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EXPERIMENTAL INVESTIGATION OF A BIO-BASED PHASE-CHANGE MATERIAL TO IMPROVE BUILDING ENERGY PERFORMANCE

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ABSTRACT

Phase Change Material (PCM) plays an important role as a thermal energy storage device by utilizing its high storage density and latent heat property. One of the potential applications of the PCM is in buildings by incorporating them in the envelope for energy conservation. During the summer cooling season, the main benefits are a decrease in overall energy consumption by the air conditioning unit and the time shift in peak load during the day. Experimental work was carried out by Arizona Public Service (APS) in collaboration with Phase Change Energy Solutions (PCES) Inc. with a new class of organic-based PCM. The experimental setup showed maximum energy savings of about 30%, a maximum peak load shift of ~ 60 min, and maximum cost savings of about 30%.

INTRODUCTION

Thermal energy can be stored as latent heat when a substance changes from one phase to another by either melting or freezing. The storage media employing this principle is known as phase change material (PCM). These materials are a useful remedy when there is a mismatch between the supply and demand of energy. The PCM finds several applications in thermal protection of flight data and cockpit voice recorders, hot and cold medical therapy, transportation of perishable foods, solar power plants, photovoltaic cells, solar-activated heat pumps, waste heat recovery, buildings etc. as researched by Salyer et al [1] and Fatih Dermirbas [2] . This paper focuses on the use of PCM in building energy conservation and air conditioning applications.

The global demand for air conditioning has increased significantly in the past decade and huge demands in electric power consumption have led to interest in energy efficiency and conservation, as stated by Dincer and Rosen [3]. Energy consumption in buildings varies significantly during the day and night according to the demand by business and residential activities. In hot climate areas, most of the energy is consumed during the day time due to high ambient temperatures and intense solar radiation. This has led to varying pricing system for the on-peak and off-peak periods of energy use. Potential cost savings by reduction in energy consumption and by shift of peak load during the day can be achieved by incorporating PCMs in the walls of the residential and business building establishments.

There are several promising ongoing developments in the field of PCM applications for heating and cooling of buildings. Frank [4] performed a review on using PCM in the walls and in the ducts of the cooling units of the building to provide both heating and cooling effects. Pasupathy et al. [5] performed experimental and simulation analysis of incorporating PCM in the roofs of the buildings. Guo [6] carried out an experimental work on a new kind of PCM and found that the heat storing/releasing ability of it was significantly higher than other PCMs. He also performed a simulation and calculation based on the effective heat capacity method to verify the result. Huang [7] applied a validated model to predict the energy conserving capability of the PCM by fabricating them in walls of the buildings. Experimental study was conducted by Takeda et al. [8] to analyze PCM usage on floor supply air conditioning system to enhance building thermal mass. Similar work by

Farid and Chen [9] presented a simulation of under floor heating with and without the presence of PCM layer. Frank [10] studied a storage system for both heating and cooling seasons that comprises two different PCMs integrated into a reverse cycle refrigeration heat pump system.

Many PCMs are derived from paraffin-based materials which are highly flammable and thus hinders their use in buildings. A newly developed organic-based PCM, here termed 'BioPCM,' improves safety since it is less flammable than traditional PCMs. Fire retardant materials can also be added to paraffin based PCMs to reduce its flammability, but at the expense of altering the thermophysical properties of the material. The BioPCM can also be manufactured such that the melting point can be made from -22.7 °C to 78.33 °C (−73 °F to +173 °F), and this facilitates its use in various climatic zones. This paper reports experimental data for BioPCM applied to one of two small test sheds in Tempe, Arizona, including the shift in time of peak load, and energy consumption and cost savings.

BIOPCM PROPERTIES

The properties of the BioPCM used in the experimental setup are described in Table 1. Additionally, commonly available paraffin based PCM, GR27 researched by Huang [7] and water properties are shown for comparison.

Table 1: THERMOPHYSICAL PROPERTIES OF BIOPCM, PARAFFIN BASED PCM AND WATER

DESCRIPTION	BIOPCM	GR27	WATER
Melting Point (ºC)	29	28	0
Density (kg/m3)	860	710	1000
Specific Heat (kJ kg^{-1} $°C^{-1}$)	1.97	1.125	4.179
Latent Heat (kJ/kg)	219	72	334
Viscosity @ 30 ºC (cp)	7	-	0.798
Boiling Point (°C)	418	-	100
Thermal Conductivity (W m^{-1} $°C^{-1}$)	0.2	0.15	0.6

The phase change temperature range for the charging process during day time and discharging during night time are respectively 26.4 °C to 32.2 °C and 22.2 °C to 26.2 °C. The value of 29 °C was chosen to conventionally represent the approximate peak of the heating curve and to avoid the two separate ranges of temperatures. The BioPCM offers significant advantage over the conventional PCM with its high specific heat and high latent capacity. On the other hand, water with its superior properties could be an ideal candidate for PCM applications in buildings. However, it cannot be used in buildings because of storage-associated problems and as the liquid-gas phase change occurs at a higher temperature (boiling point) which is not possible to reach in practical situations.

The BioPCM is not packaged as a continuous sheet, but rather is organized into small blocks that are separated from one another as pictured in Fig 1. The BioPCM mat in the walls has 60 square blocks per 24” x 16” size of mat, with each block of dimension 1.3” x 1.3”. For attic space, a BioPCM mat consisted of 4 rectangular blocks per 24” x 16” size of mat, with each individual block of dimension 7” x 11”.

During manufacturing suitable precautions are taken for volumetric expansion of BioPCM during phase change and to prevent rupturing of the encapsulation.

Figure 1: BIOPCM MAT USED IN WALLS

EXPERIMENTAL SETUP

The experimental measurements were carried out at the Arizona Public Service (APS) Solar Testing and Research (STAR) facility in Tempe, Arizona (in the Phoenix metropolitan area), and data were collected for the entire 2008 calendar year. The set up consists of two nominally identical sheds as shown in Fig. 2, named as North and South with length, width and height dimensions as 4.876m x 3.657m x 2.436m (16’x 12’x 8’) and with a 4/12 pitch roof. Both sheds face east, and were located to ensure that there were no shading and had unobstructed wind flows.

The North shed was filled with BioPCM in all the four walls, roof and floor with different thickness, whereas the south shed was of conventional construction without any installed BioPCM.

Figure 2: EXPERIMENTAL SETUP OF SOUTH (NON BIOPCM) SHED AND NORTH (WITH BIOPCM) SHED

Walls were constructed with 2” x 4” studs 16” O.C. with R-13 fiberglass insulation, T-111 siding and ½” finished gypsum board. The structures had enclosed attic space with R-30 fiberglass mat between 24” O.C. of ceiling. 1/2” OSB roof sheathing was covered with 15 lb. roofing felt and standard three tab fiberglass desert tan shingles. Standard BioPCM mat with a PCM density of 0.56 lbs. per cubic foot was installed in all walls between the fiberglass insulation and sheetrock of the North shed. In addition, 1 lb. per cubic foot density BioPCM was installed in both the ceiling and floor of the North shed. The total resistances in the wall with and without PCM were calculated as 13.49 °C/W and 13.33 °C/W respectively. The percentage increase in resistance with inclusion of PCM is just above 1% and hence the performance of the PCM shed can be credited to the heat storage capacity of the PCM. Similar calculations can be also shown for the resistance of the roof and the floor.

Both sheds were fitted with identical Amana AH093 window-mounted heat pumps to study the energy consumption and to establish the performance of the BioPCM. Two Honeywell 7500 series 7-day programmable thermostats replaced the conventional thermostats to yield accurate results. They were selected after bench testing where they were shown to have less than 0.1 degree Fahrenheit variation between the two. An interface relay panel was installed for each building. Thermostats were set on auto switchover mode and were programmed with the settings for all the 7 days as shown in Table 3.

Table 3: THERMOSTAT SETTINGS FOR THE EXPERIMENT

TIME (Hours)	HEAT °C (°F)	COLD °C (°F)
06:00	22.7 (73)	25.0 (77)
08:00	22.7 (73)	25.0 (77)
18:00	22.7 (73)	25.0 (77)
20:00	20.5 (69)	22.3 (72)

RESULTS AND DISCUSSION

Table 2 summarizes the peak load shift and the monthly energy usage calculated for all the months from the experimental data.

The peak load was calculated by finding the average of the maximum load values of all days in a month measured during a particular time interval. For example, consider the month of June which has experimental data effectively for 25 days with data being collected every minute for the PCM shed. Let us find the peak load between 10:00 and 10:15 am. This 15 min time duration had 15 readings for a given day. The maximum of these 15 readings was found. Similarly, the maximum peak loads between 10:00 and 10:15 am for the remaining 24 data available days were calculated. The average of these 25 readings (maximum load values) gives the peak power between 10:00 and 10:15 am for the month of June. Zero values, if any, are

Table 2: PEAK LOAD SHIFT AND ENERGY USAGE

MONTH	DATA AVAILABLE DAYS	TIME INTERVAL FOR WHICH DATA WERE TAKEN (min)	PEAK LOAD SHIFT		MONTHLY kWh ENERGY USAGE		
			OBSERVED	(min)	WITHOUT PCM (kWh)	WITH PCM (kWh)	PERCENTAGE DIFFERENCE (%)
January	24	10	No	-	157.193	111.897	28.82
February	28	10	No	-	113.551	91.364	19.54
March	30	10	No	-	92.421	83.919	9.20
April	24	1	No	-	95.727	81.526	14.83
May	15	1	No	-	126.217	108.618	13.94
June	25	1	Yes	60	273.204	240.165	12.09
July	22	1	Yes	15	318.775	268.152	15.88
August	27	1	Yes	45	292.695	234.417	19.91
September	26	1	Yes	30	188.927	140.031	25.88
October	30	1	No	-	94.104	71.272	24.26
November	22	1	No	-	60.209	42.595	29.25
December	18	10	No	-	152.988	116.219	24.03

omitted in the average calculation. The same procedure is repeated for finding the peak loads for the remaining hours with a time interval of 15 min and we get 96 data points. The entire procedure is repeated for the non-PCM shed. These 96 average peak load values each for the PCM and non-PCM sheds are plotted against time for the month of June as shown in Figure 3.

Figures 3 – 6 present the monthly average peak loads for the summer months in 2008, for both the North (with BioPCM) and South (no BioPCM) sheds. The dotted line indicates the occurrence of peak load and the corresponding hour and is found to take place between 3:15 to 4:45 PM, the time of intense insolation and high ambient temperature in Tempe, Arizona. The time duration between the two dotted lines indicates the peak load shift time between the two sheds. The time shift in peak power consumption was seen only for the summer months (June to September). The maximum time shift occurred in June (60 min), and the minimum for the summer occurred in July (15 min). The possible reasons for no peak-load time shift during the other months of the year might be due to very shorter time frame involving phase change transition of the PCM.

The energy savings were highest for the month of November with nearly 30% while March recorded the least value of about 9%. Referring to the NREL [13] weather data for Phoenix, it was observed that some winter months (Jan, Feb, and Dec) had no days and other months (Mar & Nov) had few days with ambient temperature above the melting point of the PCM. So, we believe that the solar radiation would have been the prime factor that would have caused considerable phase change during winter.

The energy savings during winter months can be attributed due to partial melting (solid and liquid phase) of the PCM in shorter duration (noon till evening) by moderate ambient temperature or by mild solar radiation or both. The combined solid and liquid phase change has the highest heat capacity and would have aided in storing thermal energy thereby preventing passage of heat to the interior. The solidification of the PCM takes places later in the evening by discharging heat to the interior of the shed. This additional heat liberated by the PCM helps in heating the shed, thus reducing work load on the air conditioning unit.

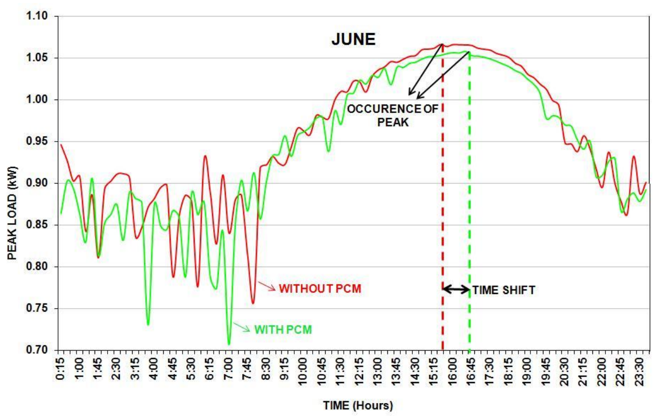

Figure 3: EXPERIMENTAL PEAK CURVE FOR JUNE

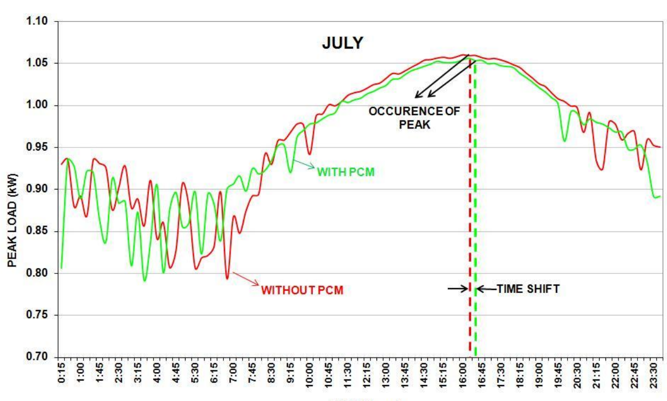

Figure 4: EXPERIMENTAL PEAK CURVE FOR JULY

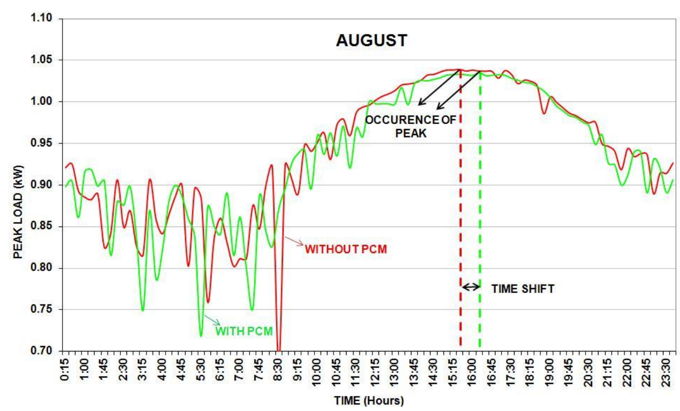

Figure 5: EXPERIMENTAL PEAK CURVE FOR AUGUST

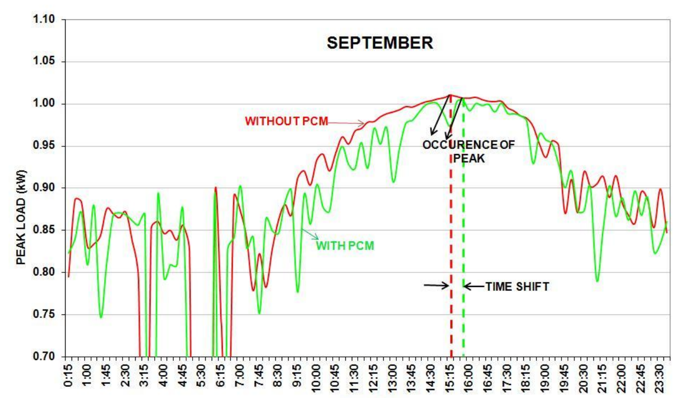

Figure 6: EXPERIMENTAL PEAK CURVE FOR SEPTEMBER

Other technical difficulties faced during the setup were due to attic ventilation which was additionally installed after mid-June. This had a dramatic effect on the performance because the lack of adequate attic ventilation hindered the attic BioPCM phase transition during this period. This can be seen by the substantial performance improvement following the months after June.

From the experimental data in Figs. 3 - 6, it can be observed that large fluctuations occurred during the early mornings and late nights indicating the additional work done by the air conditioning unit to keep the shed at the desired temperature.

This is due to the discharge process of the BioPCM during which heat is released both inside and outside the shed. The additional heat released by the PCM has to be removed by the air conditioning unit thereby consuming more power which causes oscillations in the curve. This increased air conditioning load during the nighttime can possibly be reduced by removing heat from the BioPCM by flowing tap water through copper tubes in contact with the BioPCM, as suggested by Pasupathy et al. [5]

Figures 3 - 6 show various fluctuations because experimental data were recorded with some interruptions during the year. For instance, the data were initially recorded with an interval of ten minutes, and the time interval was later changed to one minute to better understand the performance of the BioPCM.

To accurately calculate cost savings, billing cycles adopted in Arizona were used. Different billing cycles (Tables 4 and 5) are used for on-peak hours (9:00 am to 9:00 pm) and off-peak hours (9:00 pm to 9:00 am). The billing cycle is varied also for different classes of residential and business establishments and also for summer and winter seasons. It can be noted that the summer and on-peak hours are priced slightly higher than their counterparts as expected due to higher demand during those of the hours of the day and time of the year.

Table 4: RESIDENTIAL BILLING CYCLE

BILLING CYCLES	RESIDENTIAL RATES	
	On-Peak Hours (9:00 am to 9:00 pm)	Off-Peak Hours (9:00 pm to 9:00 am)
Summer (May to Oct)	$0.1581 per kWh	$0.0511 per kWh
Winter (Nov to Apr)	$0.12845 per kWh	$0.04925 per kWh

Table 5: BUSINESS BILLING CYCLE

BILLING CYCLES	BUSINESS RATES	
	On-Peak Hours (9:00 am to 9:00 pm)	Off-Peak Hours (9:00 pm to 9:00 am)
Summer (May to Oct)	$0.14329 per kWh	$0.10607 per kWh
Winter (Nov to Apr)	$0.12847 per kWh	$0.09124 per kWh

Table 6 presents the potential cost savings for this small shed realized by employing BioPCM. A maximum percentage cost savings of about 30% (October) was observed at the residential utility rate, and 28% (November) was observed at the business utility rate. This suggests that the currently employed BioPCM with melting point of 29 °C works most efficiently in the transition between summer and winter season during which less intense insolation and ambient temperatures were observed. March was found to have the least cost savings of around 10% for both the residential and business utility rate. This might be due to the climatic condition in which the day was significantly hotter and night was considerably colder, thereby requiring the cooling units in both the sheds to do more work to maintain comfort conditions. This can be verified by the small difference in energy usage between the two sheds for March in Table 2.

Table 6: COST SAVINGS BY BIOPCM

MONTH	RESIDENTIAL COST SAVINGS	BUSINESS COST SAVINGS
	$ (%)	$ (%)
January	3.38 (31.28)	4.20 (28.13)
February	1.78 (18.44)	2.40 (18.55)
March	0.93 (9.60)	1.28 (10.47)
April	1.62 (14.13)	1.76 (14.62)
May	1.46 (12.97)	2.07 (13.78)
June	6.21 (16.98)	4.93 (13.57)
July	7.15 (19.25)	6.91 (16.85)
August	7.69 (21.63)	7.39 (19.54)
September	7.71 (29.19)	7.78 (27.99)
October	3.77 (29.38)	3.58 (28.08)
November	1.33 (26.66)	1.98 (28.23)
December	2.64 (25.13)	4.13 (24.34)

The use of BioPCM has shifted the energy usage in the on-peak hours to the off-peak hours, the values depending upon the seasonal months, by storing heat (charging process) during the day time and releasing them back in the night time (discharging process). This is highly crucial for business buildings as they are major consumers of energy during the on-peak hours in summer. This can also help cut down operation of power plants during peak hours of the day and reduce non-renewable fuel consumption, associated emissions and distribution losses.

The reductions in peak hour demand are calculated based on the formula

$$\text{Percentage Peak} = \frac{\text{On-Peak Energy Usage}}{\text{On-Peak Energy Usage} + \text{Off-Peak Energy Usage}}$$

Table 7: REDUCTION IN ENERGY DEMAND DURING ON-PEAK HOURS

MONTH	ENERGY USAGE WITH BioPCM			ENERGY USAGE WITHOUT BioPCM		
	On-Peak (kWh)	Off-Peak (kWh)	% Peak	On-Peak (kWh)	Off-Peak (kWh)	% Peak
January	25.26	67.18	27.33	40.47	86.27	31.93
February	30.55	59.62	33.88	37.36	73.39	33.73
March	39.23	50.46	43.74	42.75	57.8	42.52
April	54.73	22.93	70.47	63.37	27.85	69.47
May	40	67.92	37.06	45.2	80.38	35.99
June	170.74	65.48	72.28	213.76	53.84	79.88
July	152.37	115.91	56.8	195.28	123.12	61.33
August	148.3	86.4	63.19	194.69	93.4	67.58
September	101.63	51.37	66.42	146.06	64.7	69.3
October	52.16	16.06	76.46	75.13	18.8	79.99
November	14.05	28.38	33.11	18.35	41.2	30.81
December	18.89	95.63	16.49	26.19	124.75	17.35

The reduction in on-peak hour energy usage is noticeable during the summer season (June to October) for BioPCM sheds indicating potential energy savings. These results are quite consistent with the observed peak load time shift as seen in Table 2. Also a very small peak hour energy reduction is observed for December and January.

CONCLUSION

In this paper, experimental evaluation of organic-based BioPCM in the building envelope is discussed and compared with traditional building construction without it. The setup was tested for climatic conditions of Phoenix, Arizona.

The investigation showed significant energy and cost savings as well as peak load time shift and reduction in energy usage during on-peak hours of summer months. Furthermore, BioPCM with its less flammable properties and its availability with a wide range of melting points is a proven technology for prospective energy conservation in buildings.

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