

A COMPARATIVE HEAT TRANSFER EXAMINATION OF STRUCTURAL INSULATED PANELS (SIPs) WITH AND WITHOUT PHASE CHANGE MATERIALS (PCMs) USING A DYNAMIC WALL SIMULATOR

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ABSTRACT

The main focus of this paper was to present data to advance the design of a previously developed thermally-enhanced structural insulated panel (SIP) that had been outfitted with phase change materials (PCMs) (Medina et al., 2008). To advance the development of the previous design, which had only been evaluated under full weather conditions, a set of well-controlled laboratory experiments was carried out. For this, a dynamic wall simulator was built, where a range of important parameters was evaluated. This was done through a comparative heat transfer examination of SIPs, with and without PCMs; where parameters, such as, foam core material of the SIP and material of the PCM holding containers (i.e., encapsulating pipes) were evaluated. Instantaneous heat transfer rates measurements are presented. The two parameters considered (i.e., foam material and pipe material) were found to have first-order effects on the performance of PCM-enhanced SIPs. The PCM outfitted SIPs reduced the peak heat fluxes when compared to their own kind, but without PCM. The results indicate that SIPs with molded expanded polystyrene (EPS) cores would benefit more from the PCM enhancement than SIPs with urethane cores. PVC pipes as holding containers for the PCMs did not prove as efficient as metal pipes.

INTRODUCTION

An existing design of the Phase-Change Structural Insulated Panel (PCSIP) was to be further fine-tuned as part of this research. The existing design is shown in Figure 1. In this panel, the two outer layers of structural sheathing material were made of nominal 7/16" sheets of oriented strand board (OSB) separated by 4" nominal of polystyrene foam insulation core in which copper pipes, having outside diameters of 1", were integrated in contact with the interior face of the interior sheathing. The pipes contained the phase-change material (PCM), which was n-Octadecane. The principle of operation for summer application of the PCSIP follows that

during the daytime, and as the result of solar activity, the temperature of the PCSIP increases making the PCM material to melt, and in the process the PCM absorbs heat. This heat is stored for a period of time and then released when the temperature of the PCSIP decreases, usually at nighttime and/or early morning hours. During the release of heat, the PCM changes from liquid to solid. During a typical summer day, the absorption, storage and release of heat by PCSIPs make it possible for the peak wall and cooling load to be reduced and a portion of this cooling load to be shifted to later times of the day. During the phase change process the wall temperature remains relatively stable, which can potentially increase the comfort of occupants. In a typical winter day, heat from the furnace and other heating devices is absorbed and stored in the PCSIP, which is later, upon cooling, released back to the heated space. This also results in a relatively stable room air temperature, which could also potentially translate to occupant comfort. Because of the temperature stability of the walls, the use of PCSIPs could reduce cooling and/or heating devices cycling, which would increase equipment life and also increase the performance (or efficiency) of the devices. Preliminary results show that under some climates the use of PCSIPs could lower the electric demand from compressor-driven air conditioners, reduce compressor sizes, or even eliminate the need for compressor-driven electrical air conditioning in some areas (Medina, 2007).

SUMMARY OF EVALUATED DESIGNS

First, the industry-standard SIP (4" EPS) was used as the control SIP. This SIP was referred to as *plain/EPS*. In addition to this SIP, there were the *plain/urethane*, which had a 4" nominal urethane core, the *PCM/EPS/copper*, which was the PCSIP, the *PCM/urethane/copper*, which was similar to the PCM/EPS/copper except that the material of the core was urethane foam, and the *PCM/EPS/PVC*, which was similar to the PCM/EPS/copper except that

instead of having copper pipes to hold the PCM, this one used PVC pipes. In all the designs that included PCMs the PCM was n-Octadecane with a concentration of 15 percent. The concentration was defined as the ratio of the weight of the PCM in the SIP to the weight of the interior OSB.

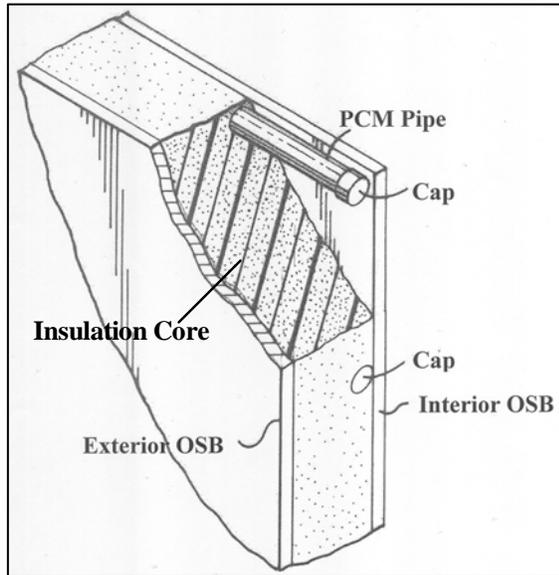


Figure 1. Schematic of the PCSIP

DYNAMIC WALL SIMULATOR

The testing was conducted in a dynamic wall simulator, a picture of which is shown in Figure 2. The simulator was designed as a cubic box made up of six equally sized removable wall panels of dimensions 4 ft x 4 ft.



Figure 2. Dynamic Wall Simulator

Infrared heat sources (incandescent light bulbs) of varying output were placed equidistant vertically and horizontally at the center of the simulator. The output of the heat sources was controlled by a combination of potentiometer and digital timer, which together had been calibrated to simulate daylight hours with their varying solar intensities. Under this configuration, the inside of the simulator represented, or simulated, the outside of building walls, and the laboratory space represented, or simulated, the conditioned indoor space of a building. Two small electric fans were placed inside the simulator to circulate and stir the air.

The panels were made in-house following strict guidelines used by the SIP the industry. In the cases where the SIPs were outfitted with PCM, the PCM was encapsulated in pipes (PCSIP). Figures 3 and 4 show SIPs with the PCM encapsulated in copper pipes and encapsulated in PVC pipes, respectively.



Figure 3. PCSIP with Copper Pipes

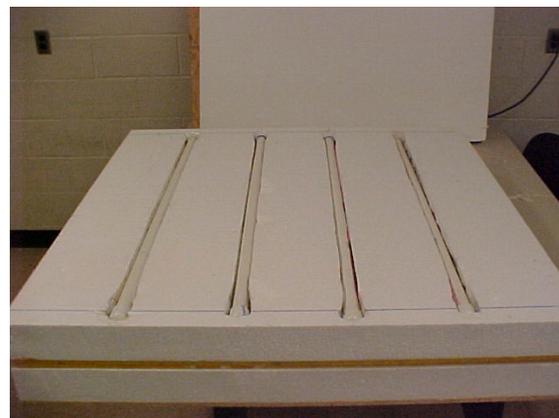


Figure 4. PCSIP with PVC Pipes.

Type T thermocouples (T/Cs) were used to measure both air and surface temperatures. The accuracy of the thermocouples was plus or minus 1 °F. The thermocouples were shielded with aluminum tape to minimize radiation effects. Each SIP was

instrumented with 34 T/Cs, 17 in the interior surface and 17 in the exterior and with four heat flux meters (HFMs) installed on the exterior surface. The HFMs were attached on the outside surface of the wall panels via pressure with screws. The HFMs had an accuracy of 2% deviation over the repeatable range of measurements. The locations of T/Cs and HFMs were selected to represent positions directly over foam core and pipes. The 17 T/Cs on each surface of the SIP were averaged to provide a single, more representative SIP surface temperature. For better comparison, the sensors were located exactly in the same locations in all panels, inside and outside. A schematic is shown in Figure 5.

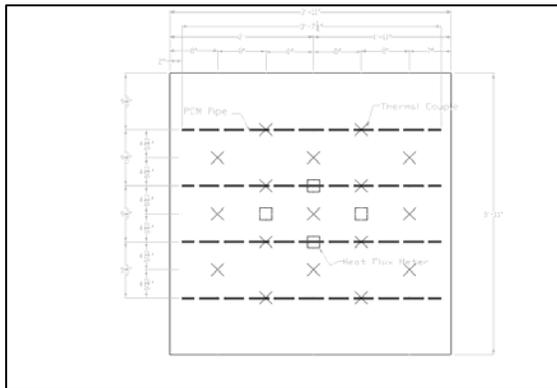


Figure 5. Location of Thermocouples and Heat Flux Meters in a Sample Wall Panel (X represented T/C and □ represented HFMs)

The data were measured continuously every 30 seconds through the duration of the tests. The data were integrated every hour. Table 1 shows the sensors and their corresponding accuracies

Table 1. Sensors and Their Accuracy

Sensor	Range	Accuracy (Deviation)
Heat Flux Meter	0 - 3.1×10^5 W/m ² (0-10 ⁵ Btu/hr-ft ²)	2 %
Type T T/C	-18 - 93 °C (0-200 °F)	0.6 °C (1 °F)

PCM Type

A paraffin-based PCM (n-Octadecane) was used. This PCM was chosen because of its high heat storage capacity, its non-toxicity, its ecologically harmless nature, and because it was 100% recyclable, and had a long life with stable performance through the phase change cycles. The physical and chemical properties of the PCM are listed in Table 2.

Table 2. PCM Properties (Rubitherm GmbH, 2003)

Property	Description
Physical State	Solid at room temperature
Color	White/Whitish
Odor	Practically odorless
pH value	Neutral
Congealing range	75-82°F(24-28°C)
Melting point	77°F(25°C)
Density at 77°F(25°C)	About 44lb/ft ³ (700 kg/m ³)
Heat storage capacity (temperature range 15°C to 30°C)	56 Btu/lb _m (131 kJ/kg)
Molar mass	265 kg/kmol
Volume expansion at ΔT=55 k	16%
Heat conductivity-solid	0.2 W/mk (0.1 Btu/h ft °F)
Kinematic Viscosity at 40 °C (104 °F)	4.10 mm ² /s (1.71 ft ² /h)
Flash point	>=100°C(212 °F)
Corrosion	Chemically inert with respect to most materials
Toxicology	Non-toxic and ecologically harmless
Water hazard	No water endangering substance

RESULTS

Heat Flux Comparison Between the Plain/EPS SIP and the PCM/EPS/Copper SIP

Figure 6 shows recorded data of heat flux across one set of SIPs. The solid line represents the hourly heat flux across the Plain/EPS SIP. That is, this SIP represents the standard SIP without any PCM. The dashed line represents the PCM/EPS/Copper SIP. From the figure it can be observed that during the first 24-hours of testing, the value of the heat flux across the plain/EPS panel reached its highest heat flux value at 2.74 Btu/hrft². The heat flux across the PCM/EPS/copper SIP, on the other hand, reached its highest value at 2.10 Btu/hrft², or 23.5% lower than the plain/EPS SIP. During the second day the highest values of heat flux were 2.66 Btu/hrft² for the plain/EPS and 2.06 Btu/hrft² for the PCM/EPS/copper, or 22.6% lower than the plain/EPS SIP.

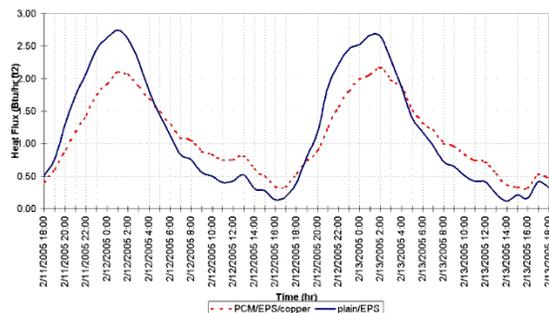


Figure 6. Hourly Heat Fluxes Across the Plain/EPS and for the PCM/EPS Copper SIP

From Figure 6 several observations are worth mentioning. As expected, the solidification of the PCM took place during the cooling down process

period. This is shown when the dashed line values were higher than those of the solid line. According to the collected data (not all shown in this paper, but can be found at Zhu, 2005), this solidification of the PCM took place even when the inside surface temperature of the panel did not drop below approximately 73 °F. This could be significant because this means that this technology could be applicable in places where nights are not necessarily very cold. Of importance also was the detail that the difference in areas during both the heating up process (between 18:00 and 1:00) and cooling down process (between 1:00 and 18:00) were not equal. This means that because the area during the heating up mode is greater than the area under the cooling down process, there would be less heat entering the conditioned space. Another observation was the slight “time shift” that is seen in the dashed line. This was more noticeable in day 2. This means that the thermal load was peaking at a “later” time. This is significant in buildings because it could potentially help lower the peak demand on the electric grid during the summer.

The total heat transferred for day 1 for the PCM/EPS/copper panel and plain/EPS panel were 26.64 Btu/ft²-day and 28.33 Btu/ft²-day, respectively. This indicated that the total heat transfer reductions were 5.98% and 3.49% for days 1 and 2, respectively. In Figure 7, which represents the heat fluxes across the panels during the heating up process, the shape of the line representing the heat flux across the PCM/EPS/copper SIP (dashed line) indicated that the phase change material was in the process of melting.

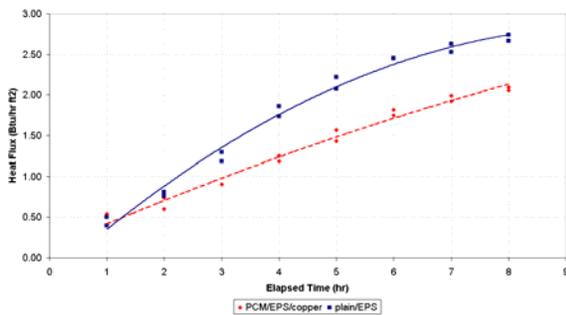


Figure 7. Heat Flux Across the Panels Versus Elapsed Time for the Plain/EPS SIP and PCM/EPS/Copper SIP During the Heating Up Process

Heat Flux Comparison Between the Plain/EPS SIP and the PCM/EPS/PVC SIP

Figure 8 shows the measured heat fluxes across the Plain/EPS (solid line) and the PCM/EPS/PVC SIP. That is, the PCSIP used PVC pipes instead of copper pipes. From the figure, it is evident that among the controlling parameters that affected the performance of a PCSIP was the conductivity of the PCM-holding material. In day 1, for example, the value of heat flux across the plain/EPS SIP had a maximum value of 2.71 Btu/hrft². At the same time, the heat flux across the SIP that held the PCM inside PVC pipes reached a peak value of 2.39 Btu/hr ft². This represented a reduction in peak heat flux of 11.8%. The peak values for the plain/EPS and PCM/EPS/PVC SIPs for day 2 were 2.59 Btu/hrft² and 2.25 Btu/hrft², respectively, or a reduction in peak heat flux of 13.1%. The total heat transferred for day 1 for the plain/EPS SIP was 26.22 Btu/ft²-day and for the PCM/EPS/PVC SIP it was 24.54 Btu/ft²-day. Therefore, the total heat transferred difference for day 1 was 6.41%. The total heat transferred for day 2 for the plain/EPS SIP and for the PCM/EPS/PVC SIP were 24.83 Btu/ft²-day and 23.10 Btu/ft²-day, respectively, or a 6.97% different.

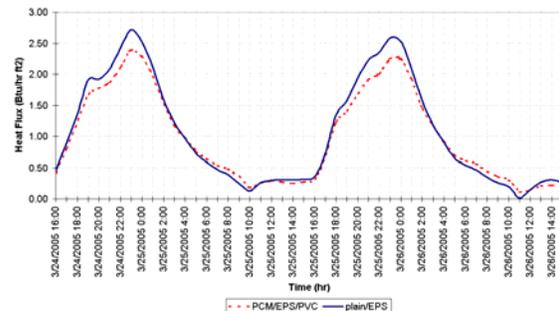


Figure 8. Hourly Heat Fluxes Across the Plain/EPS SIP and the PCM/EPS/PVC SIP

In relation to the performance of PCM-enhanced SIPs using copper pipes, the peak heat flux reduction was about 12 percentage points lower in the SIP with PVC pipes. The overall daily heat transfer reductions were about 2 percentage points higher in the SIPs with the PVC pipes. It appears that this can be explained by the fact that some of the PCM did melt but not as much as it did in the case when copper pipes were used, and therefore, the process of solidification of the PCM released only relatively a small amount of heat in the direction towards the outside of the simulator (location of the HFMs).

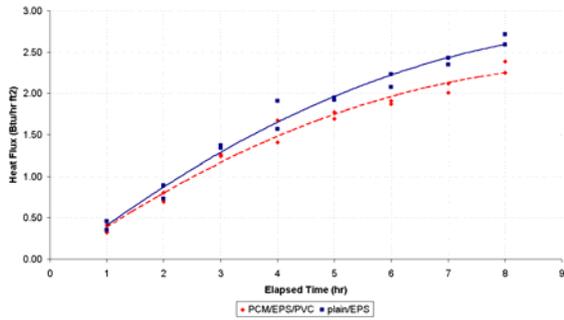


Figure 9. Heat Flux Across the Panels Versus Elapsed Time for the Plain/EPS and the PCM/EPS/PVC SIPs During the Heating Up Process

In contrast to Figure 7, the dashed line in Figure 9, which represents the heat transfer rate across the PCM-enhanced SIP using PVC pipes, followed the shape of the solid line consistently. This may help to conclude that little melting was taking place.

Heat Flux Comparison Between the Plain/EPS SIP and the Plain/Urethane SIP

As shown in Figure 10 the heat transfer rate across the plain/urethane SIP was much lower than the heat transfer rate across the plain/EPS SIP. This was expected since the R-value of urethane was higher than that of the EPS foam. During the first day, the plain/EPS SIP reached a maximum heat flux of 2.74 Btu/hrft². The plain/urethane SIP maximum’s value was 1.92 Btu/hrft², or 30% lower. During the second day, the plain/EPS SIP reached a maximum heat flux value of 2.66 Btu/hrft² and the plain/urethane panel a value of 1.86 Btu/hr ft², which translated to a reduction of 30.3%.

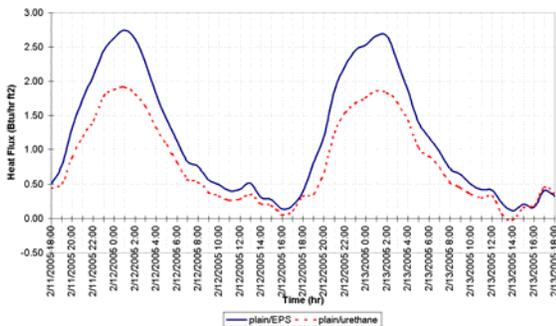


Figure 10. Hourly Heat Fluxes Across the Plain/EPS SIP and for the Plain/Urethane SIP

The total heat transferred for day 1 for the plain/EPS and for the plain/urethane were 28.33 Btu/ft²-day and 19.93 Btu/ft²-day, respectively, or a

percent reduction by the plain/urethane panel of 29.6%. For the second day, the plain/EPS and plain/urethane panels transferred 29.29 Btu/ft²-day and 19.84 Btu/ft²-day, respectively, or a reduction of 29.9%.

Heat Flux Comparison Between Plain/Urethane SIP and the PCM/Urethane/Copper SIP

Figure 11 depicts the similarity in thermal performance, based on heat flux data, between the plain/urethane and the PCM/urethane/copper SIPs. During the first 24 hours, the plain/urethane SIP reached a maximum heat flux value of 1.92 Btu/hrft² while the PCM/urethane/copper SIP reached a value of 1.80 Btu/hrft². The peak heat flux reduction was 6.24%. During the second 24 hours, the plain/urethane SIP reached a maximum heat flux value of 1.86 Btu/hrft² while that of the other SIP was 1.76 Btu/hrft². Thus the peak heat flux reduction percentage was 4.96%. The time shift created by the PCM in the PCM/urethane/copper SIP (dashed line) was clear. Interestingly, the total heat transferred for day 1 for the plain SIP and for the PCM SIP was 19.93 and 22.11 Btu/ft²-day, respectively, or a difference of -10.92%, meaning that the SIP with the PCM transferred more heat into the conditioned space. For the second day, the totals were 19.84 and 22.22 Btu/ft²-day for the plain and PCM SIPs, respectively, or an -11.98% reduction.

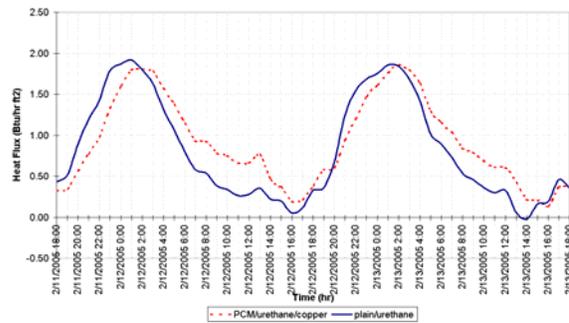


Figure 11. Hourly Heat Fluxes Across the Panels for the Plain/Urethane SIP and PCM/Urethane/Copper SIP

In Figure 12 the area formed by the two lines in the graph represented the average of the heat absorbed by the PCM during the heating up process shown in Figure 11. Similarly, in Figure 13, the area formed by the two lines in the graph represented the average of the heat released by the PCM during the cooling down process shown in Figure 11.

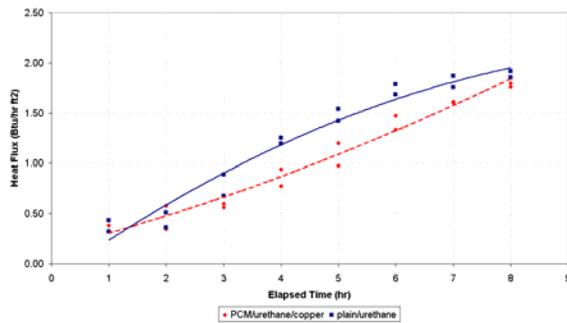


Figure 12. Heat Flux Across the Panels Versus Elapsed Time for the Plain/Urethane SIP and the PCM/Urethane/Copper SIP During the Heating Up Process

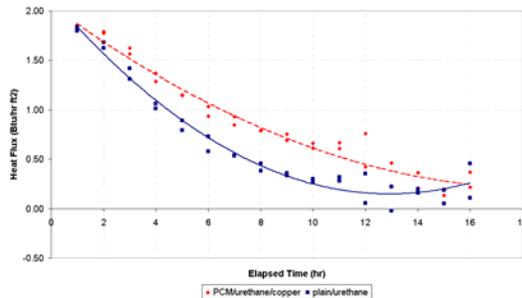


Figure 13. Heat Flux Across the Panels Versus Elapsed Time for the Plain/Urethane SIP and the PCM/Urethane/Copper SIP During the Cooling Process

The area representing the heat released (Figure 13) is the greater of the two. This explains in part why more heat was transferred into the conditioned space in the SIP outfitted with PCM. In comparing Figure 12 with Figure 7, it was seen that at the end of the heating up process in Figure 12, the curves came closer together, whereas in Figure 7 the curves separate further. Thus explaining that by the time the peak heat flux was reached, both panels were transferring approximately the same amount of heat regardless of the fact that one panel was outfitted with PCM.

Equivalent Thermal Resistance

Thermal resistance is the resistance to heat flow through a material caused by a temperature difference across the material, and is evaluated under steady-state conditions. The rate at which heat flows through a slab of homogenous material under steady-state conditions is given by:

$$\dot{Q} = \frac{A \times \Delta T}{R} \quad (1)$$

Where:

\dot{Q} = total heat flow (Btu/hr or Watt)

A = surface area perpendicular to the heat flows (ft² or m²)

ΔT = the temperature difference between the warm and cold sides of the wall (°F or °C)

R = the thermal resistance per unit area of the piece of material (ft²°Fhr/Btu or m²°C/W)

The value of the thermal resistance of a piece of a material can be thought of as the temperature difference across it required to allow one unit of heat flow per unit area. Therefore,

$$R = \frac{A \times \Delta T}{\dot{Q}} = \frac{\Delta T}{\dot{Q}/A} = \frac{\Delta T}{\dot{q}''} \quad (2)$$

Where

\dot{q}'' = heat flow through one unit area = heat flux (Btu/hr ft² or W/m²).

The $\frac{\Delta T}{\dot{q}''}$ value under steady state is the R-value. In

the experiments presented in this paper, the heating up and cooling down processes were under unsteady

states conditions. Therefore, the $\frac{\Delta T}{\dot{q}''}$ values at any

point in time during heating up or cooling down processes were referred to as *equivalent thermal resistance*, R_e

Figure 14 shows the equivalent thermal resistances estimated during the heating up and cooling down processes in the first 24-hours of the test corresponding to the plain/EPS and PCM/EPS/copper SIPs. The R_{eq} 's are plotted in terms of temperature difference across the SIPs.

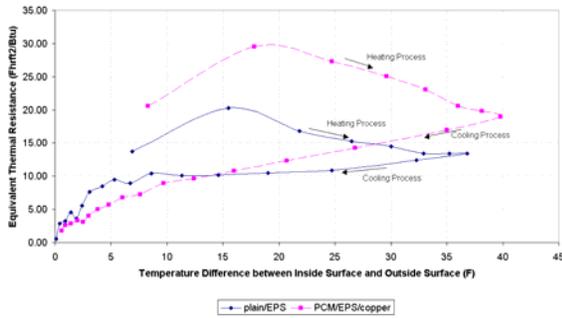


Figure 14. Equivalent Thermal Resistance for the Plain/EPS SIP and the PCM/EPS/Copper SIP

The fact that during heating up the values of the equivalent thermal resistance of the PCM/EPS/copper SIP are higher or the fact that during cooling down process the values switch sides, from being higher to being lower, was not surprising, in fact, this was expected, given the definition of the R_{eq} . Except for the “shift” observed in the PCM curve, the shape of the curves representing R_{eq} was very similar during the heating process. It was interesting to observe how the maximum resistance to heat flow in both cases occurred at approximately 0.45 of the maximum ΔT . During the cooling down process, there was a long period when the plain SIPs sustained the nearly constant R_{eq} , which in the plain/EPS SIPs was close to 10 hr-ft²-°F/Btu. Figure 15 shows the unsteady state thermal resistance for both the Plain/EPS and urethane SIPs. The plain urethane SIP achieved an equivalent thermal resistance of approximately 35 hr-ft²-°F/Btu. The R_{eq} during the cooling down process was sustained nearly constant at 16 hr-ft²-°F/Btu.

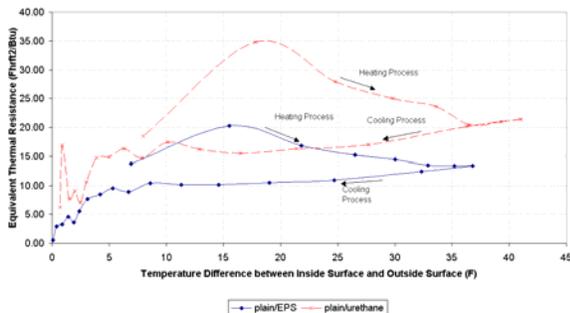


Figure 15. Equivalent Thermal Resistance for the Plain/EPS SIP and Plain/Urethane SIP

The largest values in R_{eq} were observed in the PCM/urethane/copper SIPs (Figure 16). The approximate peak values in R_{eq} were 20 hr-ft²-°F/Btu for the Plain/EPS SIPs, 30 hr-ft²-°F/Btu for the PCM/EPS/copper SIPs, 35 hr-ft²-°F/Btu for the Plain/urethane SIPs, and 57 hr-ft²-°F/Btu for the PCM/urethane/copper SIPs. This is depicted in Figure 17.

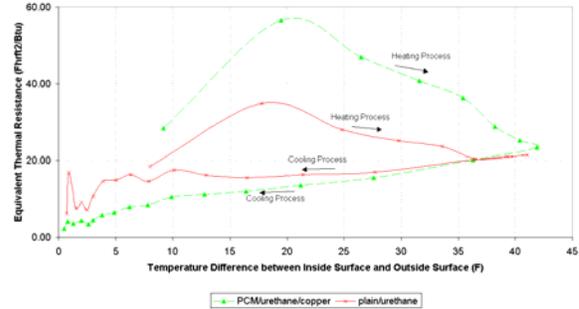


Figure 16. Equivalent Thermal Resistance for the Plain/Urethane SIP and the PCM/Urethane/Copper SIP

The maximum R_{eq} of the PCM/EPS/PV SIP was estimated at 24 hr-ft²-°F/Btu.

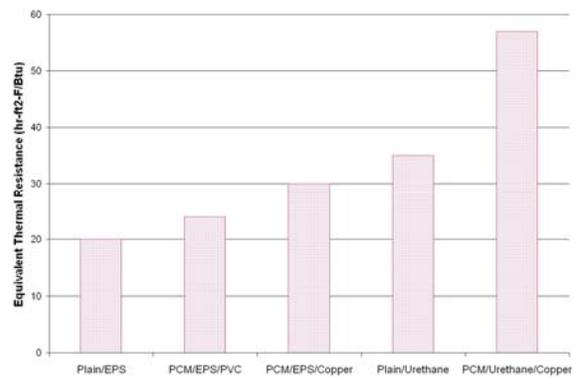


Figure 17. Maximum Equivalent Thermal Resistance of the Plain/EPS, PCM/EPS/PVC, PCM/EPS/Copper, Plain/Urethane, and PCM/Urethane/Copper SIP

CONCLUSIONS

The purpose of this research was to set up an experimental system that could test and evaluate the thermal performance of structural insulated panels (SIPs) with the idea of advancing a previously developed PCM-enhanced SIP. A dynamic wall simulator with six equally sized planes was designed where differently configured SIP panels could be mounted and evaluated. The simulator was constructed and then equipped with sensors and a monitoring system to measure and collect thermal performance parameters of the various SIP designs, including temperatures and heat fluxes. Several tests were run to compare and to evaluate the thermal performance of the differently configured SIP panels. The experiments were designed to last 48 hours, where 8 hours were for the initial heating, followed by 16 hours of cooling. This constituted one cycle. Two cycles were allocated per test. The SIPs that were outfitted with phase change material (PCM) were fitted with a concentration of

15% based on the weight of one 7/16" nominal OSB board. The PCM used was n-Octadecane with a melting temperature of 77°F and a congealing point between 75.2°F and 82.4°F. The PCM was encapsulated in copper and PVC pipes in separate experiments and put inside the insulation core of SIP panels in contact with what would normally be the interior face of the indoor OSB. On average, the results related to peak heat flux reduction produced by the various designs were as follows: The PCM/EPS/Copper SIP reduced the peak heat flux, when compared to the plain/EPS SIP, by 23%. The PCM/EPS/PVC SIP reduced the peak heat transfer rate by 12.5% over the plain/EPS SIP. The plain/urethane SIP produced a reduction in peak heat flux of 30.1% when compared with a plain/EPS SIP. The PCM/urethane/copper SIP reduced the peak heat flux by 5.6% over the plain/urethane SIP.

In terms of maximum equivalent thermal resistance values, the rank orders were: plain/EPS (20 hrft²°F/Btu), PCM/EPS/PVC (24 hrft²°F/Btu), PCM/EPS/copper (30 hrft²°F/Btu), plain/urethane (35 hrft²°F/Btu), and PCM/urethane/copper (56 hrft²°F/Btu). The urethane panel transferred less heat due to its large thermal resistance; thus, the PCM contained in urethane core SIPs absorbed small amounts of heat during the heating process. Therefore, it is not beneficial for a urethane core SIPs to be outfitted with PCM. In summary, it was discovered that the plain/urethane SIP produced lower indoor heat fluxes than the plain/EPS SIP, the PCM outfitted SIPs reduced the peak heat fluxes when compared to their own kind, but without PCM, the EPS SIP would benefit more from the PCM enhancement than the urethane core SIP and PVC pipes as holding containers for the PCM did not prove as efficient as copper pipes.

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