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Using Phase Change Materials (PCM) to Reduce Energy Consumption in Buildings

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Abstract. The article discusses the use of phase change materials (PCM) to enhance thermal energy storage (TES) in residential buildings. The building sector consumes a significant amount of energy, and energy efficiency is crucial in reducing overall energy consumption. PCM has emerged as a promising approach to decrease energy consumption for space cooling and heating in buildings. The article uses DesignBuilder software to evaluate the energy consumption of a residential building. EnergyPlus is the calculation method used by DesignBuilder. The researchers considered a baseline dwelling house located in Moscow and used EnergyPlus, a simulation tool, to analyze the performance of building components integrated with PCM to reduce energy consumption while maintaining a comfortable indoor temperature. The study used the one-dimensional finite difference conductivity (CondFD) algorithm in EnergyPlus to simulate a building element with PCM. Using BioPCM M91/Q23 can significantly reduce heating and cooling costs. The article concludes that integrating PCM into building components can improve indoor thermal comfort, reduce energy demand for heating and cooling, and enhance occupant comfort. The use of PCM has the potential to mitigate the effects of outdoor temperature changes on indoor thermal comfort, making it a cost-effective and clean energy-saving material.

1 Introduction

The building sector consumes about 40% of global energy, making energy efficiency in buildings an essential target for energy policies [1]. Enhancing building efficiency is crucial in reducing overall energy consumption as the building sector is predicted to be the leading energy consumer in the future [2]. The surge in industry and urbanization has led to the amplified use of fossil fuels, resulting in pollution. Energy modeling of buildings is an effective approach to evaluate the dynamic relationship between climatic conditions, building envelope, and HVAC systems, which are crucial in energy analysis [3]. Space heating and cooling maintain thermal comfort factors such as average air temperature, airflow, and relative humidity within specified limits. As the demand for cooling and heating is expected to rise in the built environment, a sustainable approach to decrease energy consumption for heating and cooling is necessary.

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Thermal energy storage (TES) has emerged as a promising approach to reduce energy consumption for space cooling and heating in buildings. Researchers are conducting extensive research on the application of phase transition material (PCM) as an effective TES medium for energy savings. PCM possesses a large amount of latent heat [4-6] and a wide temperature range with phase transition [7], making it a desirable TES medium. PCM is a cost-effective and clean energy-saving material [8], with potential to mitigate the effects of outdoor temperature [9] changes on indoor thermal comfort, reduce energy demand for heating and cooling, and improve occupant comfort [10]. Thermal energy PCMs have unique characteristics such as low cost, high heat capacity, high density, reliability, heat resistance, permanent melting, no segregation, corrosion resistance, less toxicity, and low or no supercooling, making them suitable for various applications [11-12]. In this study, the energy consumption of a residential building was assessed using DesignBuilder software, which is a building energy simulation tool with a graphical user interface [13]. DesignBuilder employs the EnergyPlus simulation engine as its calculation method [14].

2 Methods

EnergyPlus employs three algorithms to calculate heat transfer for the opaque building envelope, namely the conductivity transfer function (CTF), the finite difference conductivity method (CondFD), and the advanced heat and moisture transfer algorithm (HAMT algorithm).

The article discusses the impact of using phase change materials (PCM) on the thermal comfort of a dwelling house located in Moscow, where the climate is characterized by cold winters and relatively warm summers. To evaluate this impact, the authors considered a baseline dwelling house with specific dimensions 19.8 m × 12.75 m, a 1-story building with a facade structure, a floor height of 4.2 m, and a window-to-wall ratio of 30%, which they used as a reference for comparison purposes. The authors used EnergyPlus, a simulation tool, to analyze the performance of building components integrated with PCM [15], [16]. BioPCM is a type of material that can store heat and release it when needed. It is made from plants such as soybean and palm oil and has a lifespan of almost 100 years. To make sure that animals like rodents don't damage it, the material has been treated to remove certain types of fats. The aim is to reduce energy consumption while maintaining a comfortable indoor temperature. The wall structure without PCM was made up of 70 mm thick granite stone, 250 mm thick outer brickwork, 140 mm thick mineral wool insulation, and 30 mm thick cement, plaster, or mortar layer. This wall had a U-factor of 0.258 W/m^2-K. The wall design with PCM had several layers, starting with a 70mm granite stone layer, followed by 250mm exterior brickwork, 140mm mineral wool insulation, a BioPCM layer, and finally a 30mm layer of cement, plaster, or mortar. The PCM wall construction used different types of BioPCM materials with specific melting points and thicknesses. The BioPCM materials used were labeled M27, M51, and M91, each with varying melting points labeled Q23, Q25, Q27, Q21, Q29, and so on. The thickness of the BioPCM layer also varied, with a thickness of 0.011m for M27, 0.021m for M51, and 0.037m for M91. Each of the BioPCM materials had a different enthalpy value, with Q21 having an enthalpy value of 289.545, Q23 having 300.420, Q25 having 322.285, and Q27 having 322.093.

The roofing system without PCM comprises 25 mm thick clay tiles (used for roofing purposes) and 160 mm of mineral wool insulation with a fibrous wool structure, along with 5 mm roofing felt with a U-factor of 0.254 W/m^2-K. The PCM roofing system comprises 25mm thick clay roof tiles, 150mm of fiber mineral wool insulation, a layer of BioPCM material, then 5mm of roofing felt. In comparison, the first roofing system consists of clay tile, thick mineral wool insulation, and roofing felt, whereas the second system has an extra layer of BioPCM material between the insulation and the roofing felt. In this study, the researchers utilized a bio-based phase change material (PCM) known as BioPCM, which is available in the material library of Design Builder simulation software. BioPCM has a specific heat capacity of 1970 J/kg-K, a thermal conductivity of 0.2 W/m-K and a density of 235 kg/m3. The letter M in the BioPCM nomenclature represents the heat storage capacity of the PCM in kJ/m^3, while the letter Q represents the transition temperature in degrees Celsius.

To model building energy consumption, EnergyPlus utilizes external weather files and internal data on temperature, humidity, and solar profiles. Global horizontal radiation, direct normal radiation, relative humidity, atmospheric pressure, dry bulb temperature, diffuse horizontal radiation, dew point temperature, wind direction, and wind speed are among the primary meteorological variables needed to create a weather file for DesignBuilder. Fig. 1. presents a three-dimensional view of the model of the residential house. Hourly data from the city of Moscow were entered into the study using Meteonorm software.

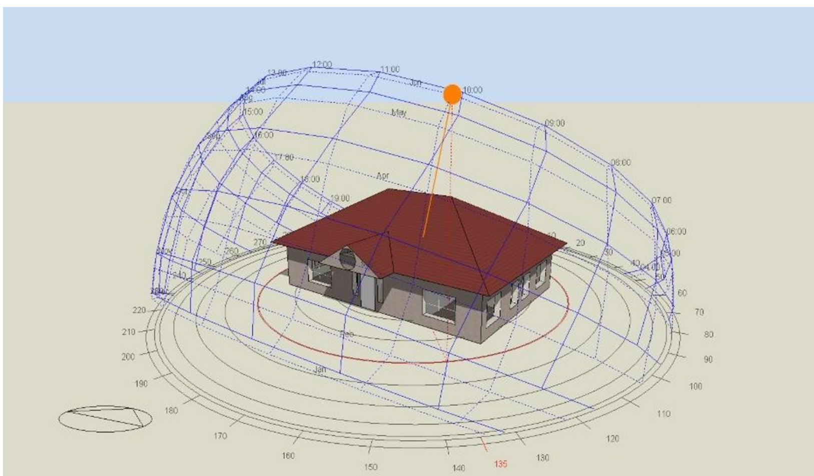


Fig. 1. 3D view of the residential building model.

The rate at which temperature changes through building elements can be determined using the Fourier law [17], as shown in equation (1).

$$\rho C_p \frac{\partial T}{\partial \tau} = k \frac{\partial^2 T}{\partial x^2} \quad (1)$$

where $\frac{\partial T}{\partial \tau}$ the temperature change rate, $\frac{\partial^2 T}{\partial x^2}$ the space gradient along coordinates, and ρ, Cp, k is the density, specific heat capacity and thermal conductivity of the element material respectively.

In the CondFD model, the building component is divided into a grid of cells or nodes, and the heat transfer equation is solved for each cell. The heat transfer equation takes into account the thermal properties of the materials, the boundary conditions at the edges of the component, and any heat sources or sinks within the component. The CondFD model is particularly well-suited for simulating heat transfer in building components with complex geometries, such as irregularly shaped walls or roofs with varying thicknesses of insulation. One advantage of the CondFD model is that it can be used to accurately predict the temperature distribution within a building component, which is important for evaluating the risk of moisture damage or degradation of the materials. It can also be used to optimize the design of building components to minimize heat loss or gain and improve energy efficiency.

The study used the one-dimensional finite difference conductivity (CondFD) algorithm in EnergyPlus to simulate a building element with phase change material (PCM). The CondFD algorithm is solved numerically using two schemes in EnergyPlus: a semi-implicit Crank-Nicholson scheme or a fully implicit scheme, both based on the Adams-Moulton solution approach [18]. The study selected the fully implicit scheme, which is given in equation (2) and can be used to express the implicit formulation of the inner node.

$$\rho C_p \Delta x \frac{T_i^{j+1}-T_i^j}{\Delta t} = k_{int}\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x} + k_{ext}\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x} \quad (2)$$

where ρ is the material density, Cp is the specific heat capacity, x represents the thickness of the space between the finite-difference layer nodes, k is the thermal conductivity, T is the node temperature, and Δt is the time step. The indices j+1 and j represent the current and previous time steps respectively; i denotes the node being modelled, while i-1 and i+1 represent the inner and outer nodes respectively.

In the CondFD algorithm, all elements are discretised using equation (3), which can also be expressed as a Fourier number function (Fo).

$$\Delta x = \sqrt{c\alpha\Delta t} = \sqrt{\frac{\alpha\Delta t}{F_0}} \quad (3)$$

where Δx is the layer thickness depends on Fourier number F0, α is the thermal diffusivity of the material, Δt is the time step, c is the spatial dispersion constant.

In EnergyPlus, the enthalpy (h) and thermal conductivity (k) of the PCM are related to temperature by the following relations.

$$h_i = h(T_{i,j}) \quad (4)$$

$$k_i = k(T_{i,j}) \quad (5)$$

The CondFD algorithm in EnergyPlus uses an enthalpy-temperature function to determine the specific heat capacity of PCM in a building element over time. The calculation is based on equation (6), and the enthalpy of each node is updated at every iteration. Accurate definition of this function in EnergyPlus is important for accurate prediction of the behavior of PCM in the building element.

$$C_p = \frac{h_i^{j+1}-h_i^j}{T_i^{j+1}-T_i^j} \quad (6)$$

As a result, the CondFD approach can be used to fully describe the heat transfer and absorption of PCM embedded in a building. Fig. 2. shows the enthalpy temperature curve from the melting point.

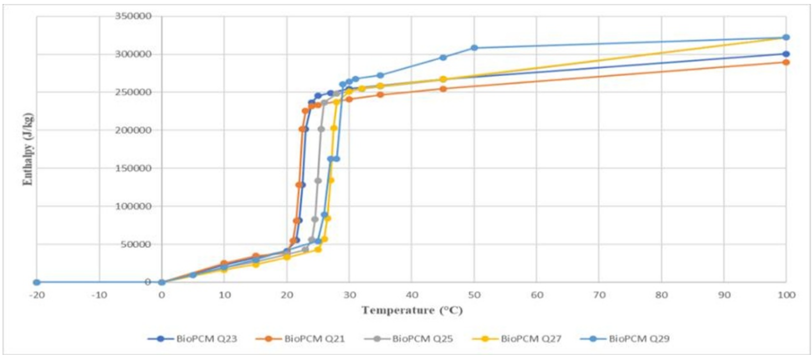


Fig. 2. Enthalpy-temperature curve of the PCMs.

The researchers utilized the enthalpy-temperature plot of phase change materials (PCMs) to account for the energy involved in the phase change process. A temperature-enthalpy dataset with sixteen temperature/enthalpy pairs was developed to represent the PCM. This dataset was inserted into DesignBuilder software and linearly interpolated to determine the enthalpy for each node and time step. The BioPCM enthalpy-temperature graph was selected for the study due to its superior specific heat capacity and latent capacity compared to conventional PCMs [20].

3 Results

Fig. 3. shows the air temperature inside the building for different cases: building without PCM, building with PCM. In order to find the smallest temperature variation, statistical analysis methods were used such as standard deviation and variance. These methods helped in calculating the variation in temperature values in the dataset, thereby enabling the determination of the smallest temperature variation. By using the standard deviation method, which identifies values that are close to the mean temperature with low variability, it was found that BioPCM M91/Q23 had the smallest standard deviation among all the BioPCMs. The highest standard deviation was observed in cases where a PCM was not used. Therefore, it can be concluded that the BioPCM M91/Q23 resulted in the smallest temperature variation in the building.

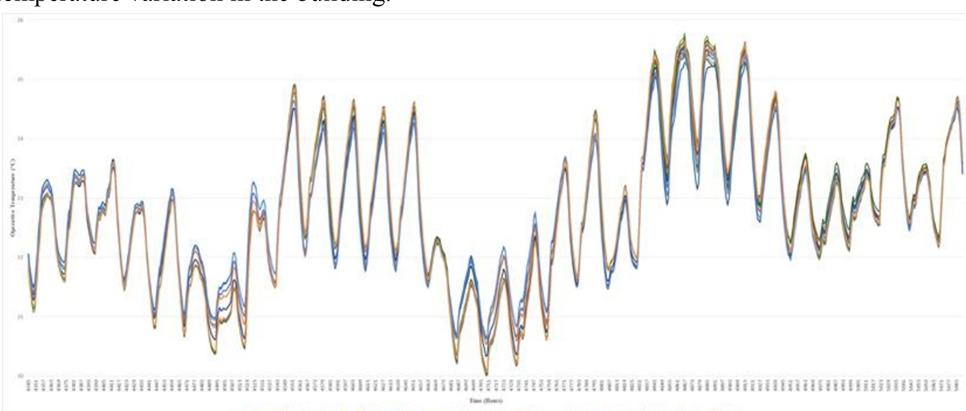


Fig. 3. Relationship between BioPCM and simulated indoor operative temperature.

Fig. 4. shows a comparison of energy consumption levels for various scenarios, including a building without PCM and buildings with different BioPCM materials such as M51/Q21, M51/Q23, M51/Q25, M51/Q27, M51/Q29, M27/Q23, M27/Q25, M27/Q27, M91/Q23, M91/Q25, M91/Q21, and M91/Q27. The study was conducted in July, and the lighting, load, and equipment schedules were kept constant. The results indicate that incorporating a PCM layer in a building can substantially reduce energy consumption for both heating and cooling. BioPCM M91/Q23 showed the lowest energy consumption among the listed scenarios, with 56.14 kW for heating and 6.3 kW for cooling. The high heat storage capacity of PCM helps to minimize peak loads, resulting in lower energy consumption. Incorporating PCM in building construction can be a promising approach to achieving energy efficiency and sustainability objectives in thermal energy storage.

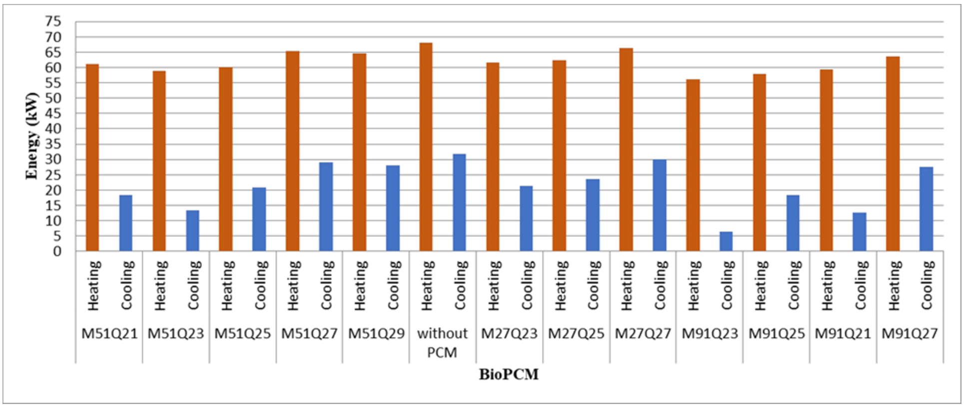
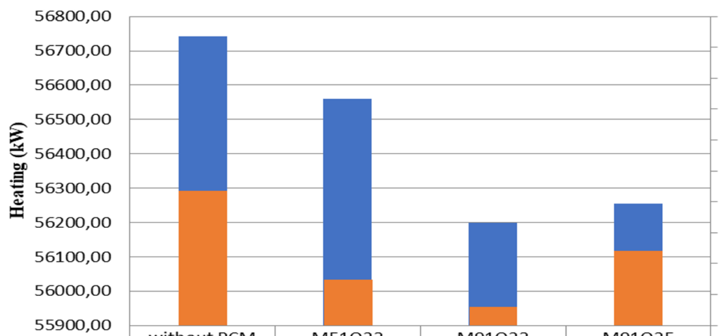


Fig. 4. Energy consumption for different cases: building without PCM, building with PCM.

BioPCM is an environmentally-friendly and cost-effective material that can be used to improve thermal performance in buildings [21]. The wide range of melting temperatures available allows for comfortable indoor temperatures, while also ensuring energy efficiency. To maintain human comfort, it is important to choose a melting point between 19-24°C. BioPCM has many advantages, including compatibility with other building materials, non-toxicity, and recyclability. However, it also has some limitations, such as low thermal conductivity and flammability. Overall, BioPCM is a promising solution for energy-efficient and sustainable building design.

4 Discussion

Phase change material (PCM) is an efficient thermal energy storage (TES) solution that has potential for saving energy in buildings. A building without PCM has an annual heating and cooling load of 56741.64 kW 43.41 kW respectively, resulting in an annual heating and cooling energy demand of 56785.05 kW. Figure 5 illustrates the annual energy demand for heating and cooling with and without PCM. The three types of PCM considered were M51/Q23, M91/Q23, and M91/Q25. The graph shows a clear difference between the energy demand for the building with and without PCM. The results indicate that incorporating PCM into building construction can lead to significant energy savings for both heating and cooling. Using BioPCM M91/Q23 can significantly reduce heating and cooling costs, with a reduction of 0.96% for heating and 86.58% for cooling. This is because PCM has a high heat storage capacity, which reduces the peak loads on heating and cooling systems. Overall, the results suggest that the use of PCM in building construction can be a promising approach to achieving energy efficiency and sustainability goals. In this study, different types of BioPCM with melting points of 23°C and 25°C were tested for their effectiveness in reducing energy consumption in a building. When BioPCM M51/Q23, M91/Q23, and M91/Q25 were used, the annual cooling requirement of the building was reduced to 14.72 kW, 5.83 kW, and 24.15 kW, respectively. For heating, the annual requirements were 56559.83 kW, 56198.90 kW, and 56255.66 kW, respectively. The highest percentage of savings for cooling were observed in May (100%), June (95.53%), July (82.32%), and August (99.33%). When BioPCM M91/Q23 was used, the building's annual heating demand was reduced by 1.64% in October, 0.91% in November, 0.43% in December, 0.36% in January, 0.41% in February, 0.9% in March, and 1.4% in April.



	without PCM	M51Q23	M91Q23	M91Q25
Heating	56741,64	56559,83	56198,90	56255,66
Cooling	43,41	14,72	5,83	24,15

Fig. 5. Annual energy demand for heating and cooling without PCM and with PCM M51/Q23, M91/Q23, M91/Q25.

Placing a BioPCM layer in front of the 140 mm thick mineral wool insulation in the wall structure could lead to an increase in heating and cooling loads. The results of the modelling during the month of July showed that there was a 3.19% increase in heating load and a significant increase of 419.88% in cooling load. The use of PCM can save energy, but appropriate parameters need to be selected [21]. The thermal conductivity, melting point, thickness, and phase transition temperature radius of PCM are important factors that affect its thermal performance [21].

Increasing the thickness of the PCM layer by 30 mm can potentially save on heating and cooling costs, but the magnitude of the savings will depend on various factors, such as the thermal conductivity of the materials, the location and orientation of the building, and the local climate conditions. A thicker PCM layer can potentially increase the thermal mass of the building envelope, which can help to reduce temperature fluctuations by absorbing excess heat during the day and releasing it at night. This can lead to a reduction in heating and cooling loads, which can translate into lower energy costs. It's also important to note that increasing the thickness of the PCM layer will increase the cost of construction, which may offset some of the energy savings over the lifetime of the building.

In Moscow's climate, it is generally recommended to place the PCM on the inside of the wall, closer to the living space. This is because the winters in Moscow are very cold and long, so placing the PCM on the outside of the wall could result in the PCM being frozen for an extended period, reducing its effectiveness.

The study followed EnergyPlus guidelines and assumptions for the PCM model, such as a continuous PCM layer of constant thickness and constant density in both liquid and solid phases. The simulations used a 3-minute time step, 3 space discretization, and a relaxation coefficient of 1, while neglecting hysteresis effect, supercooling, and phase separation. The results demonstrated the importance of selecting appropriate thermal parameters for PCM to achieve energy savings in buildings.

5 Conclusions

The article discusses the use of phase change materials (PCMs) as a promising approach to reducing energy consumption for heating and cooling in buildings. The study used DesignBuilder software and EnergyPlus simulation engine to assess the energy consumption of a residential building. The authors considered a baseline dwelling house with specific dimensions and a window-to-wall ratio of 30% and analyzed the performance of building components integrated with BioPCM, a type of PCM made from plants such as soybean and palm oil. The results show that incorporating BioPCM into building construction can lead to significant energy savings for both heating and cooling. Using BioPCM M91/Q23 can significantly reduce heating and cooling costs. The study also found that appropriate parameters need to be selected for the PCM, such as thermal conductivity, melting point, thickness, and phase transition temperature radius, to ensure effective thermal performance. It's also important to note that increasing the thickness of the PCM layer will increase the cost of construction, which may offset some of the energy savings over the lifetime of the building. Overall, BioPCM is a promising solution for energy-efficient and sustainable building design.

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