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Energy Storage Using Phase Change Materials - Challenges and Opportunities for Power Savings in Residential Buildings

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Abstract. The energy consumption in residential buildings is mainly combined with the interior environment's heating and cooling energy demand. One solution is to reduce these energy consumptions by implementing a phase change material (PCM) based thermal energy storage (TES) technique. Thermal energy storage with phase change materials can be applied for peak electricity demand saving or increased energy efficiency in heating, ventilation, and air-conditioning (HVAC) systems. The primary grid benefit of thermal energy storage is load shifting and shedding by replacing heating, ventilation, and air conditioning system operation during peak times and recharging the storage system during off-peak times. Additional efficiency benefits come from shifting HVAC system operations to periods when the system can operate more efficiently and at a lower cost. This paper discusses the present state-of-the-art PCMs for thermal energy storage systems for buildings space heating/cooling applications and the limitations of incorporating phase change materials that negatively impact the performance. The limits are supercooling, low thermal conductivity, phase segregation, fire safety, corrosion, and cost. This study briefly explored how some of these issues can be limited or eliminated. The application of phase change materials has been demonstrated as a solution to decrease the energy demand of an apartment building. Results for two available and environmentally friendly PCMs (BioPCM and DuPont Energain) with different melting ranges applied inside the exterior walls and the roof is analyzed and presented. Simulations have been performed with and without the application of PCM materials. It was demonstrated that PCM could store heat energy from solar radiation and the surrounding environment, thus reducing energy consumption for heating and cooling scenarios.

INTRODUCTION

Increasing worldwide energy demand is a progressively vital issue in terms of energy supply and climate change. At present, the world uses 80% of fossil fuels by pushing climate change and decreasing fossil fuel reserves rapidly. The USA building sector is responsible for about 40% of energy consumption [1]. The demand for energy increases because of the increasing trend of population and industry. This energy consumption is mainly related to the heating and cooling load of the indoor environment to provide thermal comfort to the occupants. Implementing phase change materials (PCMs) and technologies for thermal energy storage (TES) in buildings is one new way to lower these consumptions.

The use of phase change materials for buildings heating and cooling has shown an excellent performance [2]. PCM changes from solid to liquid in an endothermic process by absorbing heat, and from liquid to solid phase change occurs when the phase change material releases heat in an exothermic process [2]. The energy utilized to change the PCM phase will result in a more stable and comfortable interior environment since the phase change temperature is close to the targeted comfort level. Peak cooling and heating electricity demand, as well as energy consumption spikes, are reduced when phase change materials are used [3]. The application of phase change materials for thermal energy storage systems reduces the mismatch between demand and supply of electricity, improves the performance and reliability of electricity distribution networks, and plays a vital role in conserving energy [4-8]. Several researchers

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have been studied using phase change materials (PCMs) in buildings application to reduce energy consumption rates. Ascione et al. [9] developed a phase change material and integrated it to the inner side of the external walls were analyzed in-depth and by varying their melting temperature and optimization of the design. With a melting temperature of 23℃ and a freezing temperature of 21℃, this innovative material found a decrease in summer energy demands of 11.7% and enhanced summer indoor comfort. Marin et al. [10] studied the application of phase change materials in lightweight relocatable buildings as a passive technology to save energy under different weather conditions. The results found the potential of using PCM enhanced gypsum boards in lightweight buildings to improve the energy performance during heating and cooling periods in arid and warm temperate main climate areas.

The paper's main aim is to map the possibilities for using thermal energy storage in residential buildings and show the opportunities for increased energy efficiency and reduced heating and cooling peak loads using thermal energy storage. As a test case, we have explored the use of Thermal Energy Storage in a building under the Wichita, Kansas climate. However, the investigation tried to identify thermal energy storage technologies and system solutions that offer broader applications, including other climate conditions. The technical focus is on the need to keep a specific indoor temperature range in a building with the help of phase change materials for thermal energy storage.

METHODOLOGY

This study and analysis compared the energy consumption performance of a residential building with and without the application PCMs. The residential building energy consumption was determined by utilizing the EnergyPlus model software, and the finite conduction differences heat balance algorithm, which is briefly discussed in the mathematical model section. Several authors [11-12] had previously confirmed this software's model validation and verification. These authors [11-12] followed the ASHRAE Standard 140 [13], which calls for combining analytical verification, comparison testing, and empirical validation. This method can be used to figure out the amount of energy usage on a monthly and annual basis [11] of a residential building.

Selection of Phase Change Materials

The selection of appropriate phase change materials is critical for residential building applications. Researchers need to find the proper phase change materials for residential building applications with high thermal conductivity, no supercooling or phase segregation effects, meet fire safety requirements, and be acquired at a relatively low cost. Furthermore, previous studies observed that the performance of the same phase change material in different residential building applications varied significantly with the local weather condition.

Supercooling is described as the state in which a liquid solidifies below its normal freezing point [14], delaying the commencement of the solidification process [15]. This reduces the phase change material's performance and, over time, results in slower heat recovery from the phase change material. Inorganic phase change materials are more likely to be affected by this constraint. Supercooling can be considerably minimized by introducing a nucleating agent [16].

If phase change materials have a low thermal conductivity, heat transfer rates into and out of a latent heat thermal energy storage system are slower [17]. Low thermal conductivity can restrict phase change materials' potential in thermal energy storage systems by slowing the heat release/absorption rate during the solid-liquid phase transition [18]. Using additives and composites, many research initiatives have been conducted to improve the thermal conductivities of phase change materials [19].

Phase segregation is one of the most significant negative influences on phase change materials' cyclic thermal stability [20]. The long-term stability of the PCM in use is hampered by phase segregation. For viable thermal energy storage applications, it has been argued that PCM must work successfully for many years. As a result, researchers have looked into novel techniques for removing phase segregation's deleterious impacts from PCMs.

The materials employed in the residential building envelope can considerably impact the development of a fire inside a building [21]. Several studies have attempted to identify the use of fire retardants to mitigate the negative impacts of organic phase change materials in building envelopes on fire safety [22, 23].

Compatibility is the most important aspect while designing latent heat thermal energy storage systems for building applications. If the PCM material is not compatible with the container, it will result in corrosion and changes in PCM properties. The ultimate result is the poor performance of the heat storage system [24].

Finally, the end-user must assess if phase change material systems are worthwhile investments. However, the public is unaware of phase change materials and their benefits. As a result, it requires marketing these solutions to the public, highlighting their benefits.

This study analyzed two different PCMs (BioPCM and DuPont Energain PCM) with varying melting ranges. Some of the key features of BioPCM and DuPont Energain PCM are given in Table 1.

TABLE 1. Key features of BioPCM [26] and DuPont Energain PCM

Name of PCM	Key features
BioPCM	• Environmentally friendly. • The product is non-toxic and biodegradable. • More BTUs per pound of PCM; tunable energy storage capacity. • More BTUs in the same volume due to tunable density. • Tunable thermal conductivity for improved reactivity to temperature fluctuations. • The material is non-corrosive. • Chemically inert. • Long service life, with no loss of melting temperature or thermal energy storage after thousands of freeze/melt cycles (100+ years). • During phase transition, there are minor volume fluctuations.
DuPont Energain	• DuPont Energain consists of a compound containing paraffin wax. •DuPont Energain panels are safe to handle and do not contain toxic substances. •The heat storage capacities due to phase change are 515 kJ/m^2. •The Energain board is rated as Class E under BS EN 13501: Reaction to Fire. (Class E is the worst class that passes the tests.) But note that Energain is usually covered with ordinary plasterboard. • DuPont Energain panels are reliable for an extended period and will not deteriorate in functionality significantly with time.

Table 2 lists the technical features of these materials, and the enthalpy change to the temperature of PCMs are shown in Fig. 1(a) and 1(b) [12, 27].

TABLE 2. PCM properties

Properties	BioPCM	DuPont Energain
Conductivity (W/m k)	0.20	0.16
Thickness (m)	0.01	0.01
Density (Kg/m^3)	860	855
Specific heat (J/Kg k)	1970	2500
Latent heat (KJ/Kg)	219	130
Melting point (°C)	29	21.6

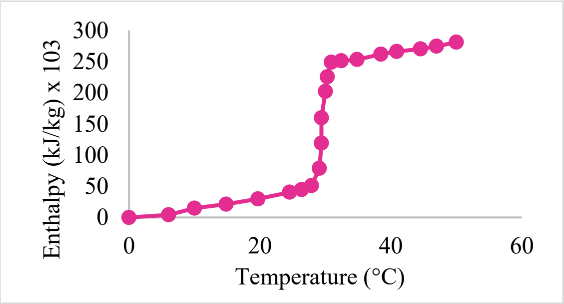

FIGURE 1. (a). Enthalpy, Temperature Plot for BioPCM

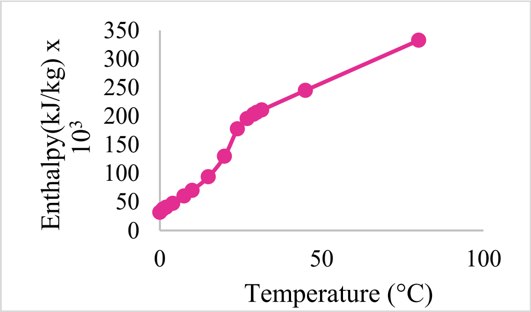

FIGURE 1. (b). Enthalpy, Temperature Plot for DuPont Energain PCM

Building Description

The building under investigation is a model of a midrise apartment complex developed by the Department of Energy (DOE) [28]. It was chosen as the base case model for this energy use simulation from the US Department of Energy Commercial Reference Building Models from the National Building Stock (Fig. 2).

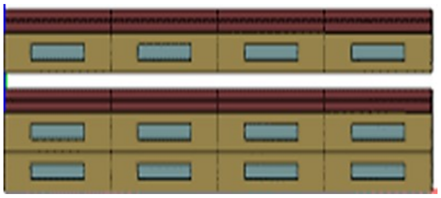

FIGURE. 2. Building model (DOE midrise apartment building)

The exterior wall of the building consists of a 25 mm stucco, 5/8-inch gypsum board, typical insulation R-13.45, and a 5/8-inch gypsum board from outside to inside. The PCM layer was put between the standard R-13.45 insulation and the four-sided outside wall's 5/8-inch gypsum board. The roof consists of a roof deck, typical insulation R-19.72, and plasterboard from outside to inside. Between the conventional insulation R-19.72 and the plasterboard, the PCM layer was to be put.

TABLE 3. Exterior wall and roof construction

	Material	**Conductivity (W/m k)**	**Thickness (m)**	**Density (Kg/m^3)**	**Specific heat (J/Kg k)**	**Thermal resistance (m^2. k/W)**
Exterior wall	25 mm stucco	0.72	0.0254	1856	840	0.0353
	5/8 in gypsum board	0.16	0.0159	800	1090	0.099375
	Typical insulation R-13.45	-	-	-	-	2.368
	PCM		Depend on the type of PCM from Table 1			
	5/8 in gypsum board	0.16	0.0159	800	1090	0.099375
Roof	Roof deck	0.14	0.019	530	900	0.1357
	Typical insulation R-19.72	-	-	-	-	3.472204
	PCM		Depend on the type of PCM from Table 1			
	Plasterboard	0.16	0.01	950	840	0.0625

Mathematical Model

This dynamic energy simulation was carried out using EnergyPlus 9.4.0. The conduction transfer function (CTF) is the main algorithm used in EnergyPlus to determine surface heat transfer. In an algebraic equation, the conduction transfer function addresses the transient conduction technique with time series coefficients. The CTF solution has the advantage of requiring only a few simple linear equations with constant coefficients. The one-dimensional conduction finite difference (CondFD) solution procedure in EnergyPlus is depicted in Fig. 3 [11]. In EnergyPlus, the CondFD method employs an implicit finite difference technique., with the user having the option of choosing between an implicit and Crank-Nicholson scheme.

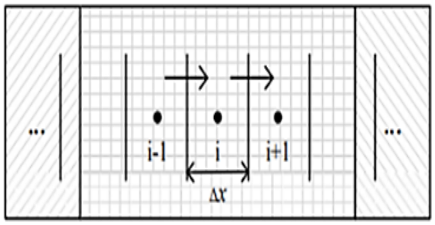

FIGURE 3. Control volume for heat conduction

Fourier's equation can be used to calculate heat conduction from control volume "i-1" to control volume "i" (assuming steady-state conditions). Through a time step, the rise in enthalpy for control volume "i" is accumulated as equation (2). Equation (3) is found by plugging equation (1) into equation (2) and by expressing the specific enthalpy change as a temperature change multiplied by the specific heat capacity. The Enthalpy-Temperature function can be used to update the specific heat in each iteration depending on user-input data, as shown in equation (4). The node enthalpies are updated at each step of these procedures, allowing the variable properties of the phase change material to be properly calculated. All elements in the CondFD method are discretized automatically using equation (5), which is dependent on the material's thermal diffusivity, a spatial discretization constant c, and the time step. We selected three as the default space discretization value (corresponding to a Fourier number F0 of 1/3) and entered the other values:

$$\mathrm{q}_{\mathrm{i}}^{\mathrm{j+1}} = -\frac{k\left(T_i^{j+1}-T_{i-1}^{j+1}\right)}{\Delta x} - \frac{k\left(T_{i+1}^{j+1}-T_i^{j+1}\right)}{\Delta x} = -k\frac{\left(T_{i+1}^{j+1}-T_{i-1}^{j+1}\right)}{\Delta x} \tag{1}$$

$$\frac{\rho\Delta x(h_i^{j+1}-h_i^j)}{\Delta t} = -(q_i^{j+1} - q_i^j) \tag{2}$$

$$\frac{\rho c_p\Delta x(T_i^{j+1}-T_i^j)}{\Delta t} = k\ \frac{(T_{i+1}^{j+1}-T_i^{j+1})}{\Delta t} + k\frac{(T_{i-1}^{j+1}-T_i^{j+1})}{\Delta t} \tag{3}$$

$$c_p = \frac{(h_i^{j+1}-h_i^j)}{T_i^{j+1}-T_i^j}) \tag{4}$$

$$\Delta x = \sqrt{(c}.\alpha.\Delta t) = \surd(\frac{\alpha\Delta t}{F_0}) \tag{5}$$

Weather Data

Some methodologies and considerations were made to perform the EnergyPlus simulations. The weather data for Wichita, Kansas, USA, in energy plus weather (EPW) file format, was used for this simulation. The simulation was conducted for one year, and the simulation produced annual results.

RESULTS AND DISCUSSION

Heating and cooling energy demand

Figure 4 shows a case study of heating energy requirements without the use of PCMs (Reference) and with the use of PCMs.

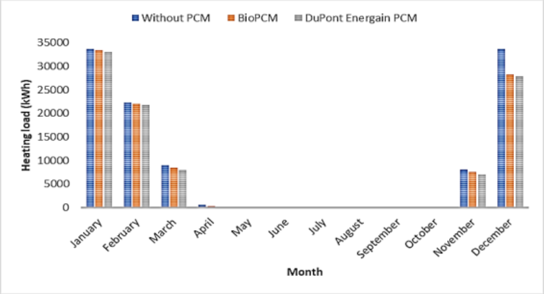

FIGURE 4. Heating energy requirements for a reference solution and with PCMs

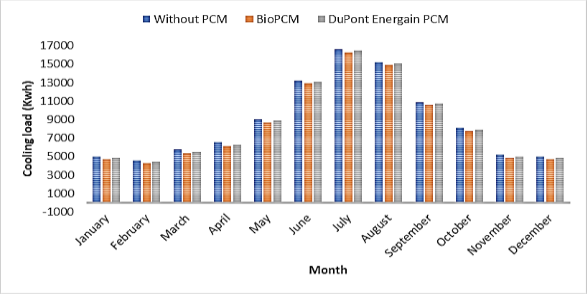

FIGURE 5. Cooling energy requirement for reference solution and with PCMs.

The heating needs of buildings in Wichita, Kansas, are often substantially higher from December to February due to the weather. It was feasible to demonstrate that all PCMs examined allowed for a reduction in heating requirements by assessing the heating energy requirements. The DuPoint Energain PCM produced better results for heating energy needs since it allowed for a reduction of 4,440 kWh in a year, which is a 4.34 percent reduction over the reference solution.

Figure 5 depicts a case study of cooling energy requirements without the use of phase change materials (Reference) and with the use of phase change materials. The cooling loads of the building were 105049 kWh per year, as shown in Table 4, and the use of phase change materials allows the cooling load to be greatly reduced. The implementation of BioPCM for cooling energy needs yielded considerable benefits. When compared to the reference situation of no phase change material inclusion, the use of this type of material lowered the cooling load by at least 3.74 percent.

In terms of total energy usage, it is discovered that using this sort of material reduces these indices significantly, as indicated in Table 4. When looking at the PCM that has fewer impacts (BioPCM), it is feasible to see that the energy requirements are reduced by 2.94 percent. The application of DuPont Energain PCM allows for a more significant reduction in energy consumption. This material lowered energy use by 6,563 kWh over the course of a year, a reduction of 3.2 percent.

TABLE 4. Annual HVAC system energy loads and savings

PCM	Without PCM	BioPCM	DuPont Energain PCM
Heating load (kWh)	102,352	100,177	97,912
Savings (%)	-	2.13	4.34
Cooling load (kWh)	105,049	101,125	102,926
Savings (%)	-	3.74	2.02
Total energy load (kWh)	207,401	201,302	200,838
Savings (%)	-	2.94	3.2

PCM's Impact on the Indoor Environment

Researchers frequently look at the indoor temperature profile during a brief representative period in the summer or winter to evaluate the performance of PCMs. The energy utilized with and without the PCM is then compared in the evaluation [29]. As a result, this study evaluates the indoor environment during two days in August (the cooling season) and two days in January (the heating phase).

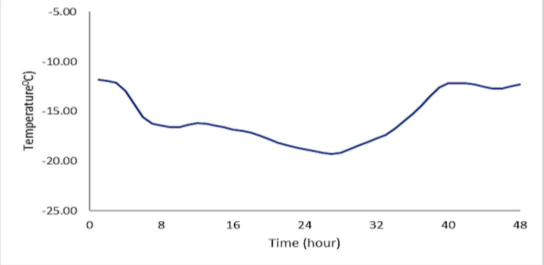

FIGURE 6. Wichita, Kansas, outdoor air temperature in the winter (14-15 January)

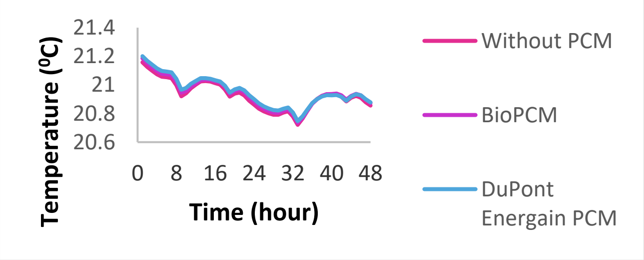

FIGURE 7. Effect of PCMs on indoor air temperature in a ground-floor residence in Wichita, Kansas during the winter (14-15 January).

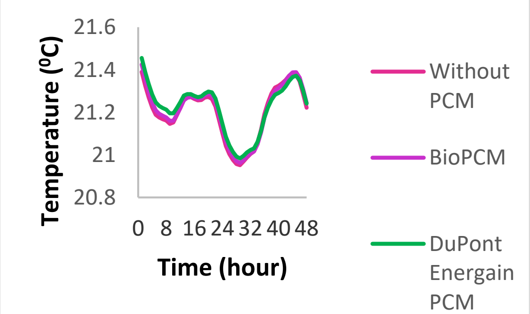

FIGURE 8. Effect of PCMs on indoor air temperature in a middle floor residence in Wichita, Kansas during the winter (14-15 January).

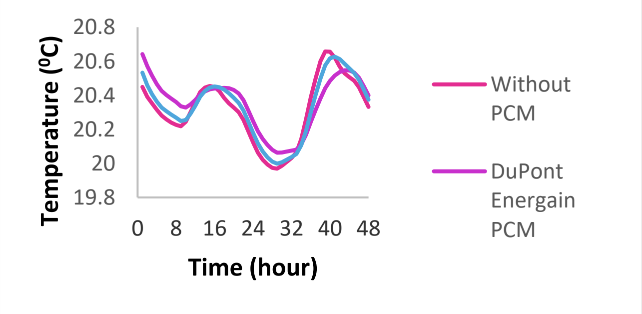

FIGURE 9. Effect of PCMs on indoor air temperature in a top floor residence in Wichita, Kansas during the winter (14-15 January).

Figure 6 shows outdoor air temperature in Wichita, KS, on 14-15 January, representing wintertime temperature. It can be seen from the fig. 6 that the outdoor air temperature in winter varies from -19.5°C to -12.5°C. As a result, heating is required to raise the indoor air temperature to a comfortable level for the occupants.

Figure 7 depicts the internal air temperature at a ground-floor apartment in Wichita, Kansas, on the 14th and 15th of January. In January, the figure demonstrates that an interior air temperature of 20.7 °C to 21.2 °C, which is within the comfort range of 20 °C to 26 °C for Wichita, KS, uses less energy.

Figure 8 depicts the internal air temperature in a middle-floor flat in Wichita, Kansas, on the 14th and 15th of January. The figure indicates that using PCMs resulted in a comfortable interior air temperature range of 20.95 °C to 21.45 °C with lower energy use.

Figure 9 shows the indoor air temperature for the top floor apartment for 14-15 January in Wichita, KS, within 20°C to 20.65°C. It can also be seen that PCM can slightly increase indoor air temperature.

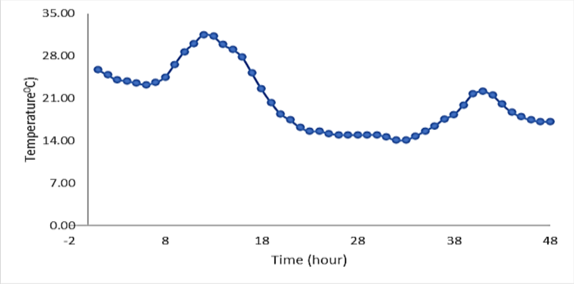

FIGURE 10. Temperature outdoor in Wichita, Kansas (14-15 August).

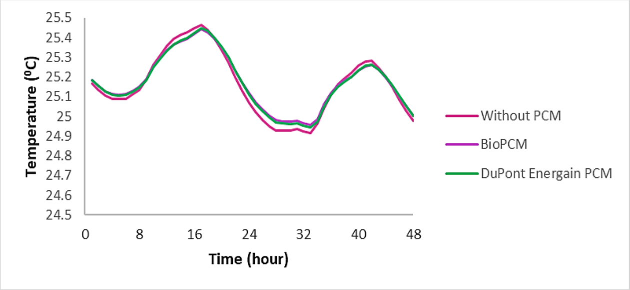

FIGURE 11. Wichita, KS: Effect of PCMs on indoor air temperature in a ground-floor residence in the summer (14-15 August).

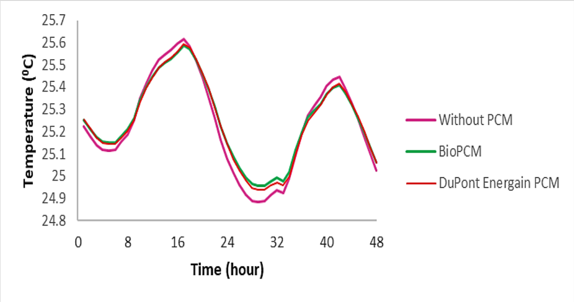

FIGURE 12. Wichita, KS: Effect of PCMs on indoor air temperature in a middle floor residence in the summer (14-15 August).

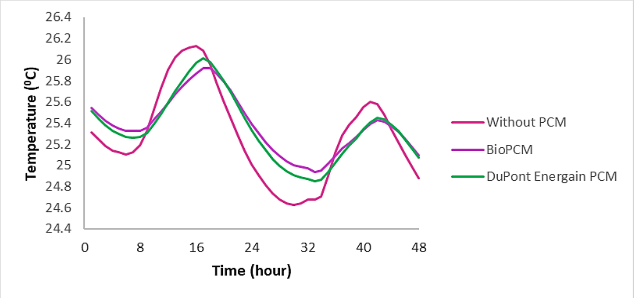

FIGURE 13. Wichita, KS: Effect of PCMs on indoor air temperature in a top floor residence in the summer (14-15 August).

Figure 10 shows outdoor air temperature in Wichita, KS, on 14-15 August, representing summertime temperature. It is clear from fig. 10 that the outdoor air temperature in summer varies from 14°C to 31.5°C. As a result, cooling is essential to lower the internal air temperature and give comfort to the occupants.

Figure 11 depicts the internal air temperature at a ground-floor apartment in Wichita, Kansas, on August 14-15. In August, integrating PCMs resulted in a comfortable indoor air temperature with fewer energy use, as seen in the graph.

Figure 12 represents the indoor air temperature for middle floor apartment 14-15 August in Wichita, KS. The figure shows an indoor air temperature between 25 °C and 25.6 °C. It also illustrates that PCM can maintain the comfort level of indoor air temperature with less energy consumption.

Figure 13 shows the indoor air temperature for top floor apartment 14-15 August in Wichita, KS. The figure shows an indoor air temperature between 24 °C and 26 °C.

This model uses PCMs with melting values of 21.6°C (DuPont Energain PCM) and 29°C (BioPCM). When the zone reached melting temperature, the PCMs melted and stored energy as latent heat as a result of the melting process (changing phases), preventing the zone's ambient temperature from rising. The PCMs resolidified at night when the temperature dropped below 21.6 °C or 29 °C, releasing the stored heat and raising the zone ambient temperature.

CONCLUSION

The use of PCMs to reduce the consumption of a residential building has been discussed. Two distinct PCMs with melting points ranging from 21.6 °C to 29 °C were investigated in this study. The study was conducted using a dynamic simulation of a DOE midrise apartment building's energy performance, as well as weather data for Wichita, Kansas, with and without the usage of PCMs materials.

It can be deduced from the numerical analysis findings of the application of PCM on the building's external walls and roofs that PCM can store heat energy from solar radiation, hence reducing energy consumption for heating and cooling the space. The phase change materials investigated resulted in a maximum decrease of 4.34 percent in heating energy requirements, a maximum reduction of 3.74 percent in cooling energy requirements, and a maximum reduction of 3.2 percent in overall energy requirements.

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