OAK RIDGE NATIONAL LABORATORY

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ORNL/NFE-06-00469

CRADA FINAL REPORT
FOR
CRADA NO. NFE-06-00469

Development of New Generation of Thermally-Enhanced Fiber Glass Insulation

March 2010

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UT-BATTELLE

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Energy and Transportation Science Division

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ABSTRACT

This report presents experimental and numerical results from thermal performance studies. The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC and John's Manville was to design a basic concept of a new generation of thermally-enhanced fiber glass insulation. Different types of Phase Change Materials (PCMs) have been tested as dynamic components in buildings during the last 4 decades. Most historical studies have found that PCMs enhance building energy performance. Some PCM-enhanced building materials, like PCM-gypsum boards or PCM-impregnated concretes have already found their limited applications in different countries. Today, continued improvements in building envelope technologies suggest that throughout Southern and Central U.S. climates, residences may soon be routinely constructed with PCM in order to maximize insulation effectiveness and maintain low heating and cooling loads. The proposed thermally-enhanced fiber glass insulation will maximize this integration by utilizing a highly-efficient building envelope with high-R thermal insulation, active thermal mass and superior air-tightness. Improved thermal resistance will come from modifications in infrared internal characteristics of the fiber glass insulation. Thermal mass effect can be provided by proprietary thermally-active microencapsulated phase change material (PCM). Work carried out at the Oak Ridge National Laboratory (ORNL) on the CRADA is described in this report.

PROJECT OBJECTIVES

The main purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC and John's Manville was to design a basic concept of a new generation of thermally-enhanced fiber glass insulation. This CRADA project report presents experimental and numerical results from thermal performance study if this new dynamic insulation. The main objective of this work was to develop and test blown fiber glass insulation modified with a novel spray-applied microencapsulated PCM. Experimental results are reported for both laboratory-scale and full-size building elements tested in the field. In order to confirm theoretical predictions, PCM enhanced fiber glass insulation was evaluated in a guarded hot box facility to demonstrate heat flow reductions when one side of a test wall is subjected to a temperature increase. The laboratory work showed reductions in heat flow of 30% due to the presence of approximately 20 wt % PCM in the insulation. Field testing of residential attics insulated with blown fiber glass and PCM was completed in Oak Ridge, Tennessee. The second main project objective was to generate theoretical performance data for different U.S. climatic conditions. That is why experimental work was followed by detailed whole building EnergyPlus simulations in order to generate energy performance data for different U.S. climates. In addition, a series of numerical simulations and field experiments demonstrated a potential for application of a novel PCM fiber glass insulation as enabling technology to be utilized during the attic thermal renovations.

CRADA BENEFITS TO DOE

The main purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC and John's Manville was to design a basic concept of a new generation of thermally-enhanced fiber glass insulation. The primary goal of this CRADA was development of a new type of blow fiberglass insulation blended with microencapsulated PCM. The second project goal was experimental and numerical analysis of the energy performance of PCM-enhanced fiber glass insulation with relatively complex, multilayer configuration of two or more different materials, including blown glass fibers, very fine PCM powders, adhesives, and the occasional use of fire retardants. The laboratory work showed reductions in heat flow of 30% due to the presence of approximately 20 wt % PCM in the insulation. Numerical analysis confirmed performance predictions based on the field testing. We believe that the research results described here points the way to a new generation of affordable, comfortable, very-low energy buildings.

TECHNICAL DISCUSSION

During the late 1980s and early 1990s, Oak Ridge National Laboratory (ORNL) tested several configurations of gypsum boards enhanced with phase-change materials (PCMs) [Tomlinson et al. 1992]. In 1994 blends of lightweight aggregates and salt hydrates were analyzed and tested [Petrie et al. 1997]; and in 2002, an ORNL research team started working on fiber insulations blended with microencapsulated PCMs [Kośny et al. 2006 Kośny et al. 2007a, Kośny et al. 2007b]. These PCM–insulation mixtures function as lightweight thermal mass components. It is expected that these types of dynamic insulation systems will contribute to the objective of reducing energy use in buildings and to the development of "zero-net-energy" buildings. This is a consequence of this technology's ability to reduce energy consumption for space conditioning and reshape peak-hour loads. Other anticipated advantages of PCMs include improvements towards occupant comfort, compatibility with traditional wood and steel framing technologies, and potential for application in retrofit projects.

ORNL research demonstrated that PCMs can be mixed with fiber insulations, incorporated into structural and sheathing materials, or packaged for localized application. Results from a series of small-scale laboratory measurements and field experiments indicate that a new generation of PCM-enhanced fiber insulations could have excellent potential for successful application in U.S. buildings because of their ability to reduce energy consumption for space conditioning and reduce peak loads [Kośny 2008, Kośny et al. 2009]. New PCM applications require a careful selection of materials, identification of PCM locations, bounding of thermal resistances, and specification of the amount of PCM to be used. This report describes the results from small-scale dynamic testing, laboratory-scale, and full-size field testing of building elements using PCM-enhanced blown fiber glass insulation.

The major goal of this CRADA work was experimental and numerical analysis of the energy performance of PCM-enhanced fiber glass insulation with relatively complex, multilayer configuration of two or more different materials, including blown glass fibers (Fig. 1), very fine PCM powders, adhesives, and the occasional use of fire retardants. The amount of PCM in the insulation blend must be accurately determined before any further thermal analysis can be performed. This is not a trivial task [Kośny et al. 2009]. During the installation process, specific amounts of PCM are added to the fibrous insulation in multilayer fashion. For the purpose of this project a 20% blend of PCM and proprietary adhesive blend was utilized. This new material was jointly used with blown fiber glass as shown on Fig. 1.

Fig. 1. Microscopic view of a complex network of glass fibers within the blown insulation, and installation of the blown fiber glass into the test wall.

THERMAL BALANCE OF A ONE-DIMENSIONAL SAMPLE OF PCM ENHANCED THERMAL INSULATION

The estimated area heat storage capacity for a specific PCM-enhanced product is a key indicator of its future dynamic thermal performance. A theoretical model of the material with temperature-dependent specific heat can be used to calculate phase change processes in most common materials [6]. The one-dimensional heat transport equation for such a case is:

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] , \tag{1}$$

where

ρ and λ are the material density and thermal conductivity,
h and *T* are enthalpy density and temperature,
The enthalpy derivative over the temperature (with consideration of constant pressure) represents the effective heat capacity, with phase change energy being one of the components.

$$c_{\text{eff}} = \frac{\partial h}{\partial T}. \tag{2}$$

After Eq. (1) is integrated over the thickness d and time interval [t_1, t_2] we can obtain the thermal balance of the equation associated with the enthalpy change generated by heat transfer between the top and bottom surfaces of the sample. After changing the integration order, and assuming constant material density, we obtain

$$\int_{t_1}^{t_2}\int_{0}^{d}\frac{\partial}{\partial t}(\rho h)\,dx\,dt = \int_{0}^{d}\rho\,\Delta h(x,t_1,t_2)\,dx = \int_{t_1}^{t_2}\left[q(0)-q(d)\right]dt \tag{3}$$

$$q(x,t) = -\lambda\frac{\partial T(x,t)}{\partial x} \tag{4}$$

where q is heat flux.

The increase of enthalpy density Δh in point x and in time interval [t_1, t_2] is caused by the temperature change. It can be expressed as follows:

$$\Delta h(x,t_1,t_2) = \int_{t_1}^{t_2}\frac{\partial h}{\partial t}dt = \int_{t_1}^{t_2}\frac{\partial h}{\partial T}\frac{\partial T}{\partial t}dt = \int_{T(x,t_1)}^{T(x,t_2)} c_{\text{eff}}(x,T)\,dT. \tag{5}$$

Integration of $c_{\text{eff}}(x, T)$ over temperature can be conducted in the case in which the final temperature distribution in the sample is known. However, in specific cases, such as the addition of uniformly distributed PCM to thermal insulation, it is possible to determine enthalpy change without performing detailed heat transfer calculations. The change can be expressed as:

$$c_{\text{effMicr}}(T) = c_1 + \left(c_{\text{effMicr}}(T) - c_1\right), \tag{6}$$

where α denotes the percentage of PCM, and c_{ins} denotes the specific heat of insulation without PCM and $c_{\text{effMic}r}$ denotes the effective heat capacity of microencapsulated PCM.

In this project a new type of non-petroleum-based PCM was used. This product received the 2009 R&D 100 award. The project team combined the following elements to produce a sturdy, efficient, flame-resistant product:

- a microencapsulated PCM having a methyl ester core, which is less costly and less flammable than paraffin;
- smaller particles (3–6 µm, reduced from a typical size of ~15 µm);
- a flame retardant applied to the capsule surfaces during drying;
- a flame-retardant additive applied to produce 30–50 µm aggregates; and
- a design in which the PCM is not directly exposed to the interior of the building.

The addition of low levels of various inorganic flame-retardants to the exterior of the capsules provides an added layer of ignition resilience protection.

The phase change enthalpy of this new organic PCM is about 170 J/g (73 BTU/lb), which is an approximate 40% improvement when compared to the competitive paraffinic PCMs. Figure 2 depicts the temperature-dependent enthalpy change for microencapsulated PCM, generated by Differential Scanning

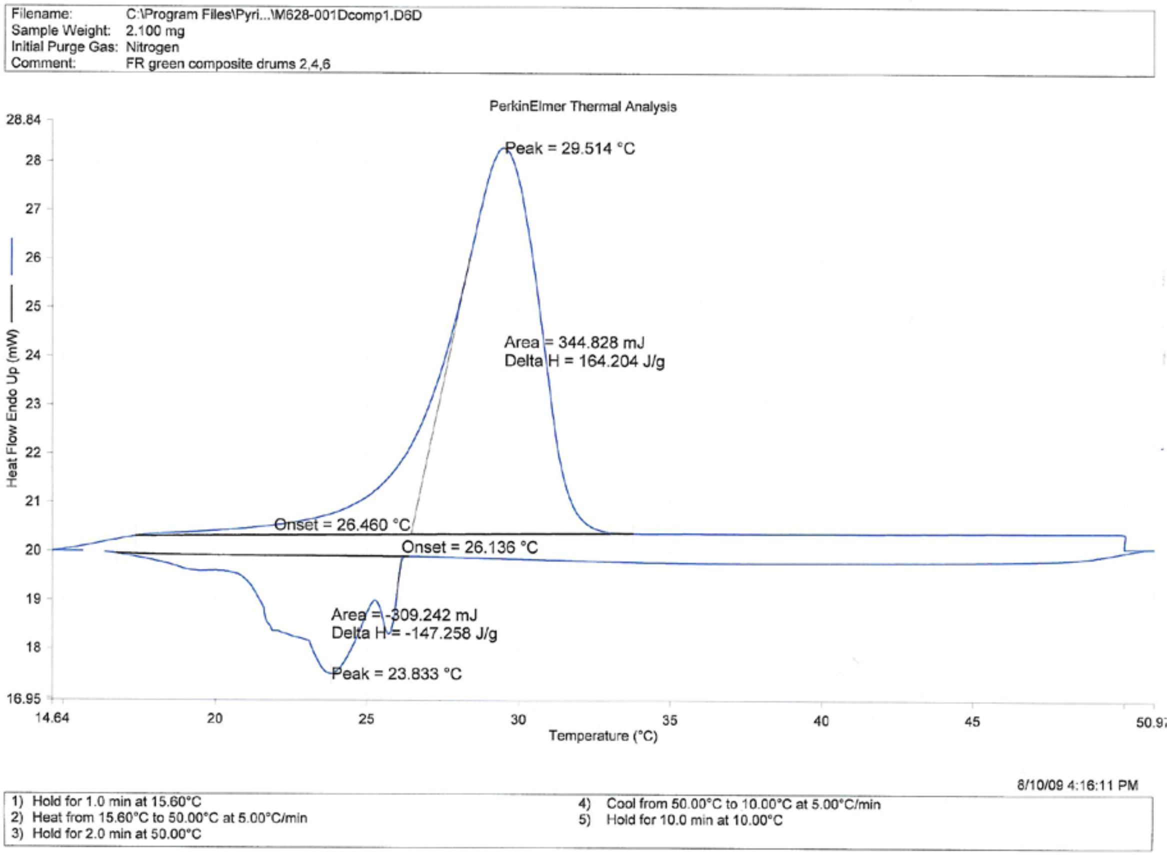

Fig. 2. Temperature-dependent enthalpy change for non-petroleum-based microencapsulated PCM used in the project.

Calorimeter (DSC) testing. In this material, the phase change process takes place at 29°C (84°F). The effective heat capacity of PCM may be represented by a specific heat equation denoted by:

$$c_{\text{effMicr}}(T) = c_1 + \left(c_{\text{effMicr}}(T) - c_1\right), \tag{7}$$

where c_l represents the specific heat in the liquid state—which is constant for PCM.

The integral over the temperature range of the phase change process represents the melting total enthalpy density H_m. It can be denoted by Eq. (8):

$$\int_{T_1}^{T_2} \left(c_{\text{effMicr}}(T) - c_1\right) dT = H_m \,. \tag{8}$$

Now, let us assume, for a sample of material containing PCM, an asymptotic heating process from initial steady-state conditions characterized by boundary temperatures on both surfaces of T_{01} i T_{d1}, to another steady-state condition with a higher boundary temperature of ΔT. Let us also assume that the initial temperatures T_{01} and T_{d1} are below the freezing point of the PCM, and that heating by ΔT will melt all of the PCM. After performing integration on Eq. (5) with an assumption of constant thermal density and thermal conductivity, and taking into account Eqs. (6), (7), and (8), the heat balance Eq. (3) will look as follows:

$$\int_{t_1}^{t_2} \left[q(0) - q(d) \right] dt = \rho d \left\{ c_{ins} \Delta T + \alpha \left[\left(c_l - c_{ins} \right) \Delta T + H_m \right] \right\}. \quad (9)$$

Equation (9) can be used for an experimental determination of the amount of PCM in blends with other materials if all the thermal characteristics of all the other individual components of these blends are known. In this case, the transient heat flow meter apparatus experiment can be utilized. In earlier works of Kossecka and Kośny [Kossecka and Kośny 2008, Kossecka 1998, Kossecka and Kośny 2002], a similar testing was used for determination of thermal characteristics of PCMs necessary for numerical energy analysis.

ENCOURAGING RESULTS OF DYNAMIC HOT-BOX MEASUREMENTS OF A WALL CONTAINING PCM-ENHANCED FIBER GLASS INSULATION

Since 1998, ORNL has been the world's only laboratory performing dynamic hot-box experiments on a daily bases. In this project, an 8 × 8-ft wood-framed wall containing blown fiber glass insulation combined with microencapsulated PCM was utilized for dynamic hot-box testing. The test wall was constructed with nominal 2 × 6-inch studs installed on 16-inch spacing. As shown on Fig. 1, three wall cavities were insulated with conventional blown fiber glass at a density of about 29-kg/m^3 (1.8-lb/ft^3). The other three wall cavities were insulated with a multilayered fiber glass-PCM mixture.

As shown in the Fig. 3 test wall cavity was instrumented with temperature sensors installed at 2.5-cm (1-in.) intervals. The first 2/3 of the wall thickness (counting from the interior surface) was filled with conventional blown fiber glass of the same density as in the other non-PCM section of the wall. The remaining part of the wall cavity was filled with several layers of proprietary PCM blend with adhesive and blown fiber glass. The test wall contained approximately 20 wt % PCM. It is estimated that about 13.6-kg (30-lb) of PCM-enhanced fiber glass insulation (containing 0.79-kg/m^3 or 0.16-lb/ft^2 of PCM) was used for this dynamic experiment. As shown in Fig. 2, the PCM melting temperature was about 29°C (84°F). The phase change enthalpy was about 170 J/g (73 BTU/lb).

The dynamic hot-box experiment was performed using the same testing procedure as in earlier tests with use of PCM-impregnated foams and blends of blown cellulose insulation with microencapsulated PCM [Kośny 2008]. At the beginning of the measurement, temperatures were stabilized at about 18.3°C

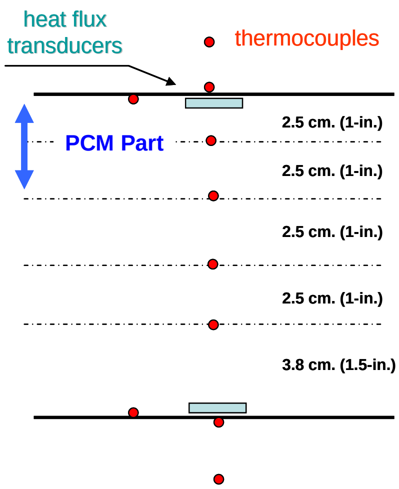

Fig. 3. Schematic of cross section and instrumentation location in the wall specimen used for dynamic hot-box testing of the PCM-enhanced fiber glass insulation.

(65°F) on the cold side and 22.2°C (72°F) on the warm side. Next, the temperature of the warm side was rapidly increased to 43.3°C (110°F)—on the side of the wall cavity containing PCM. Figure 4 shows temperature profiles recorded in both non-PCM and PCM sections of the test wall during the thermal excitation. It can be observed that PCM content in the wall stabilizes thermally the PCM section of the wall. It is associated with significantly lower local temperatures in the wall part containing PCM during the rapid heating process. Thermal lag time for that heating process is between 7 to 8 hours for the PCM part of the wall.

Test-generated heat flux results are shown in Fig. 5 for both sides of the wall. It took about 8-1/2 hours to fully charge the PCM material within the wall. Heat fluxes on both sides of the wall were measured and compared—see Fig. 5. For 2-hour and 8-1/2-hour time intervals, heat fluxes were integrated for each surface. Comparisons of measured heat flow rates on the wall surface opposite to the thermal excitation enabled estimation of the potential thermal load reduction generated by the PCM. On average, the PCM part of the wall demonstrated over 27% of the cooling effect (total reduction of the heat flow) during 8-1/2 hours, and over 50% during the first two hours of the rapid heating process.

In real field conditions, most thermal excitations generated by the climate generally last less than 5 hours (peak hour time). As a comparison, during similar previously conducted hot-box experiments with dynamic cellulose insulation containing uniformly distributed 25% PCM-cellulose blend [Kośny 2008], it was determined that during the first 5-hours after the thermal ramp period, PCM-enhanced cellulose material reduced the total heat flow through the wall by over 40%. In this case it took about 15 hours to fully charge walls PCM. Recorded load reductions for the entire 15 hours were close to 20%.

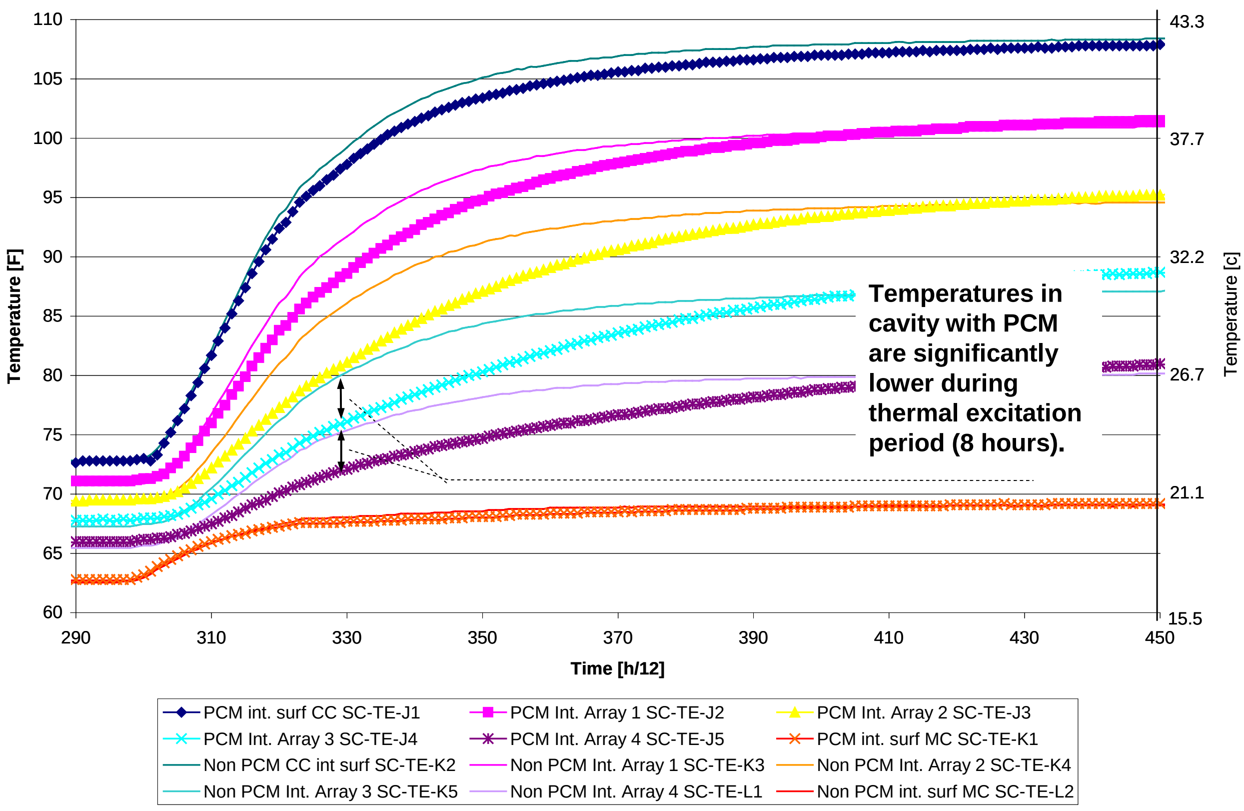

Fig. 4. Temperature profiles recorded during dynamic thermal excitation (thick lines represent PCM section of the wall, thin lines—non-PCM insulation).

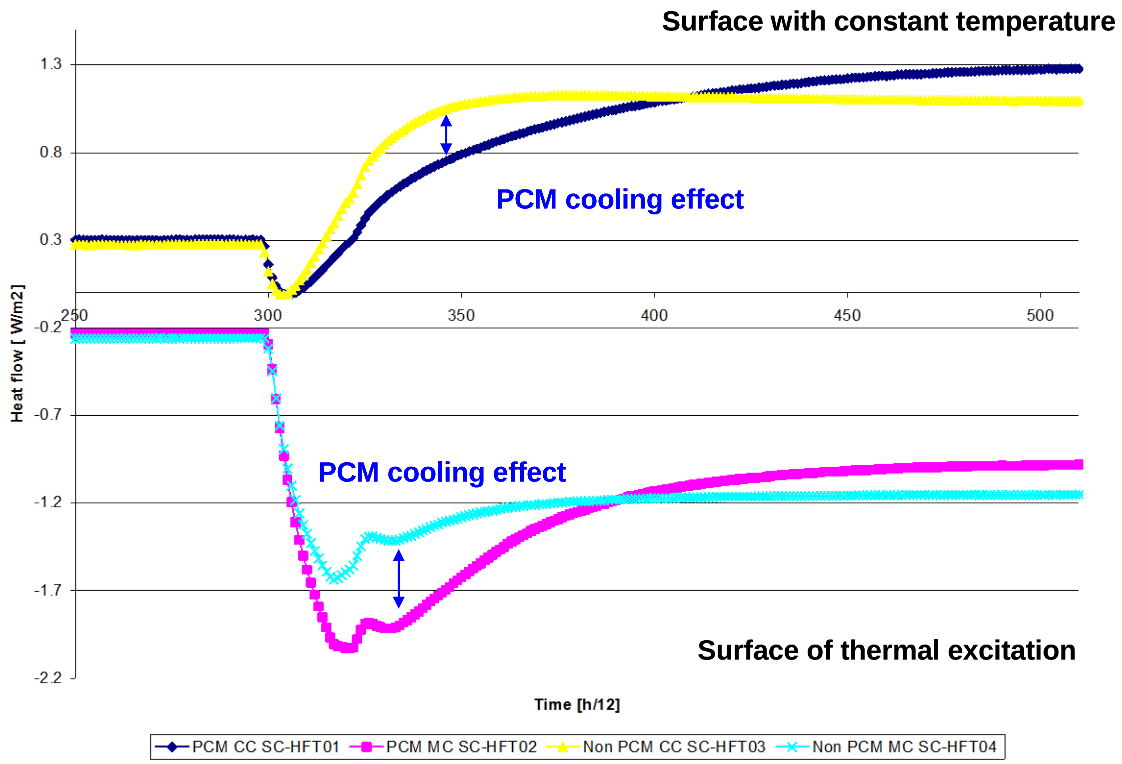

Fig. 5. Heat fluxes recorded during the dynamic hot-box measurement.

FULL-SCALE FIELD TESTING OF RESIDENTIAL ATTIC CONTAINING PCM-ENHANCED BLOWN FIBER GLASS INSULATION

During July of 2008, a full-scale experimental attic was constructed and instrumented in order to field test blown fiber glass insulation combined with microencapsulated PCM. Since melting temperature of organic PCMs can be modified, the main goal of this experiment was to investigate at what level and how often PCM was going through the phase change process. It is expected that, collected experimental results will be utilized for the future changes in the attic design, and for eventual optimization of the PCM thermal characteristics. As shown on Fig. 6 a full-scale residential attic was filled with about 25-cm (10-in.) of blown fiber glass insulation of approximate density 29-kg/m^3 (1.8-lb/ft^3). Next, on top of this insulation, four 1.3-cm (1/2-in.) thick layers of PCM-adhesive blend were installed with 1.3-cm (1/2-in.) thick layers of blown fiber glass installed in-between. The total thickness of added PCM-fiberglass multilayer sandwich was approximately 10-cm (4-in.). PCM melting temperature was at about at 29°C (84°F). As shown on Fig. 2, the PCM sub-cooling effect was about 6°C (11°F) wide with freezing temperature close to 23°C (73°F). The phase change enthalpy was about 170 J/g (73 BTU/lb).

In this field experiment a relatively advanced attic containing an over-the-deck ventilated cavity and low-e metal cool roof (SR28 E81) was used. Monitored test data included the temperatures of the roof deck on both sides of the 5/8-in Oriented Strand Board (OSB) and the heat flux transmitted through the roof deck. As shown on Fig. 7, all test roof decks had a 2-in^2 by 0.18-in. deep routed slot with a heat flux transducer (HFT) inserted to measure the heat flow crossing the deck. Each HFT was placed in a guard made of the same OSB material used in construction and was calibrated using a FOX 670 heat flow meter to correct for shunting effects (i.e., distortion due to three-dimensional heat flow) [Miller et al. 2007]. It was a 4-in. ventilated air space between the roof deck and the roof metal cover. Reflective insulation was installed on the top of the roof deck. The attic cavities also had an instrumented area in the floor

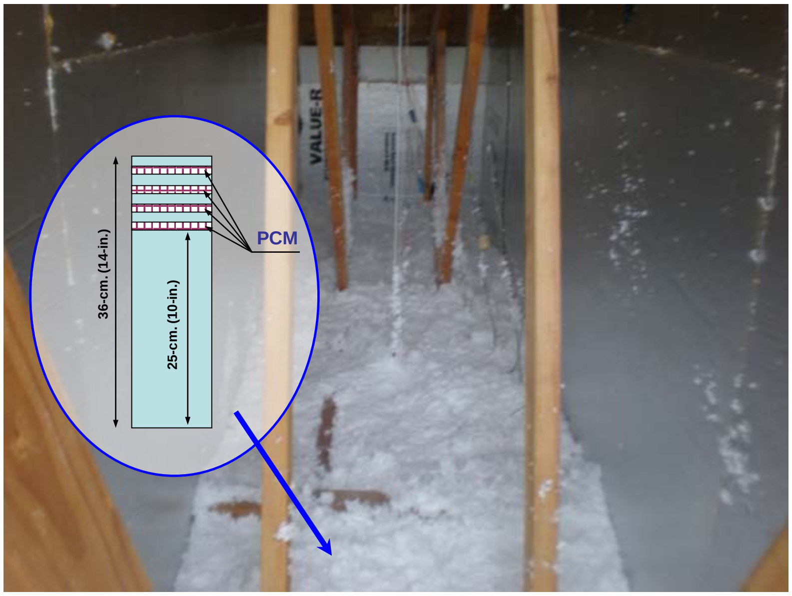

Fig. 6. Photograph of the test attic with blown PCM-enhanced fiber glass insulation.

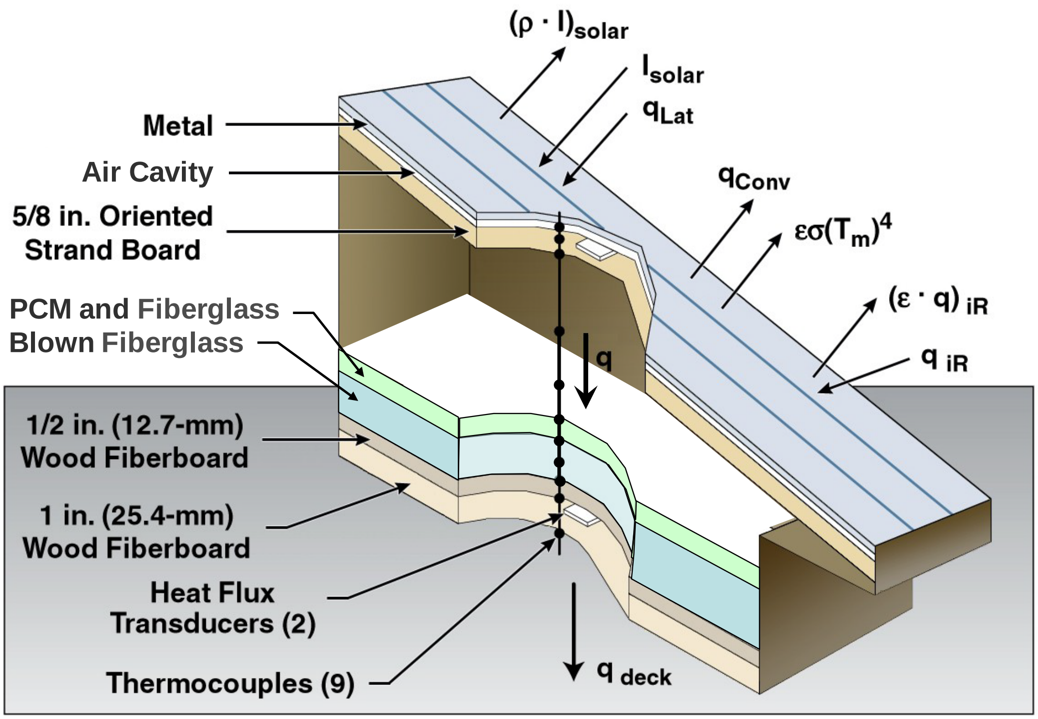

Fig. 7. Schematic of measured temperatures and heat fluxes for test attic with PCM-enhanced blown fiber glass.

(i.e., ceiling) for measuring the heat flows into the conditioned space. The attic floor under the blown fiber glass insulation consists of a metal deck, a 1-in. thick piece of wood fiberboard lying on the metal deck, and a ½-in thick piece of wood fiberboard placed atop the 1-in. thick piece (Fig. 7). The HFT for measuring ceiling heat flow was embedded between the two pieces of wood fiberboard.

In order to estimate optimum attic air temperatures for PCM (to have it fully melted and later fully frozen), a finite difference model was developed for the test attic. Attic air temperatures recorded during the summer of 2006 were used in modeling. Figure 8 depicts simulated temperature profiles within the attic insulation under transient thermal excitations generated by variable attic air temperature. Results of numerical analysis indicated that in order to make PCM fully melt, attic air temperature should be—during the peak of the day—higher than 32°C (90°F). During the night attic air temperature should be below 20°C (68°F).

Detailed temperature profiles across the roof, attic space, and within the attic insulation were collected for two summer seasons of 2008 and 2009. Recorded temperature data for summer months were analyzed from the perspective of optimum conditions for PCM to undergo through the full phase changes. It was found that during the two tested seasons, the second week of May was the beginning week for PCM to start regular freezing and melting. This process ended during the first week of October. An example of recorded temperature profiles for the test attic is presented in Fig. 9 for two days of August 17th and 18th 2008. Characteristic temperature points of melting PCM are as noticeable as in Fig. 8 for numerically generated temperature profiles.

As presented in Fig. 10, recorded temperature data for summer months were analyzed from the perspective of optimum conditions for PCM to undergo through full phase changes. For each month a number for days when PCM went through a complete phase change process was calculated. It was found that during the two tested seasons, the second week of May was a beginning week for PCM to have at least two full phase changes a week. This process ended during the first week of October. In May and September calculated number of active days for PCM was close to 50% of total number of days. During

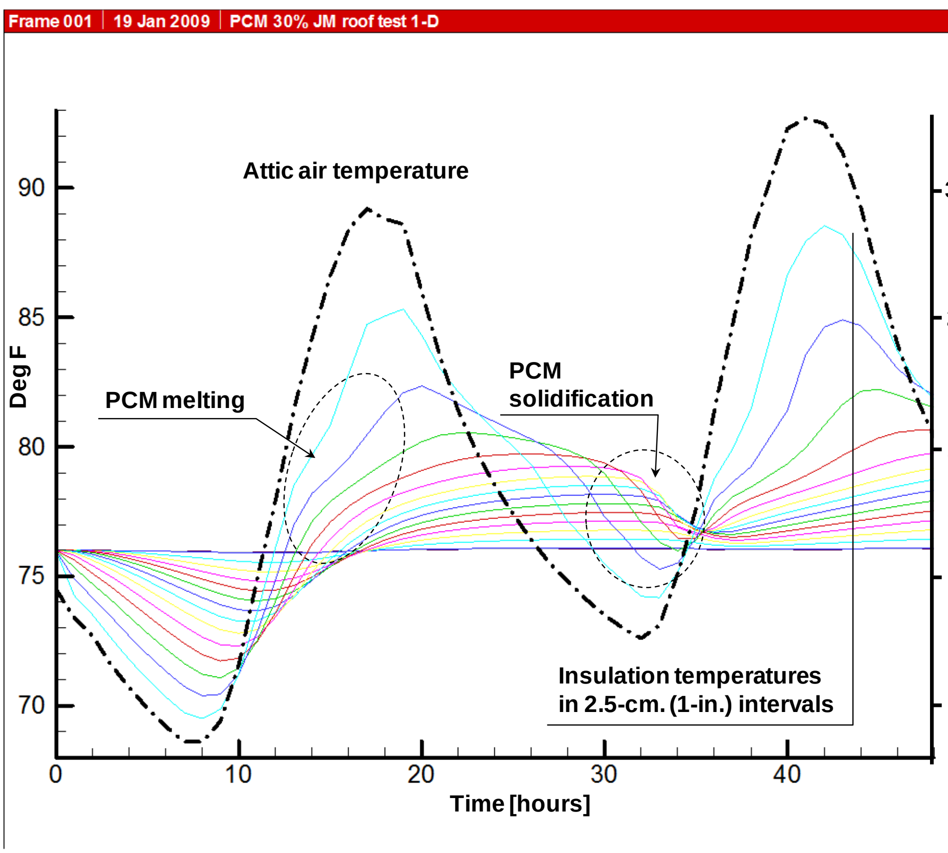

Fig. 8. Simulated temperature profiles within the PCM-enhanced attic insulation under transient thermal excitations.

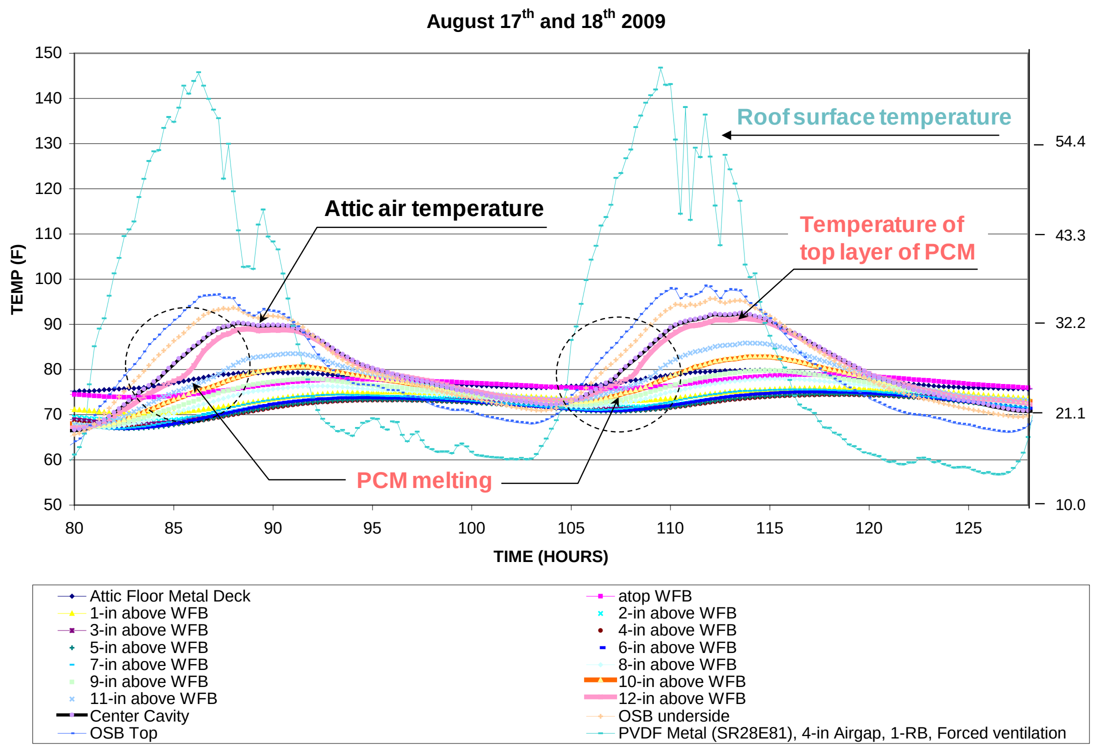

Fig. 9. Test-generated temperature profiles within the experimental attic with PCM-enhanced attic insulation.

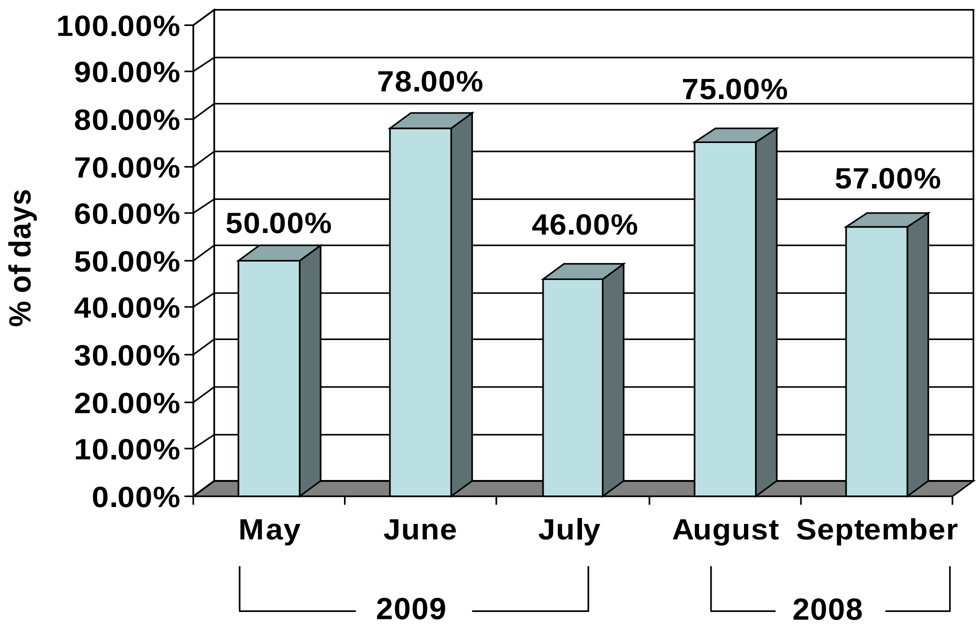

Fig. 10. Recorded percentage of days with PCM undergoing through a full phase change process.

June and August over 75% of days phase change processes took place. In July, due to increased night temperature, a number of days when PCM was fully active went down to below 50%. In order to improve PCMs effectiveness during July, it is possible to use PCM of higher melting point. However in that case, a number of active days can be reduced for May and September. Detailed numerical analysis would be necessary to optimize this design for specific climates.

ANALYSIS OF POTENTIAL USE OF PCM-ENHANCED FIBER GLASS AS ENABLING TECHNOLOGY IN RETROFIT APPLICATIONS

Whole house energy modeling and full scale field testing was performed in order to evaluate potential benefits of using PCM-enhanced fiber glass insulation for attic thermal retrofit. At the beginning, a series of EnergyPlus whole building energy simulations was performed using climatic data of Atlanta and Chicago to analyze the impact of added attic thermal insulation on building energy performance. The building considered for this study was a 16.8 m (55 ft) × 8.4 m (27.5 ft) single story ranch house with three bedrooms, one living room, and an attic—see Fig. 11. The considered task was based on the replacement of existing attic insulation with R_{SI}-6.7 (R-38) blown fiber glass combined with PCM. Three following entry levels of existing attic insulation were considered: R_{SI}-2.1 (R-12), R_{SI}-3.3 (R-19), R_{SI}-5.3 (R-30). It is necessary to mention that a case of the conventional R_{SI}-2.1 (R-12) attic represents approximate effective thermal performance of a most common old residential attic utilizing 14-cm (5.5-in) fiber glass batts installed with air voids. In addition (for comparison purposes) two most popular attic levels of insulation R_{SI}-6.7 (R-38), R_{SI}-8.8 (R-50) were simulated as well.

Attic retrofit work considered in this project was similar to what was shown on Figs. 6 and 7. At this time a full-scale residential attic was filled with about 18-cm (7-in.) of blown fiber glass insulation of approximate density 29-kg/m^3 (1.8-lb/ft^3). Next, on top of this insulation, four 1.3-cm (1/2-in.) thick

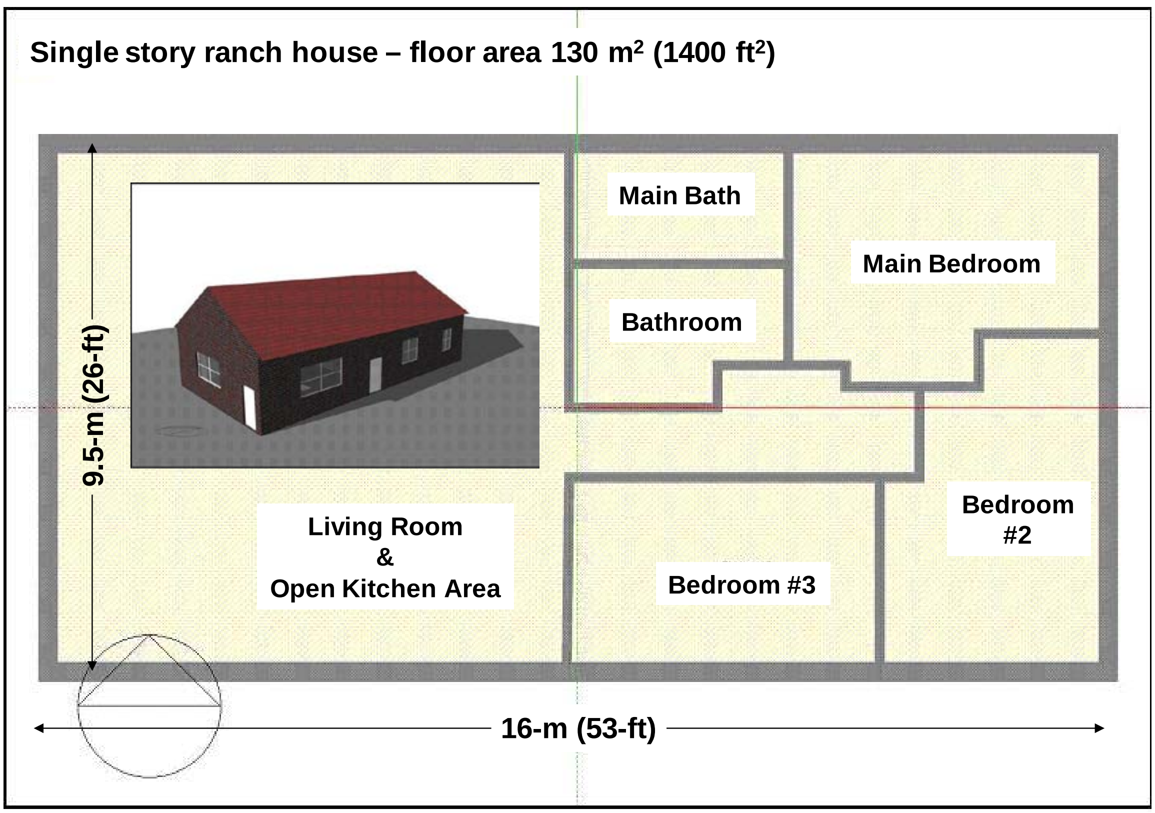

Fig. 11. Floor plan of the one-story ranch house used in whole house energy simulations.

layers of PCM-adhesive blend were installed with 1.3-cm (1/2-in.) thick layers of blown fiber glass installed in-between. The total thickness of the added PCM-fiberglass multilayer sandwich was approximately 10-cm (4-in.). The PCM melting temperature was about 29°C (84°F). The phase change enthalpy was about 170 J/g (73 BTU/lb). EnergyPlus simulations were performed for both conventional insulation cases and for dynamic insulation containing PCM. Figures 12 and 13 depict total values of ceiling heat flow simulated for two days of July 2008. Five cases of conventional attic insulation were compared against R_{SI}-6.7 (R-38) PCM-enhanced fiber glass. Simulation results for both climates demonstrated a potential for reduction of about 70% to 80% of roof-generated peak hour loads in the case when conventional R_{SI}-2.1 (R-12) attic insulation is replaced by the R_{SI}-6.7 (R-38) PCM-enhanced fiber glass.

In addition percentage changes of annual cooling loads were computed for considered levels of attic insulation. Data presented in Table 1 shows that thermal retrofitting of the residential attic with a use of the PCM-enhance insulation is significantly more effective from using only conventional insulation. For example, an upgrade from the conventional R_{SI}-2.1 (R-12) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is 1/3 more energy effective than just using conventional insulation of the same R-value. Similarly, an upgrade from the conventional R_{SI}-3.3 (R-19) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is more than 50% effective. Most interesting, the R_{SI}-6.7 (R-38) insulation containing PCM is more efficient from conventional R_{SI}-8.8 (R-50). It is necessary to realize, that since in the considered building, roof thermal loads represent approximately 15% of the total building loads, about a 10% change in annual cooling loads represents approximately 65% improvement in scale of the entire roof heat transfer.

During the second part of this project a full-scale field experiment took place in order to evaluate a potential of usage of the PCM-enhanced fiber glass insulation in attic retrofits. For this purpose energy performance of poorly insulated attic R_{SI}-1.2 (R-7) with a conventional shingle roof was experimentally compared against the retrofitted attic utilizing advanced roof structure and PCM-enhanced insulations. The question asked was what level of energy benefits can be achieved in the case of a total reconstruction of poorly insulated existing attic—using state-of-the-art thermal technologies developed during the last decade. The main two goals of this retrofit experiment were to construct a durable roof structure (using low labor-intensive process and with roof-over-the-roof construction minimizing amount of solid waste)

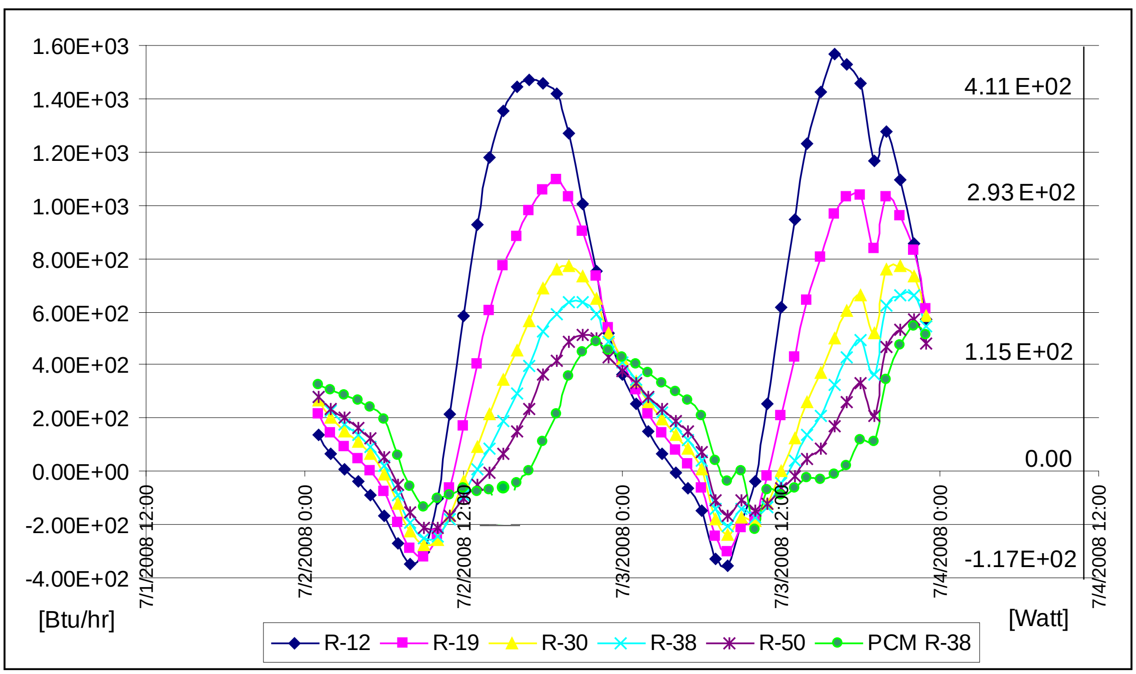

Fig. 12. Comparisons of simulated ceiling heat conduction profiles for Atlanta climatic conditions.

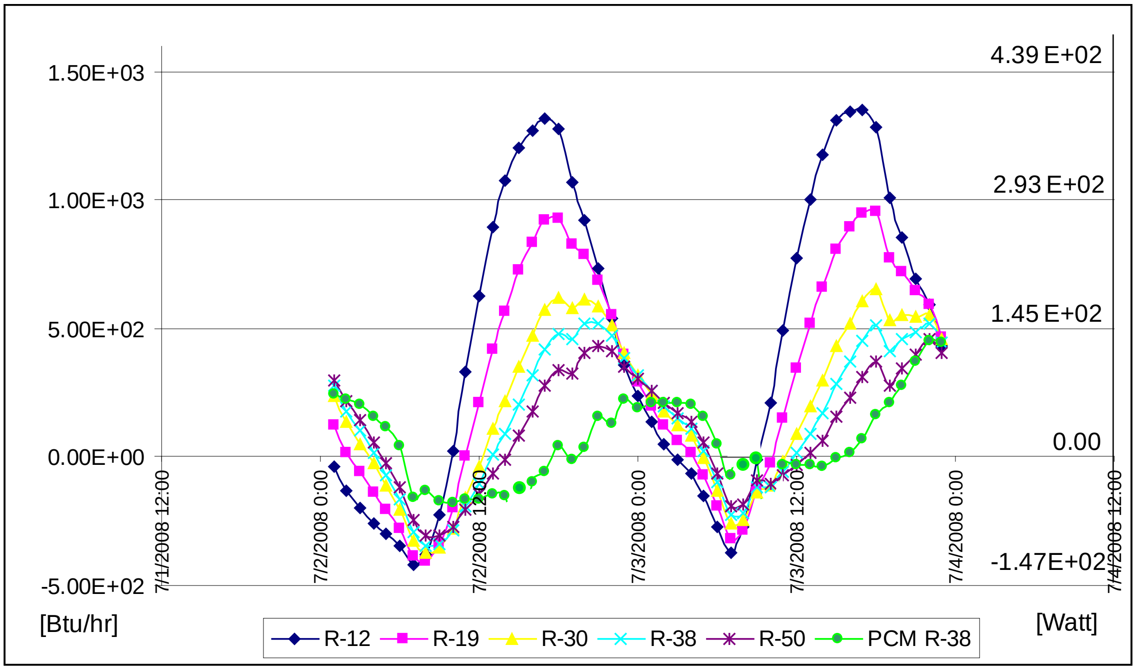

Fig. 13. Comparisons of simulated ceiling heat conduction profiles for Chicago climatic conditions.

Table 1. Annual cooling load changes due to improvement of attic insulation computed for Atlanta and Chicago

PCM addition	Annual Cooling Load [%] Change		No PCM	Annual Cooling Load [%] Change	
Attic R-value change	Atlanta	Chicago	Attic R-value change	Atlanta	Chicago
R-12 to PCM R-38	10.57%	11.46%	R-12 to R-38	6.81%	7.22%
R-19 to PCM R-38	7.13%	7.79%	R-19 to R-38	3.22%	3.37%
R-30 to PCM R-38	4.84%	5.35%	R-30 to R-38	0.83%	0.81%
R-38 to PCM R-38	4.04%	4.57%			
R-50 to PCM R-38	3.48%	4.16%	R-38 to R-50	0.58%	0.44%

and significantly reduce summer cooling loads. In order to meet these goals, considered attic reconstruction had five following key elements:

- Roof-over—the-roof installation with metal roof cover
- An application of cool roof coating (SR28 E81)
- Installation of vented air cavity
- Installation of reflective insulation inside the roof air cavity
- Installation of about R_{SI}-8.5 (R-48) of blown fiber glass insulation with the top layer containing PCM

In this experiment, a roof-over-the-roof concept was utilized in order to add more durable roof surface materials combined with maximum preservation of the existing roofing components. It is anticipated that in retrofit applications, this technology may improve overall building envelope energy performance without generating solid waste—very common in re-roofing projects. According to the Sacramento-based California Integrated Waste Management Board, approximately 11 million tons (10 million metric tons) of waste in the form of asphalt roofing shingles are generated in the U.S. each year. It is good to realize that each of the above listed elements of roof retrofit could be used independently. PCM together with other novel components is only one of enabling technologies. However in order to maximize energy savings all these technologies were integrated together and utilized at the same time.

During eight weeks of August and September 2008, energy performances of two test attics were monitored and compared. It was found that retrofitted PCM attic with low-e metal roof demonstrated on average an 82% reduction of overall cooling loads in comparison to the traditional R_{SI}-1.2 (R-7) attic with a conventional shingle roof. In order to estimate the potential impact of PCM, finite difference models were developed for the R_{SI}-8.8 (R-50) attic containing PCM-enhanced insulation and for the R_{SI}-8.8 (R-50) attic containing conventional fiber glass insulation as described in [Kośny et al. 2010]. Transient simulations were performed for one summer week utilizing experimental data recorded during the summer of 2006. Numerical analysis of heat fluxes showed about 30% lower overall cooling loads in the case of the attic containing PCM- enhanced insulation.

Another important finding of this research was the fact that double roof-of-the-roof design is by itself very effective in controlling overall cooling loads. As shown in Fig. 14, it was found that during the summer months, the maximum attic temperature in an attic with a double roof (see Fig. 4) was about 11°C (20°F) lower from air temperature in a conventional attic with a shingle roof. At the same time, minimum summer attic air temperatures were almost the same. This fact means that within almost the same attic overnight cooling potential, conventional shingle roof generates significantly higher thermal loads. However, observed reduction of the maximum attic air temperature is also affecting the amplitude of daily temperature fluctuations. In the case of the PCM application it is critical to select the phase change temperatures based on expected potential fluctuations of the attic air temperatures, or move the PCM to a different location within the attic. In addition it is possible to manipulate with the amount of PCM. However it is good to remember that in cases where PCM is not optimized, more PCM (associated with higher cost) may be necessary in order to generate the same energy savings effect.

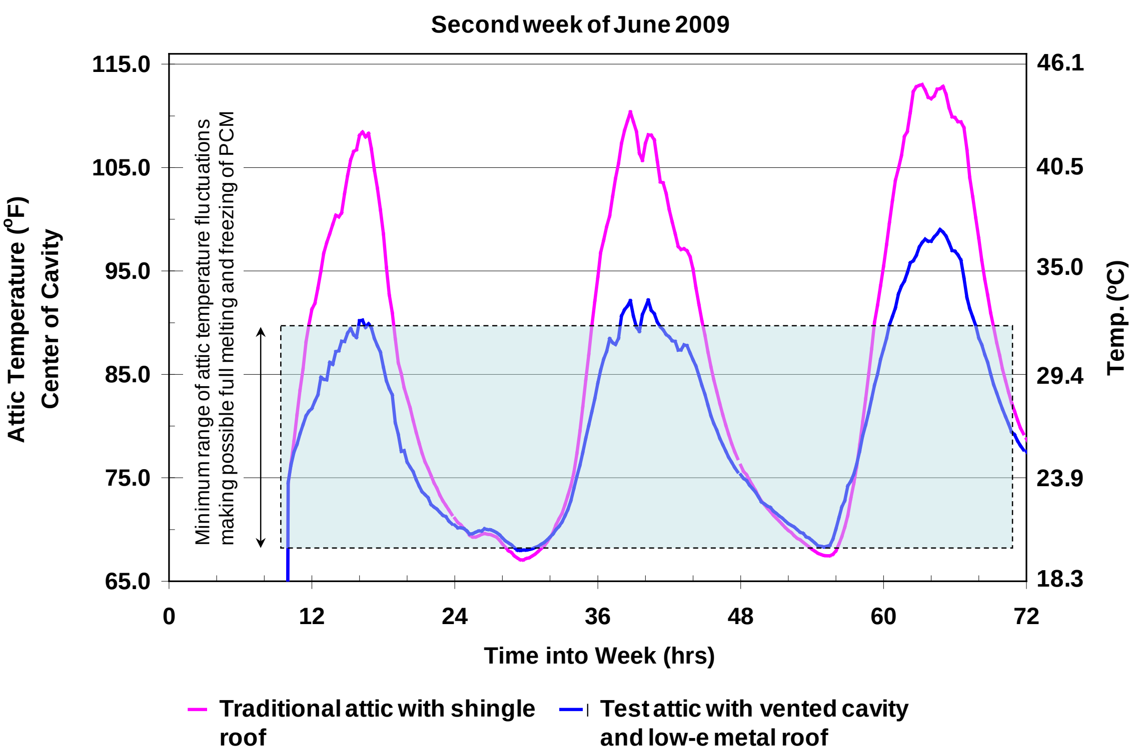

Fig. 14. Attic air temperatures recorded for two experimental attics in June 2009.

PLANS FOR FUTURE COLLABORATION

A design of the attic described in this report was optimized for cooling dominated climates. In the Northern U.S. areas, a shingle roof surface, combined with different location of PCM heat sink can be utilized as a passive solar absorber—reducing heating loads during the late fall and early spring months. It is expected that follow-up energy performance analysis for heating dominated climates and full scale field testing in the northern U.S. locations can be considered as future collaboration targets.

CONCLUSIONS

This CRADA report presented experimental and numerical results from thermal performance studies of wall and attic applications of the blown fiber glass insulation modified with a novel spray-applied microencapsulated PCM. Experimental results were reported for both laboratory-scale and full-size building elements tested in the field. In order to confirm theoretical predictions, it is necessary to remember that wall and attic designs utilized in this study were optimized for cooling dominated climates. In the Northern U.S. areas, different material configurations can be more efficient. For example, in residential buildings with a conventional attic, a shingle roof surface, combined with different location of PCM can be utilized as a passive solar absorber—reducing heating loads during the late fall and early spring months.

For wall applications, PCM-enhanced fiber glass insulation was evaluated during the dynamic guarded hot box test. The test wall contained approximately 20 wt % PCM. It was estimated that about 13.6-kg (30-lb) of PCM-enhanced fiber glass insulation (containing 0.79-kg/m^3 or 0.16-lb/ft^2 of PCM) was used. The PCM melting temperature was about 29°C (84°F). The phase change enthalpy was about 170 J/g (73 BTU/lb). Comparisons of measured heat flow rates on the wall surface opposite to the thermal excitation enabled estimation of the potential thermal load reduction generated by the PCM. On average, the PCM part of the wall demonstrated over 27% of the cooling effect (total reduction of the heat flow) during 8-1/2 hours, and over 50% during the first two hours of the rapid heating process.

Whole house energy modeling and full scale field testing was performed in order to evaluate potential benefits of using PCM-enhanced fiber glass insulation for attic thermal retrofits. Full scale field testing of residential attics using blown fiber glass and PCM was completed in Oak Ridge, Tennessee. Experimental work was followed by detailed whole building EnergyPlus simulations in order to generate energy performance data for different U.S. climates. In addition, a series of numerical simulations and field experiments demonstrated a potential for application of a novel PCM-fiber glass insulation as enabling technology to be utilized during the attic thermal renovations. Five cases of conventional attic insulation were compared against R_{SI}-6.7 (R-38) PCM-enhanced fiber glass. Simulation results for both climates demonstrated a potential for reduction of about 70% to 80% of roof-generated peak hour loads in the case when conventional R_{SI}-2.1 (R-12) attic insulation is replaced by the R_{SI}-6.7 (R-38) PCM-enhanced fiber glass. Simulation results showed that an upgrade from the conventional R_{SI}-2.1 (R-12) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is 1/3 more energy effective than just using conventional insulation of the same R-value. Similarly, an upgrade from the conventional R_{SI}-3.3 (R-19) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is more than 50% effective. During eight weeks of August and September 2008, energy performances of two test attics were monitored and compared. It was found that retrofitted PCM attic with low-e metal roof demonstrated on average an 82% reduction of overall cooling loads in comparison to the traditional R_{SI}-1.2 (R-7) attic with a conventional shingle roof.

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