Students Exposure to Sustainable Thermal Energy Storage Technologies at West Texas A&M University

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Abstract

In the mechanical and civil engineering programs at West Texas A&M University, students are exposed to a variety of sustainability-oriented projects through senior design and research courses. The projects are selected to provide an in-depth understanding of the investigated area through analytical and experimental studies. In this particular project, students in thermal design were asked to investigate the feasibility of using paraffin-oil mixture as a phase change material (PCM) in residential walls. A PCM material with a melting point of 23°C (73°F) was designed and mixed. The mass of PCM required for a 1 m^2 (10.8 ft^2) wall (the size of the test apparatus) was determined to be 5.8 kg (12.8 lb) in a vertical 3.18 cm (1.25 in) thick sheet. A wall containing the PCM and another wall designated as a "control" were placed on 1 meter cubic insulated structures and were monitored through controlled experimentation. The testing was conducted indoors and an interior heating element simulated four complete day cycles. The result of the indoor study proved conclusively that with the correct modifications and optimization, PCM, as a form of insulation, is economically viable over its lifespan of 20 years. The reduced cost to the owner of a 186 m^2 (2,000 ft^2) home is $129.73/year. The proposed design causes a minuscule 5.76 kg/m^2 (1.2 lb/ft^2) of additional load to the structure. Because the PCM is in the configuration of a uniform sheet, the majority of the extra load will be supported by the concrete slab of the home.

1. Introduction

The rise in the standards of living and the increase in human population have put a tremendous strain on electrical power demand worldwide. In the United States, the energy consumed by commercial and residential buildings amount to 29% of the energy generated. The walls of buildings play an important role in the energy consumed to heat or cool the buildings. This energy demand can be reduced by embedding phase change material (PCM) inside building walls. The purpose of this project is to have senior engineering students from both the mechanical and civil engineering programs design a prototype composite residential wall that incorporates phase change material to optimize the temperature gradient across the composite wall, and to compare the thermal performance of the PCM-embedded wall with that of a conventional wall in a controlled experimental laboratory setup that can test for different climatic conditions.

2. Project Initiation

The project discussed in this paper, design of a PCM-embedded residential wall, addresses the need to design a system for a sustainable use by relying on temporary energy storage mechanism through the use of phase change materials instead of conventional power (i.e. electrical power) for heating or cooling. The implementation of a phase change material instead of electrical power eliminates the environmental impact and fossil fuel dependency that is associated with the operation of an electrically powered system. The project identifies with ABET student learning outcome criteria and particularly those dealing with sustainability.

The project was initiated in the spring semester of 2017 when it was assigned as a project in the Thermal-Fluid Design course, offered at the senior year in the mechanical engineering program. In Thermal-Fluid Design, students are expected to apply heat transfer and fluid mechanics concepts to design thermal-fluid systems. Emphasis is placed on design calculations, component and system modeling, and optimization including economic considerations. Students learning outcomes related to this course include all of ABET accreditation criteria: 3(a) through 3(k). Criterion 3(c) recognizes the need to incorporate sustainability within engineering design.

The class consisted of 20 students which was divided into 4 groups, with each group having equal number of students. The groups were given the task to design their own PCM-embedded wall. Each group conducted their own tests to evaluate the thermal performance of the walls. At the end of the spring semester, one PCM wall design was selected (schematic is shown in Fig. 3) from among the four designs, and three senior research students from the mechanical and engineering programs were recruited to conduct further tests on the selected PCM wall during the summer term.

3. Experimental Setup

Energy consumption is a concern in all disciplines of engineering, which has led to innovative ideas for saving the consumer money on energy. One such innovation is the use of Phase Change Materials (PCM). A PCM is a solid at cooler temperatures but changes phases as it absorbs latent heat during melting. During the melting phase, the temperature does not rise, lessening energy demands for buildings. The material then releases this heat when the exterior temperature begins to decline. Many such materials exist, but are expensive due to the rarity of implementation of such systems.

This study designs and tests a simple and cost effective PCM which has a melting temperature suitable for residential insulation. The PCM used in this study is a mixture of paraffin and canola oil, with a starting melting point of 23°C (73°F). The experimental design is a sheet of PCM contained within a thin box, to be consistent with conventional residential construction. PCM thickness and melting temperature can be tailored to the climate of the region.

Experimentation was performed indoors using a light bulb inside of an insulated box. The light source was a 50W light bulb which was powered using a standard wall outlet. A PCM wall (experimental) and a standard wall (control) were tested simultaneously side by side for 16-24 hours at a time.

The main objectives of the experiment were to estimate the cost of implementing the wall in a standard size home, the added structural load and how it would impact building, the latent heat of fusion of the PCM, and the savings estimated over the life span of typical PCMs.

To begin, the investigative team decided to use for this study a simple and inexpensive mixture of canola oil and paraffin, mixed to a melting temperature of 23°C. Using this temperature as the desired PCM melting temperature, the mass fraction of oil was determined from mass weighted temperature averaging:

$$x = \frac{T_{m,p}\rho_p - T_{m,PCM}\rho_p}{T_{m,p}\rho_p - T_{m,o}\rho_o - T_{m,PCM}\rho_p + T_{m,PCM}\rho_o} \qquad (1)$$

where $T_{m,p}$, $T_{m,o}$, and $T_{m,PCM}$ are the melting temperatures of the paraffin wax, canola oil, and PCM mixture, respectively. ρ_p, ρ_o, and ρ_{PCM} are the material densities of the paraffin wax, canola oil, and PCM mixture, respectively. x is the percentage of oil in the mixture.

The mixture used was 77% by weight Paraffin and 23% by weight Canola Oil. To determine the melting temperature of the paraffin-oil PCM mixture, a sample of the mixture in its solidified state was placed in a beaker and heated using a water bath. The temperature of the paraffin PCM was monitored using thermocouples placed at two locations in the beaker (Fig. 1): at 0.5 cm (0.2 in) (T/C#1) and at 2 cm (0.8 in) (T/C#2) from the glass beaker vertical edge. Tests conducted on the paraffin-oil mixture showed the melting temperature of the mixture was not constant. The mixture started melting at 23°C (73°F) and phase transformation continued until the mixture reached a temperature of approximately 54°C (129°F). Figure 2 shows the transient response of the paraffin PCM and the water bath. It is interesting to note that as the paraffin-PCM undergoes phase transformation, the rate of temperature increase inside the PCM is lower than the rate of temperature increase in the water bath temperature.

However, as the PCM completes its phase transformation at 54°C (129°F), the rate of temperature increase inside the PCM jumps noticeably compared to the water bath.

A drying oven was used to melt and mix the oil and paraffin, with frequent stirring using an electric stirrer. The PCM mass of 5.8 kg (12.8 lb) in the wall allowed for the PCM container thickness of 3.18 cm (1.25 in).

The test apparatuses are shown in Fig. 3 with *Reflectix* insulation on top, bottom and three side walls, with the control and PCM test walls. Each apparatus is a 1 m (38 in) cube, square wood frame 5.08 cm x 10.16 cm (2 in x 4 in) with the control and PCM wall of drywall, plywood, R-13 insulation, as shown.

4. Results and Discussion

Fourteen Type-K thermocouples were used to measure the temperature at various locations, shown in Fig. 5. OMEGALOG Assistant v. 3.9.1 was used to program the data logger (Omega Data Logger Model: OM-SQ2040-2F16) and retrieve data. Plugging the bulbs into a wall timer simplified the data collection and modeled a standard day.

The heat flow out of the PCM and control walls are determined from Fourier's Law using the measured temperatures and verified by comparison with free convection from the wall using the correlation for Nusselt Number, Nu_L:

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387 Ra_L^{\frac{1}{6}}}{\left(1+(0.492/Pr)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right\}^2 \tag{2}$$

where Ra_L is Rayleigh number, and Pr is Prandtl number. The energy savings per day depends on the heat flow throughout the test as in Eqn. (3):

$$Energy = \sum_{t=0}^{test\ time\ (s)} \begin{matrix} (q_{t,control\ wall} - q_{t,pcm\ wall}) & if & T_{avg,PCM} > 23\,^{o}C \\ (q_{t,PCM\ wall} - q_{t,control\ wall}) & & T_{avg,PCM} < 23\,^{o}C \end{matrix} \tag{3}$$

where q_t is the heat transfer rate.

Assuming the walls have similar error percentages we can find the energy stored, L, by using Eqn. (4):

$$L = \frac{\sum_{t=@T_{PCM,cold} > 23\,^{o}C}^{t=@T_{max}} (q_{t,control\ wall} - q_{t,pcm\ wall})}{m_{PCM}} \tag{4}$$

where m_{PCM} is the mass of the PCM.

Finally, an economic analysis must be done using the monthly savings as an annuity as in Eqn. (5):

$$PW = A_{\$}(P\ /\ A, n, i) \tag{5}$$

The results of the transient temperatures at various locations are shown in Fig. 6 (PCM wall) and Fig. 7 (control wall). The temperature of the PCM starts higher but is overtaken by the control wall.

To further explore the temperature difference and impact of the PCM, the inside wall closest to the ambient air is shown below. The graphs formed by both the control and PCM walls are compared in Figs. 8-10.

The results show that over time the PCM wall lowers the heat flow more than can be justified by the thermal resistivity of the composite material. This difference in the value of temperature between the two materials can be converted into an energy savings. The energy savings is stored energy from the phase change. The effective latent heat of fusion of the composite material is calculated intensively by taking the total energy savings and dividing by the total PCM in the wall, calculated to be 248 kJ/kg. This value is important when trying to optimize the PCM for wall based systems. It was decided that the vessel holding the PCM must be a manageable and measurable thickness with basic construction tools. This led to a thickness of 3.18 cm based on theoretical calculations as well as convenience of construction.

Using the data occurring within 29°Celsius and 42°Celsius, the for 12.2 x 15.2 square meter house with walls 3.05 m tall was $129.73 per year.

The structural load of the PCM on the wall used was assumed to be the only increase in load. The orientation of the PCM and design of it would let it stand upright resting on the ground with minimum support needed by the beams in the wall. Most of the 5-kg load would be applied to the foundation. The structural load would be an increase of approximately 5.76 kg/m^2 of wall, and due to most of the load being primarily supported on the foundation, it would be unlikely that the PCM would change the materials needed to construct a house.

The data indicates a clear difference in the heat transfer occurring by adding the PCM. A physical post mortem investigation indicates that the PCM is not melting at constant temperature. The problem is believed due to in homogeneity within the PCM, resulting from ineffective mixing, and preferential solidification of the paraffin. Additional work is ongoing to investigate different PCM geometries and different mixtures.

5. Conclusions

Mechanical Engineering students in thermal-fluid design and engineering research courses at West Texas A&M University designed a PCM-embedded wall for sustainable use in residential buildings. The composition of the PCM was 77% by weight paraffin wax and 23% by weight canola oil. To investigate the feasibility of incorporating the PCM inside walls, the PCM-embedded residential wall was tested against a conventional (control) wall. Based on the results of field tests, the students reached the following conclusions:

- As the PCM undergoes phase transformation, the rate of temperature increase inside the PCM is lower than the rate of temperature increase in the medium surrounding the PCM.
- Compared to a conventional wall, the embedding of PCM in a wall can over time lead to a noticeable reduction in the amount of heat flow inside the wall.
- The use of a paraffin/canola oil PCM is an economically viable material to use in residential walls over a 20-year lifespan period. The reduced cost in an electrical bill to the owner of a 186 m^2 (2,000 ft^2) home is projected to be $130 per year.

Acknowledgement

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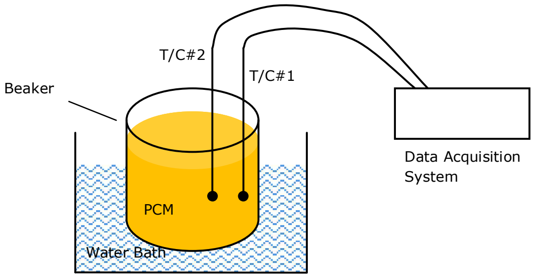

Fig.1 Temperature controlled water-bath testing for the paraffin-oil PCM phase transformation temperature

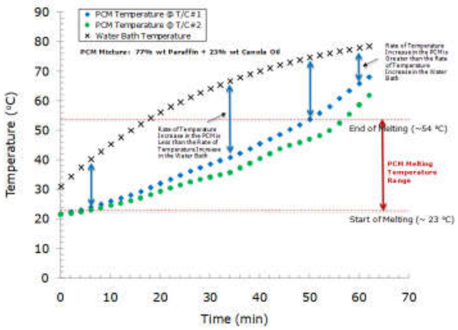

Fig.2 Phase transformation temperature range for the paraffin-oil PCM

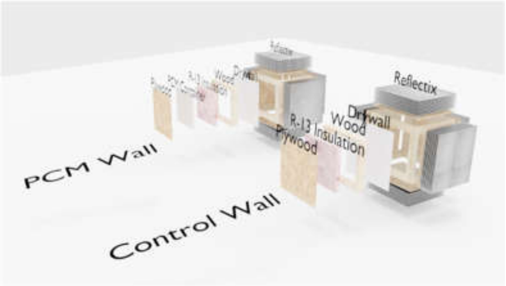

Fig.3 Setup of the PCM and Control walls

Fig.4 Interior of the cubic enclosure testing structure

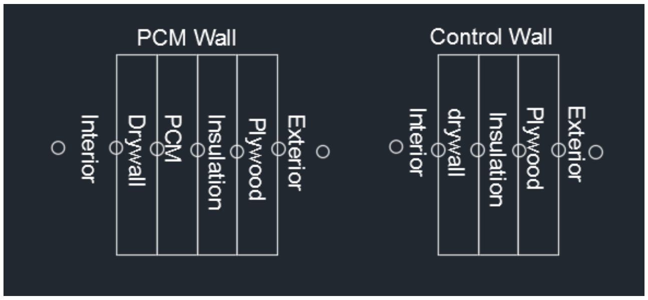

Fig. 5 Thermocouple placement inside the walls (Circles indicate the location of the thermocouples)

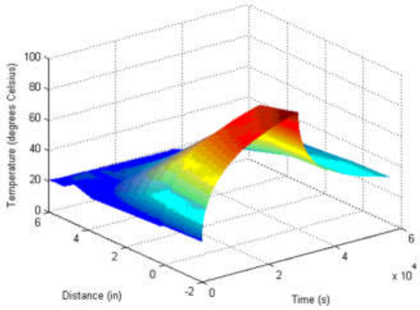

Fig. 6 PCM wall temperature time history versus location

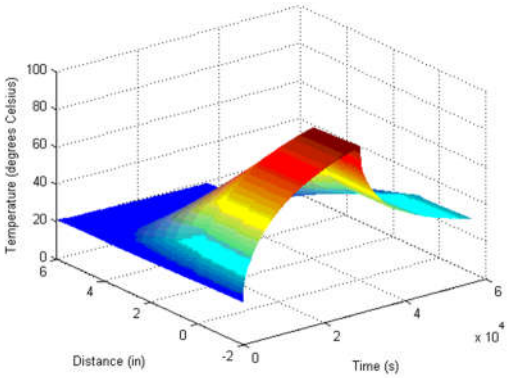

Fig. 7 Control wall temperature time history versus location

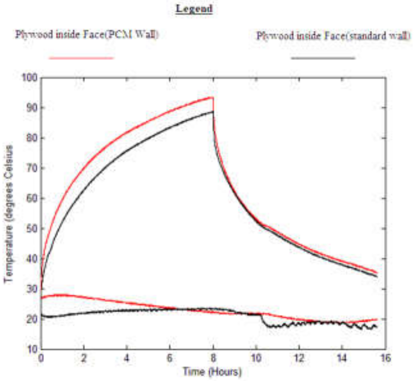

Fig. 8 Comparison between PCM wall (Red) and control wall (Black) temperatures

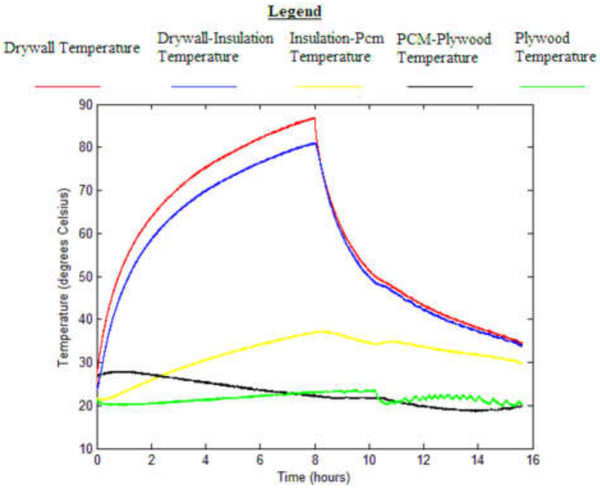

Fig. 9 PCM wall transient temperature response

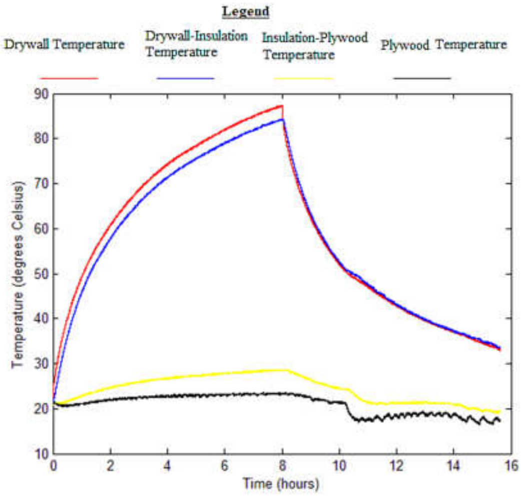

Fig. 10 Control wall transient temperature response