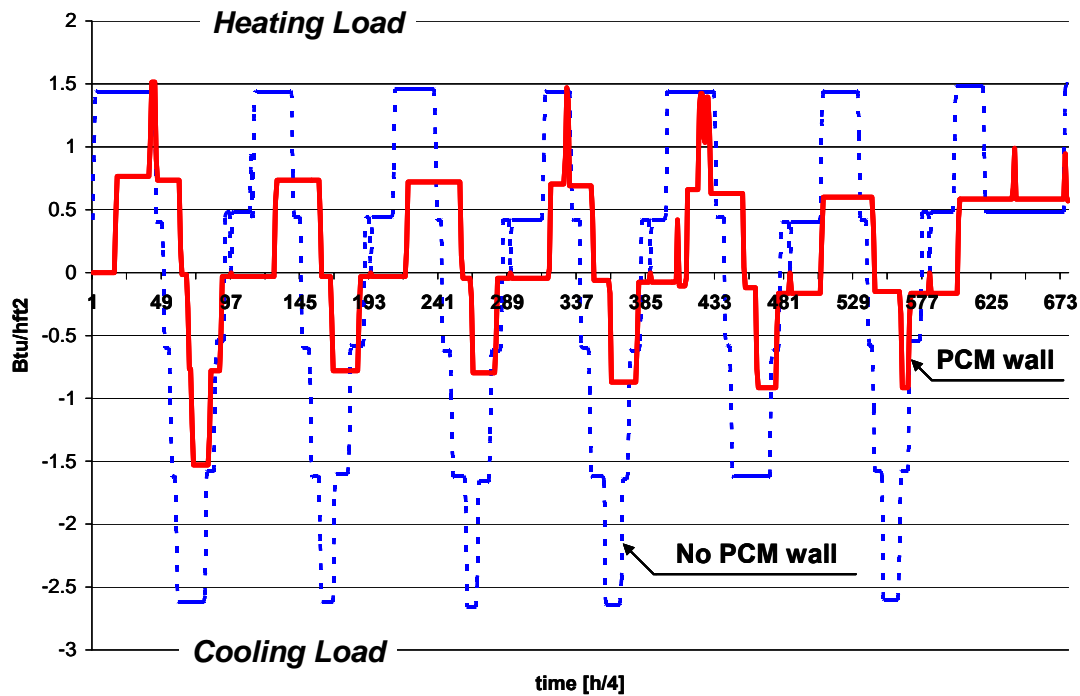
FIGURE 9. Comparison of surface heat fluxes recorded during field experiment which took place during a sunny week of April 2006.

Two small-scale field tests were performed on 2×6 in. (6×15.2 cm) wood frame walls insulated with PCM-enhanced cellulose insulation. Test walls were installed in Oak Ridge, Tennessee, and in Charleston, South .Carolina. In both cases, PCM walls were constructed next to identical wood stud 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 9 shows heat fluxes recorded in Oak Ridge on test walls during a sunny week in late April 2006. Exterior surface temperatures on the Oak Ridge walls were cycling between 120°F (49°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% compared with the conventional wall without PCM. In addition, a shift of about 2 h in the peak-hour load was observed in the PCM wall.

Analysis of the temperature profiles 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 presented in Figure 10 demonstrate clearly 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 significantly more quickly than the PCM wall.
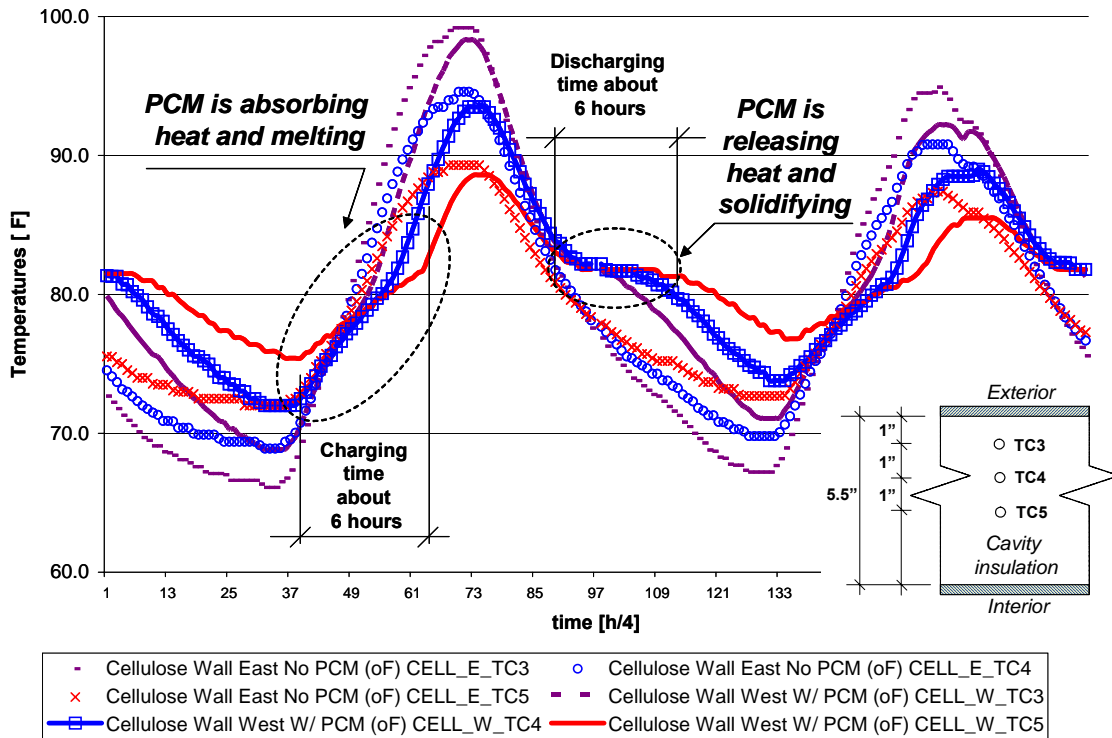
FIGURE 10. Example of temperature profiles recorded inside the wall cavities of the south-facing test walls (no-PCM wall located on the east side, PCM wall located on the west side), during the sunny week of late April 2006 in Oak Ridge, TN.

Dynamic hot-box experiments were performed on a residential attic module. The attic module was tested under periodic temperatire changes in the Large Scale Climate Simulator (LSCS). Two concentrations of microencapsulated PCM were tested (5% and 20% 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% of the PCM material should be able to fully discharge its energy before daytime operation the next day.

During the dynamic LSCS tests, the model of the residential attic was subjected to periodic changes of temperature (65°F [18°C] for about 16 h, rapid temperature ramp to 120°F [49°C] and exposure to 120° F for about 4 h, followed by natural cooling back to 65°F). The array of thermocouples installed at 1 in. (2.5 cm) intervals was used to monitor temperature distribution across the attic insulation. One of the interesting findings from the analysis of temperature fields was that only layers of insulation located higher than 4 in.(10 cm) from the bottom of the attic were involved in the phase change process. It took about 6 to 8 h to fully discharge the energy stored in these layers. No additional fans providing forced ventilation were needed to discharge the PCM. This finding will have to be confirmed in the future under full-scale whole-house field conditions. It is interesting that analysis of the temperature profiles demonstrated visual evidence of charging and discharging of PCM (similar to those presented in Figure 10 for PCM wall) even in attic insulation containing only 5% PCM. Because of the limited space in this paper, this complex attic test experiment will be described in more detail in other future publications.

CONCLUSIONS

During 2003–2006, the ORNL research team tested and analyzed several new applications of PCM-enhanced building envelope materials. In contrast to historical PCM studies, these studies showed that concentrated PCM does not have to be directly exposed to the building interior. Two forms of PCM application were considered: dispersed PCM application in cellulose insulation, and concentrated application with batt fiber insulations or as a part of a novel attic insulation system. The following conclusions can be derived from this research work:

1. Hot-box test demonstrated that DRI (dynamic reflective insulation containing PCM), installed in wood frame walls, can effectively reduce heat flow generated by dynamic thermal excitations.

2. In a field-tested residential attic with a cool-painted metal roof using reflective insulations and subventing air channels, summertime peak heat flow crossing the roof deck was reduced by about 70% compared with the heat flow penetrating a conventional shingle roof.

3. In a similar cool-roof attic containing DRI (with PCM), an additional 20% reduction of the peak-hour heat flow was observed.

4. In a tested prototype ORNL attic design, the total summertime peak heat flow crossing the roof deck was reduced by about 90% compared with the heat flow penetrating a conventional shingle roof.

5. In the prototype ORNL attic, the PCM energy storage eliminated the overnight subcooling effect.

6. ASTM C518 tests demonstrated that the addition of 30% PCM to cellulose fibers did not have negative impact on the R-value of the insulation

7. Smoldering combustion tests (ASTM C1149) indicated that the PCM did not compromise the fire resistance of the cellulose–PCM blend that was tested.

8. A dynamic hot-box test that included a 40°F (20°C) thermal ramp, performed on a 2×6 wood frame wall, demonstrated about 40% reduction of the surface heat flow as a result of the use of PCM. This finding was confirmed by the field tests.

9. 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. This finding has to be confirmed under full-scale field conditions.

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