Use of Phase-Change Materials to Enhance the Thermal Performance of Building Insulations

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Introduction

Materials that undergo a phase change at temperatures encountered in the building envelope alter the rate heat gain or loss from conditioned spaces by absorbing and releasing heat in response to changing thermal boundary conditions. One type of phase change involves transition from solid to liquid (absorbing heat) or liquid to solid (releasing heat) of a compound like n-octadecane ($C_{18}H_{38}$), which has a melting point of about 83°F (28 °C) and a heat of fusion of 65 Btu/lb_m (151 kJ/kg). Inorganic salt hydrates and other types of mixtures exhibit heat effects as hydration levels or dilution occurs. The selection of a material to use as a phase change material (PCM) in conjunction with conventional thermal insulation is guided by the phase change temperature, the magnitude of the heat effect, cost, and issues such as flammability and corrosiveness. A review of recent work in the area of cellulosic building insulation is given by Kosny et al.[1]. The performance of paraffinic PCMs like n-octadecane has been discussed by Zhang[2], Kissock[3], and Stovall [4] for wall applications. Petrie[5] has reported performance data for an inorganic PCM in an attic application.

The location of PCM in the building envelope is the second consideration. PCM mixed with building thermal insulation before application is attractive from a manufacturing and installation point of view. This type of application, however, typically results in an incomplete participation of the PCM in the heat transfer process since some fraction of the PCM may not pass through the phase-change temperature during outdoor temperature swings. The PCM must be located in a region that undergoes sufficient temperature variation to cycle across the phase-change temperature. PCM in packets, for example, can be positioned to provide optimum performance which occurs when all of the PCM participates in the phase change process. This paper deals with localized PCM applications. A companion paper in the Conference deals with distributed systems.[6]

The basic concept of localized performance is that a layer of PCM stores and releases heat as the surrounding temperatures change. During the phase change process, the temperature of the localized PCM remains constant thus achieving a constant (regulated) temperature gradient between the layer of PCM and the interior space which is held at an approximately constant temperature. The ultimate savings due to a PCM is a reduction in the heat flow into the conditioned space (cooling-load reduction) and a reduction of the heat flow out of the conditioned space (heating-load reduction).

Laboratory Evaluation of Localized PCM

A heat-flow meter apparatus built in accordance with ASTM C 518 [7] was used to access PCM performance for two types of material contained in thin packets. An initially isothermal test specimen consisting of the PCM packet between two layers of conventional thermal insulation is subjected to a rapid temperature change on one side. If the initial temperature is below the phase-change temperature then the boundary is increased to a temperature above the phase change temperature. If the initial temperature is above the phase change temperature, then one boundary is decreased to a temperature below the phase change temperature. In either case, there will be a heat flux across each boundary as the temperature profile across the test specimen adjusts to the new boundary conditions. A record of the heat fluxes across the two boundaries provides a way to access performance. Heat flux into the test specimen is taken to be positive. A comparison of the total heat flows across the boundaries of test specimens with and without PCM provides a measure of performance.

Figure 1. contains results for a measurement sequence completed with a test specimen without PCM. The layers in the test specimen from top to bottom are: (1) top temperature controlled plate, cold (2) R 9 ft^2·h·°F/Btu foam board (3) location for PCM – none in this case (4) R 5 ft^2·h·°F/Btu foam board (5) bottom temperature controlled plate, warm. The specimen is initially at a uniform temperature of 70 °F. The temperature of the top plate is rapidly changed to 120°F and heat flux into the specimen (positive) is initiated. Heat flux out of the specimen (negative) occurs within a few seconds. The heat flux equals the heat flux out, steady-state, at about 100 minutes. The top plate temperature is reduced to the starting temperature at 108 minutes with a resulting reversal of fluxes at both boundaries. The entire cycle is complete at about 180 minutes.

The procedure described above can be repeated with a layer of PCM between the two layers of insulation to observe the altered boundary heat fluxes. The heat flux across the cold boundary will be taken as heat into a conditioned space. A comparison of the flux into the conditioned space with and without a layer of PCM shows the effect of the PCM. Figure 2. is shows results for a packet containing 0.25 lb_m (113 g) of n-octadecane in the system as PCM. The PCM maintains a reduced heat flux for about 200 minutes then begins to increase to the flux observed without PCM. The area between the two curves represents the reduced heat flow into the conditioned space. Results for a PCM packet containing 0.25 lb_m (113 g) of anhydrous $CaCl_2$ with water and a filler to prevent stratification are shown in Figure 3. Two repetitions of the measurement sequence are shown to demonstrate reproducibility. Figures 1, 2 and 3 illustrate a laboratory evaluation of insulation containing PCM based on an established thermal test apparatus.

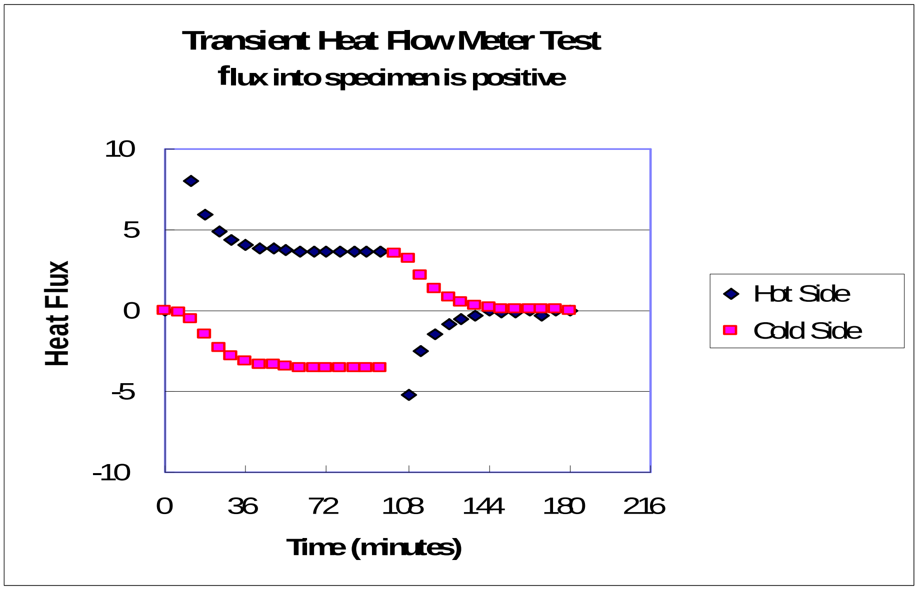


Figure 1. One Cycle of Transient Behavior for a Test Specimen without PCM

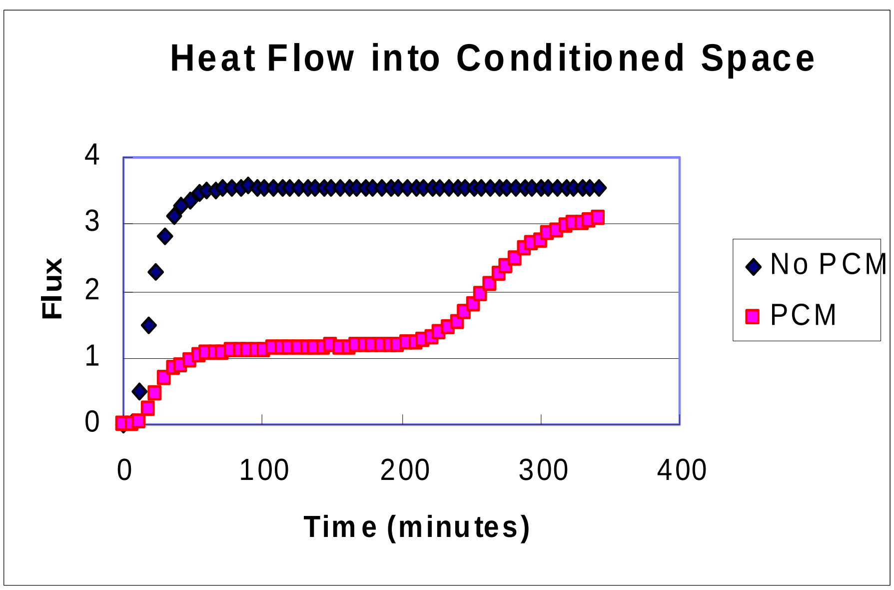


Figure 2. Heat flux into a Conditioned Space Through an Insulation with and without a Layer of PCM (n-Octadecane)

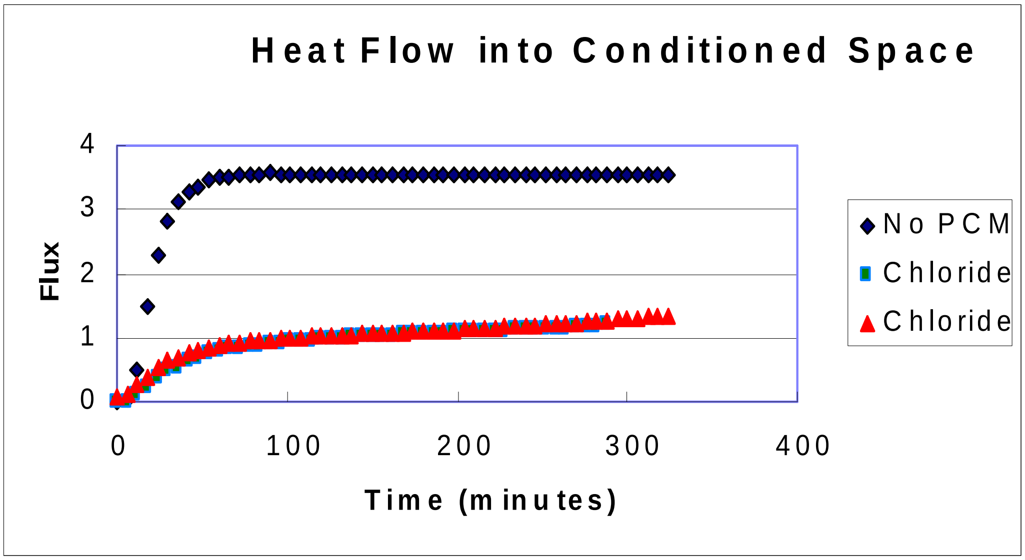


Figure 3. Heat Flux into a Conditioned Space Through an Insulation with and without a Layer of PCM ($CaCl_2$)

Small-Scale Evaluation of Insulation with PCM

A well-insulated two-compartment chamber was used to access PCM performance with a diurnal cycle imposed on one side of a test specimen containing a 0.125- inch (3.2 mm) thick layer of PCM. A diagram of the test chamber is shown in Figure 4. Three temperature measurements characterize the performance of the test specimen. Air temperatures on both sides of the test specimen and the temperature for the layer of PCM provide the temperature differences between the PCM and the “room” side of the test. The heat flux into the “room” side of the test compartment is taken to be proportional to this temperature difference. The ratio of the temperature differences with PCM to the temperature difference without PCM is then proportional to the ratio of heat fluxes. An integration in time provides a total savings to be attributed to the presence of the PCM for the cycle and conventional insulation levels selected.

The curves in Figure 5. are identified as follows from the top down in the central part of the figure The top curve [1] is the “exterior” temperature undergoing the diurnal cycle. The second curve [2] is the temperature at the intersection of the two conventional insulations without PCM while the third curve [3] is the temperature at the intersection with PCM. The bottom curve [4] is the inside temperature (conditioned space). Comparison of [3] with [2] illustrates the reduced heat flow due to the presence of the PCM. Heat flow to the “conditioned” space is proportional to the temperature differences [2]-[4] (without PCM) and [3]-[4] (with PCM). An analysis of these data can provide estimates of energy savings to be achieved for a given amount of PCM, bounding insulation, and position. The results also show a shift in the time at which the peak load (maximum inward heat flow in this case) occurs. The notations in Figure 7. indicate the times when the heat flux into the conditioned space are a maximum. In the case without PCM, the maximum load occurs at about 2 PM. The maximum load with PCM occurs at about 6 PM, a four hour shift. Figure 6. contains a photograph of a packet used to enclose the PCM.

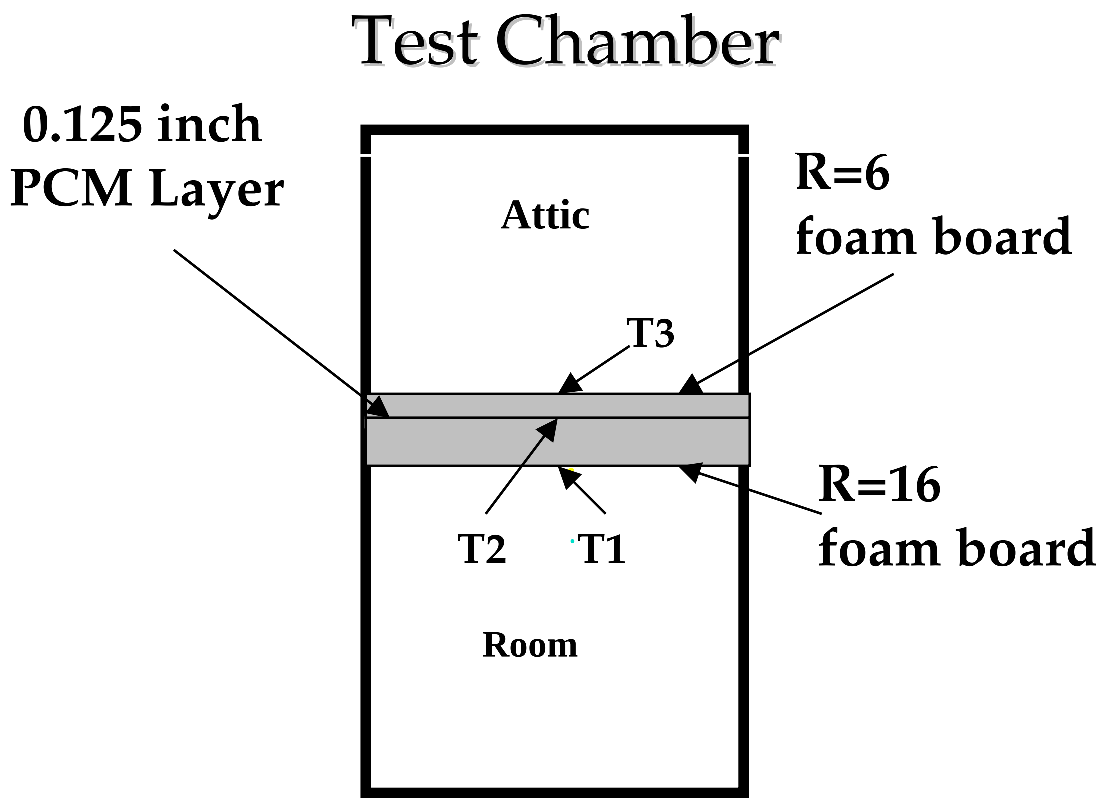


Figure 4. A Small-Scale Test Apparatus for PCM Evaluation

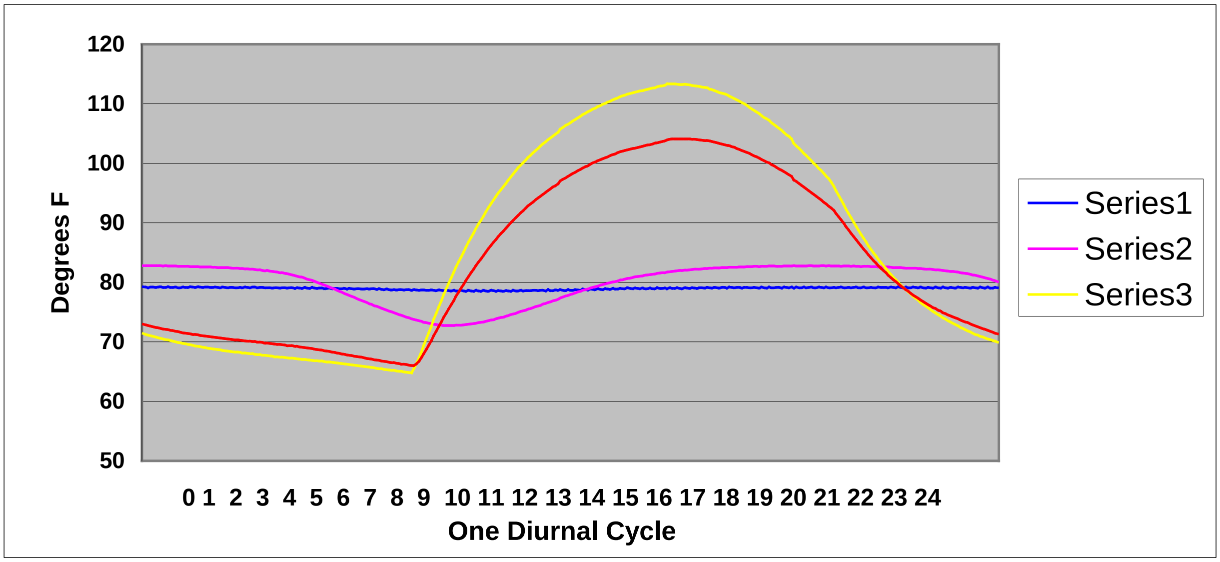


Figure 5. One Diurnal Cycle for a Test Specimen with PCM

Figure 6. Photograph of Packet Containing PCM Showing Thickness

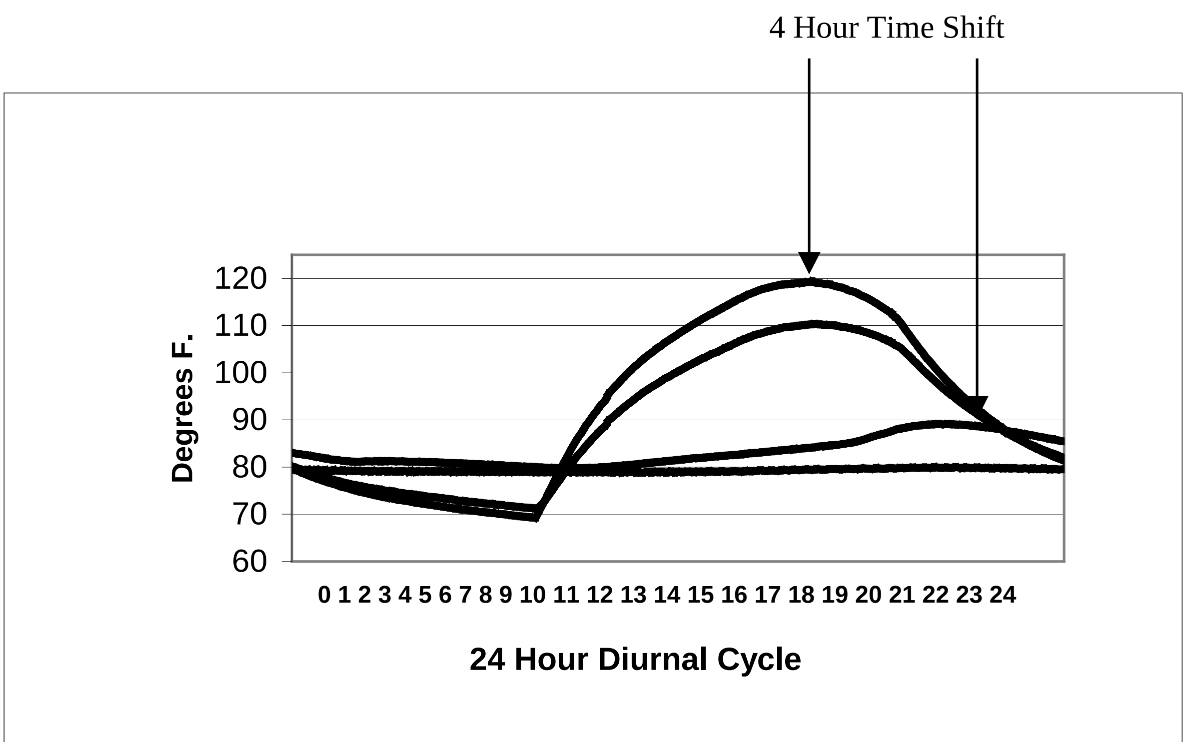
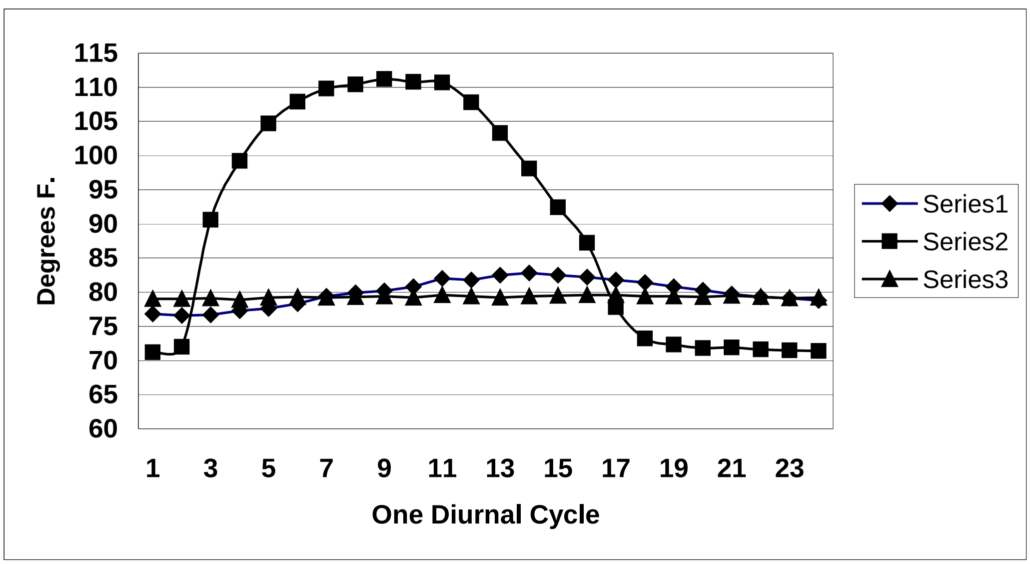


Figure 7. A Diurnal Cycle Showing Time-Shift for Peak Load

Temperature data like that shown in Figure 5. were used to calculate reductions in heat flow due to the presence of PCM. Figure 8. summarizes the calculation for one set of data. The curve labeled Series3 is the interior ceiling temperature. Series1 is the temperature of the interface between the two layers of insulation previously described with-PCM while Series 2 is the attic temperature. The set-point temperature for the conditioned space in this example is 77 °F. A summation over time of the heat fluxes calculated using Equation (1) provides the total heat flow in (requiring cooling) and heat flow out (requiring heating) for the system with and without PCM expressed as BTU/ft^2. The differences over the 24-hour period for the system without and with PCM is the reduction in heating or cooling loads. The reduced loads will result in reduced utility demand. The utility reduction requires the specification of equipment efficiencies.

$$q/A = \Delta T/R \qquad (1)$$

q/A is the heat flux
ΔT = temperature difference across a layer
R = thermal resistance of layer



Loads (BTU)				Heating Load Reduction	Cooling Load Reduction
No PCM	No PCM	With PCM	With PCM	69.10%	83.40%
Heating	Cooling	Heating	Cooling	Latent Heat Into PCM	Latent Heat Out of PCM
2.21	10.78	0.68	1.78	21.26	-6.1

Figure 8. Use of Data from Test Chamber to Access Performance

Summary

The use of localized PCM in the building envelope reduces the heat flow in and out of conditioned space resulting in reduced utility load.

Two methods of measuring the magnitude of the savings due to PCM have been discussed. A heat-flow meter apparatus can be used to measure the effect of PCM on heat flux resulting from a step-change in a boundary temperature. A two-compartment test chamber can be used to observe the performance of insulation systems with a cyclic boundary temperature.

A heating load reduction of 69% and a cooling load reduction of 83% due to the presence of PCM between insulation layers were calculated for an example configuration.

References

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