INDOOR TEMPERATURES AFFECTED BY PHASE CHANGE MATERIALS

by

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Energy costs are rapidly rising around the world and it is important to find a way to reduce energy consumption. Energy consumption in buildings can account for up to 40% of total energy consumption in developed European countries due to an increase in living space per person, an increase in the need for air conditioning, an increase in the number of appliances used in households, and other factors. Due to the increasingly frequent high temperatures during the summer and the increase in electricity consumption, it is very important to find a way to decrease indoor temperatures in urban residential buildings without using more energy, given the severe energy crisis that has engulfed Europe and the high percentage of energy and electricity consumption in the residential sector. Installation of phase changeable materials is one method for improving the thermal envelope of a building by increasing the thermal capacity of the envelope and thus affecting the reduction of indoor temperature oscillations and, consequently, reduction of summer electricity consumption. In this study, the TRNSYS software package was used to simulate and compare the indoor air temperature in typical detached houses built in period 1946 and 1970 in the Belgrade area, for both, the case without and the case with installed phase change (PCM). It was shown that incorporating a PCM with a melting temperature of 25 °C into the inter-floor construction of the house could significantly improve comfort conditions by reduce indoor temperature fluctuations during the warm period without consuming additional energy. When the temperature outside is around 30 °C, the maximum air temperature in the house drops by about 2 °C.

Key words: *building, PCM, indoor temperature, TRNSYS*

Introduction

According to the most recent Eurostat data, EU homes consumed 27% of total final energy in 2020. Natural gas accounted for nearly one-third of total energy consumption in EU households, while electricity accounted for 24.8%. When all factors are considered, space heating and cooling is without a doubt the largest energy consumer in EU households, accounting for up to 77.9% of total consumption. The EU households used the most energy to heat their homes (62.8 percent of total residential energy consumption) [1]

In Serbia, the residential sector consumes roughly 40% of total energy produced. According to estimates, Serbian families use 2.5 times the amount of heat energy per square meter

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as the rest of the EU, with some households using even more. While the EU average is less than 25%, households in Serbia consume approximately 38% of their total energy in the form of electricity [1].

Climate change has recently raised temperatures and increased the frequency and severity of heat waves. As a result, during summer heat waves, Serbia typically consumes 17% more electricity than usual. Because of the higher temperatures, citizens are forced to consume significantly more electricity for cooling throughout the summer. This occurred during the summer of 2021, when Serbia experienced four heat waves from June to August. In contrast, several heat waves were uncommon in Serbia during the middle of the twentieth century, and it was entirely normal for there to be none throughout the entire summer [2].

Belgrade has nearly 4% of the country land area and nearly 21% of the total population, living in nearly 600000 households. Currently, the city central supply of heat energy serves only about half of the total number of households, with the other half relying primarily on electricity for heating [3]. In addition to the recent increase in summer cooling electricity consumption, Belgrade has the highest share of household electricity consumption.

Following recent global events, it has become clear that most countries in Europe are in the midst of a severe energy crisis. Comfort in residential and commercial buildings, as well as industrial production, will have a very uncertain future in countries without oil and gas sources. It is necessary to develop a long-term strategy for obtaining and saving energy from additional renewable sources, as well as to work on the development of new architecture capable of achieving high energy efficiency in buildings [4, 5].

Because traditional insulation materials are insufficient to achieve the desired thermal comfort, cooling energy consumption is increasing. As a result, the development of new materials and the use of passive systems is indispensable in order to improve building energy efficiency.

One of the newer materials is PCM, which are latent heat thermal energy storage materials with a high energy storage density and the ability to store and release heat. The PCM can go through three different types of phase transitions: solid-solid, solid-liquid, and liquid-gas. The PCM that go through a solid-liquid phase transition are the most useful for building applications. It can increase the thermal mass of a building by retaining a significant amount of energy despite small temperature fluctuations. [6]. The PCM are gaining popularity as a way to save energy and create a more environmentally friendly environment [7-9].

The majority of buildings in Belgrade, as well as in developed European countries, are constructed with traditional building materials such as brick, mortar, concrete, and insulating materials to reduce energy requirements for heating and cooling. Although insulation allows different types of walls to have similar thermal conductivity, the thermal mass of the walls, or the amount of heat it receives or emits to raise or lower the temperature, can vary significantly. Thermal mass in buildings reduces temperature fluctuations, which improves occupant thermal comfort and can reduce energy consumption for cooling and peak cooling loads in some climate zones.

Researchers have been looking for ways to increase the thermal mass of building structures for about 30 years by incorporating PCM into building materials. The PCM are primarily used to increase the capacity of the building envelope for heat storage and to reduce both internal temperature changes and energy demand. The PCM principle is based on three steps: thermal energy absorption, storage, and release. By switching from one phase to another over a very narrow temperature range, PCM can store a significant amount of thermal energy. In building construction, the transformation from solid to liquid state is frequently used. The phase transition occurs at constant temperature.

The latent heat required to induce a phase change in a material is much greater than the material's specific heat. As a result, when the temperature rises above or below the PCM transition temperature, PCM effectively increases the thermal mass of the building material [5].

The PCM can be classified in general based on changes in their physical state. Only solid-liquid PCM, with a wide range of phase change temperatures available on the market, are used for building applications, particularly for integration into walls and wall panels [10]. According to Abhat [11], these PCM are classified into three types: organic, inorganic, and eutectic. Each group has a different operating temperature range and melting enthalpy.

Based on thermal performance, design, and envelope optimization, the optimal PCM features for building energy savings should include the following [12-15]: a suitable phase change temperature, good heat transfer capabilities, long-term thermal performance stability, no overcooling or undercooling, environmental friendliness, a small volume change during phase transition, and good economic viability. One of the primary criteria for selecting PCM is the phase change temperature. This physical parameter must be carefully chosen and should be within the thermal comfort temperature range (from 15 °C to 30 °C). This temperature can be selected by considering the average temperature during the day and night, as well as other weather conditions. In addition to these requirements, the chosen PCM should have a high energy storage density. In other words, the latent heat per unit volume should be sufficient to absorb and release more heat energy during the charging and discharging processes. Specific heat capacity and thermal conductivity are two other thermodynamic factors to consider when choosing a PCM.

Buildings are extremely complex objects that are influenced both internally and externally. The local weather has an impact on external influences. Solar radiation entering the building, as well as internal heat loads, cause internal impacts. An energy-efficient envelope that ensures occupant comfort while requiring minimal system energy is required for a high-energy-efficiency building. Thermal energy storage in the envelope is important from this standpoint. The following heat transfer processes occur between the surface of the wall and the air inside the building: convective heat transmission between the surface and the air, short-wave radiation-based heat transfer, and long-wave radiation heat transfer.

When PCM is incorporated into the building envelope, the type of PCM and the building environment determine its energy saving potential. The PCM is commonly incorporated into building materials or systems. The overall impact of PCM on space cooling and heating energy consumption differs depending on location and condition. Entrop *et al.* [16] identifies five factors that influence the pattern of energy use in apartments: environmental factors, job factors, building envelope factors, system factors, and apartment appliances. All of these features have some effect on PCM performance. As a result, all of the aforementioned characteristics must be thoroughly examined when designing an energy-efficient system with PCM.

Recently, a significant number of works on the application of PCM in buildings have been published. It is crucial to keep in mind that research must be done for each climate in order to identify which phase changeable material or combination of materials will have the greatest impact on lowering energy consumption and payback time [17, 18].

In Mahdaoui *et al.* [19], it is suggested that PCM be incorporated into the common hollow bricks used in Moroccan construction to enhance the thermal performance of exterior walls. Heat transfer through the hollow bricks containing PCM has been physically modeled and numerically analyzed. To determine the impact of weather conditions on this building element's thermal response, a parametric study was carried out. The influence of PCM properties is also investigated and discussed. It has been discovered that incorporating PCM into building materials stabilizes and lowers indoor temperature fluctuations. The authors of the study [20] used experimental methods to examine the thermal performance of PCM-based panels created for exterior wall finishes by fusing microencapsulated PCM with cement render and foamed concrete. The panels were put through repeated heating and cooling cycles to assess how well they performed thermally in comparison to panels without PCM. The internal surface temperature of the PCM-based panels effectively decreased during the PCM melting process by up to 7.35 °C. According to the climate of Aswan, Egypt, the study [21] examines the long-term thermal behavior of a building wall that contains various types and thicknesses of PCM during the hot summer months. Under various outdoor weather conditions, the building wall with and without the PCM layer is investigated. The findings demonstrate that the use of PCM in the wall structure lowers the indoor heat flux and brings internal wall temperatures closer to the desired ranges. Based on three-month model simulations, the average expected indoor wall temperature for the best of the different PCM materials under investigation reached 31.1 °C for the wall without PCM and 27.7 °C for the wall with PCM when 1.5 cm of inner and outer PCM were used in the wall structure position. In the study [22], a dynamic energy simulation program was used to apply an analysis of the enthalpy-temperature function based on the thermal characteristics of 22 types of shape-stabilized phase change materials (SSPCM). The SSPCM was used to increase building energy efficiency while also enhancing the low heat storage performance of wooden structures. The indoor temperature behavior during the heating and cooling periods was examined to confirm the improvement in the heat storage performance of buildings. The peak summer temperature was found to have been decreased by 4.1 °C by maintaining the thermal inertia of SSPCM. The study [23] looked at how PCM, which store night coolness, can lower the peak indoor air temperature of naturally cooled buildings in hot, humid climates. The appropriate transition temperature range for PCM has been determined through field measurement in existing structures, and macro-encapsulated PCM with various transition temperatures and quantities has been numerically examined. The findings revealed a significant decrease in the peak temperature of indoor air, especially when using PCM with lower transition temperatures and higher quantities.

This study looked into how much PCM added to the thermal envelope of family house in Belgrade, representing the typical heavy building construction for the period between 1946-1970, could decrease indoor temperature during the summer without consuming any energy for cooling.

Belgrade climate and housing stock characteristics

The largest and most developed city in the republic of Serbia and one of the biggest in Southeast Europe is Belgrade, which also serves as the country capital. Like the majority of the country, it is located in a region with a moderate continental climate. In this climate, meteorological extremes practically happen every day. In the region to which Belgrade also belongs, there is a constant and irregular change of cold and warm air currents throughout the year. This essentially means that the characteristics of a *moderate climate* are the least prevalent. Given the characteristics of various air masses, the majority of which are of tropical or arctic origin, *i.e.*, extreme characteristics, there are numerous extreme weather phenomena, which is quite normal for a moderate climate [24].

Despite the fact that it is an urban area, the proportion of individual houses in the total number of residential buildings is significant, accounting for 43.86% of the total number of buildings. In Belgrade's urban matrix, free-standing houses predominate (95.61%), with only a small percentage of buildings in a row and buildings with a neighbor on one side. Only 0.31% of houses were built before the World War I, and 12.22% were built during the interwar period. The greatest number of buildings, 31.03%, were constructed between 1946 and 1970, while the intensity of construction was mostly uniform over the next three decades (17.24% in the 1970's, 18.18% in the 1980's, and 14.73% in the 1990's). Only 6.27% of buildings were built between 2000 and 2011, which, aside from the general unfavorable economic situation, can be explained to some extent by the trend to build multi-apartment buildings on plots of land where individual houses used to be [25].

Figure 1 shows the percentage representation of various types of individual objects based on the observed periods.

A typical illustration of the form, organization of the floor plan, and construction technique from the 1950's and 1960's is the free-standing house with two residential units, fig. 2. One residential unit is located on both the ground floor and the upper floor of the building, which has a straightforward, compact form. A portion of the floor plan includes a basement that is now occupied as a living space. Brick walls with a 38 cm thickness on the ground floor and a 25 cm thickness on the upper floor make up the construction system. Stone walls 50 cm thick line the expansive basement and foundation. Clay roof tiles are used to cover the wooden roof hipped structure. The basement slab is made of reinforced concrete, the ground floor slab was built using the Avramenko system, and the slab above the upper floor that leads to the empty attic is made of wood in the Karatavan style.

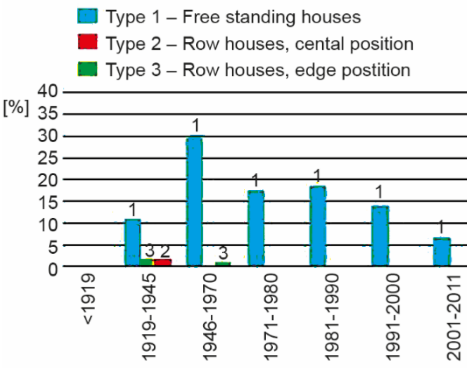

Figure 1. Percentage representation of various types of buildings for family housing in the Belgrade region based on construction period [25]

Figure 2. Typical free-standing house from 1946 to 1970 [25]

The layout of the ground and upper floors is centered on a rectangular hallway that divides the area into rooms on one side and other rooms on the other. While the kitchen, dining area, and bathroom face the courtyard (north), the bedrooms are facing the street (south). The living room, kitchen, and dining area are all located on the basement level, which has since been transformed into a residential neighborhood. The bathroom is located next to the kitchen. There is a separate exterior entrance for the basement. The ground floor and upper floor layouts are nearly identical. The dining room has been converted into a bedroom on the ground floor, and it has been divided into a dining area and a storage room upstairs (which was the original concept behind the floor plan organization). The stairs that connect the floors are narrow and difficult to use.

This study examined the potential decrease in indoor temperature during the summer in a residential building from the Belgrade region using the most prevalent single family house type built in period 1946 to 1970.

Method

The TRNSYS software developed at The University of Wisconsin-Madison in the United States was used for object modelling and thermal behavior simulation. The TRNSYS is an extremely flexible graphically based software environment used to simulate the behavior of transient systems. It is a kind of modular dynamic simulation software in which all systems are composed of many small modules, each with different functions.

Building model

The typical geometry of a free-standing building from the construction period 1946-1970 [25] on the territory of Belgrade is presented in fig. 3. The building consists of a ground floor, a second floor and an attic. The geometry of the observed house, necessary for modelling the thermal behavior, was done in Goggle SKETCHUP software. To input the geometric information into the building model, a plug-in TRNSYS 3-D for Goggle SKETCHUP has been used. The TRNSYS module Type56 models thermal performance of a building divided into three different thermal zones.

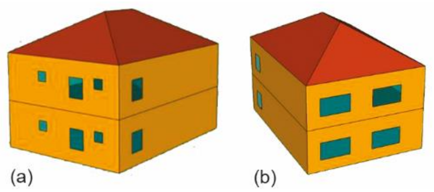

Figure 3. Typical family house for Belgrade in period 1946-1970

Table 1 shows the basic thermal envelope parameters taken from [25] to correspond to the observed typical house.

Table 1. U values of thermal envelope elements

Element	External wall	Floor construction to attic	Ground floor	External roof	Windows
U-value [Wm^{-2}K^{-1}]	1.48	0.46	1.88	3	2.89

In addition to the basic model of the house, which was based on the same geometric model, a thermal model of the described object with changes in Type56 was also created in order to analyze the impact of PCM on the building indoor temperature. Another model is shown in fig. 4 with a commercial PCM material installed in the ceiling between the second floor and the attic that is not heated or cooled. The commercial phase change material ENRG BlanketTM-Q25 from Phase Change Energy Solutions is positioned between the layers of the current ceiling. Its latent heat of fusion is 255 J/g and its phase change temperature is 25 °C.

A specially developed TRNSYS module Type1270 was used to simulate the behavior of a PCM completely placed inside the envelope, in other words the PCM is not directly adjacent to the zone air. This module is designed to interact with Type56 and can model a PCM located anywhere in the thickness of a Type56 wall.

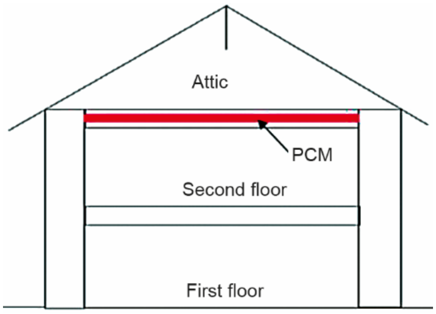

Figure 4. Position of PCM in the building envelope

The user is able to specify the physical properties of the PCM such as: density, specific heat, melting temperature, freezing temperature, and latent heat of fusion in module Type1270-b. The module also has built-in values for a specific brand of PCM where the user may select a model number directly by setting a single parameter in module Type1270-a. This TRNSYS component models a pure PCM. From a physical point of view, this means that the PCM is assumed to go through its freeze/thaw process at constant temperature, to have a constant specific heat in the solid phase and a constant specific heat in the liquid phase. It simplifies the analysis of the PCM by treating the phase change layer in bulk. It does not account for the wave front of freeze/thaw propagating through the material over time.

Simulation

Figure 5 depicts the TRNSYS Simulation studio model configuration with the PCM module. The *Building* component is a Type56 module that includes a full building model with heat gains, infiltration, and a heating, and cooling system. The building model in this paper includes basic heat gains while the heating and cooling systems are off. It was assumed that two people are always present in the zone under the ceiling being observed, that one computer with a color monitor is always on, and that artificial lighting emitting 5 W/m^2 is present. It was also assumed that infiltration is constant and amounts to 0.6 per hour, and that there is 5 ACH night ventilation from 8 p. m. to 8 a. m., corresponding to a half-open window [26].

A simulation of the thermal behavior of the basic object and an object of the same geometry with incorporated commercial PCM material ENRG BlanketTM-Q25 (PCM component in fig. 5) designed by phase change energy solutions and placed between the ceiling of the second floor and the unheated/uncooled attic was performed to analyze the influence of PCM on typical detached houses.

The ENRG Blanket is designed to consume no power and require no maintenance in order to provide consistent power and energy savings over its estimated useful life of more than 100 years. The ENRG Blanket help to reduce operating expenses and free up resources to support growth by increasing efficiency, while also addressing global and corporate concern about the impact of power consumption on CO$_2$ emissions, air pollution, and climate change. During phase changes, this PCM material absorbs and releases a tremendous amount of heat. At its target temperature, the BioPCM inside an ENRG Blanket, that is no thicker than an inch, stores as much heat as a block of concrete that is the same size but 24 inches thick.

When the ENRG Blanket is installed, the BioPCM inside absorbs heat (melts) when the ambient temperature exceeds the target room temperature and releases heat (freezes) when the ambient temperature falls below the target room temperature. The BioPCM is made from sustainably produced, plant-based byproducts and it is non-toxic and non-corrosive material. The ambient temperature within the managed environment is stabilized around the target room temperature through this recurring process. As a result, less mechanical cooling (HVAC) is required, and HVAC power consumption is significantly reduced.

The simulation was carried out with the help of the full simulation package SIMULATION STUDIO, which includes a variety of tools ranging from simulation engine programs and graphical connection programs to plotting and spreadsheet software. It is an integrated tool that is used from project design to project simulation. The simulation was run for the summer period of July 1-8, with a simulation step of 5 minutes.

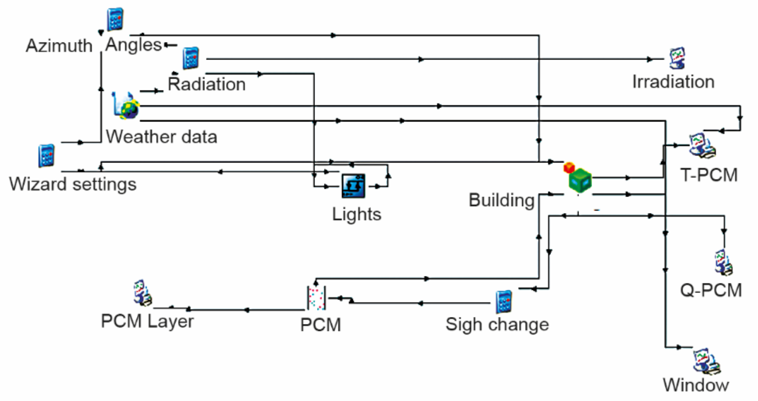

Figure 5. Configuration of the model with PCM

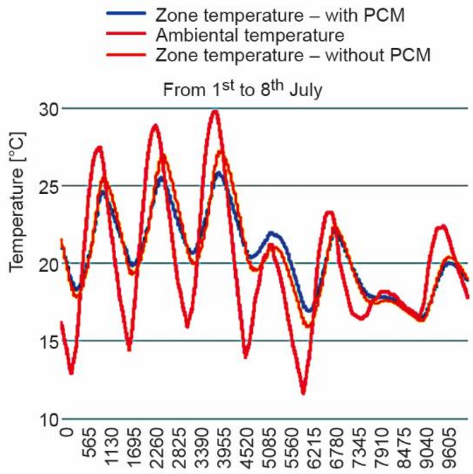

Figure 6. Zone air temperature for seven days in July

Results and discussion

The simulation results of the basic model of a typical house and the model with added PCM are shown in fig. 6. The graph represents three air temperatures, namely: outdoor air temperature (red), air temperature in the area under the attic of the basic model without PCM (yellow) and the air temperature in the area under the attic of the model containing PCM (blue).

The difference in air temperatures in the observed zone between the basic model and the model with PCM is obvious. The temperature difference changes as the outside temperature changes. When the temperature outside rises, the difference between the air temperatures in the zones of the observed models rises, so that the temperature in the zone of the model with PCM approaches the temperature of the phase transition of the installed PCM, which is 25 °C.

That difference amounts to nearly 2 °C at an outside temperature of 30 °C. In addition, if the temperature suddenly drops, the object with PCM will experience a milder temperature drop than the basic object. When the outside temperature is below 25°C for an extended period of time, the air temperatures in the zone for both models of the observed object are nearly equal. The PCM material will then be completely solid.

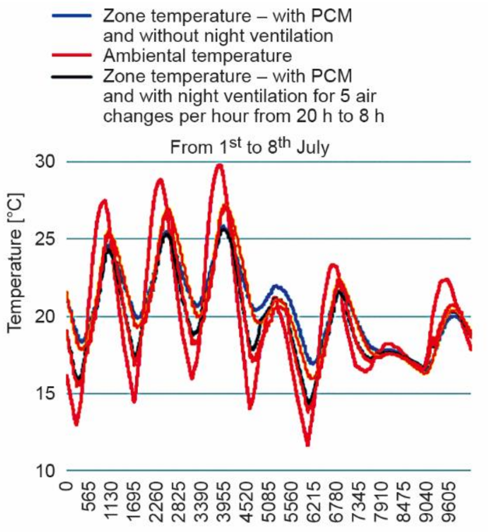

Figure 7. Zone air temperature for seven days in July

Figure 7 shows the temperatures for the observed zone as a result of simulating the thermal behavior of the object with and without the installed PCM, but with night ventilation between 8:00 p. m. and 8:00 a. m., as opposed to the previous image, which shows the ambient temperature as well as the temperatures of the observed zone for the case with and without the PCM installed. The assumption for night ventilation was five air changes per hour, or the equivalent of a half-open window [26].

As seen in the graph, night cooling can result in a significant drop in the air temperature in the observed zone during the night when there is night ventilation in the case of an object that does not have a PCM in the ceiling of the upper floor, but the maximum daytime air temperatures in the zone will still be the same (the difference between the yellow and orange lines). The maximum daily temperatures (black line) will typically coincide with the maximum daily temperature in the case of an object without night ventilation (blue line), but the average daytime temperatures should be lower on days when there are no sudden changes in outside temperature values. Night ventilation is established in the period from 8:00 p. m. to 8:00 a. m. in the case of an object with PCM in the ceiling. It is clear that when a building has PCM and natural night ventilation, the amplitude of temperature changes in the observed zone is the lowest.

Indoor temperature can thus be significantly improved without the use of energy for cooling. This is one method for improving the thermal characteristics of buildings during the summer months in a moderately continental climate characterized by short-lived but extremely hot heat waves that have become increasingly common in recent years.

It is necessary to use weather files that contain actual measured temperatures of the outside air and other parameters of the outside environment that would realistically represent the weather conditions for the duration of heat waves for a more realistic presentation of actual temperatures and energy consumption for cooling.

Conclusions

This paper investigated the viability of using PCM in detached houses typical of the construction period 1946-1970 in Belgrade, which account for roughly 30% of the total number of buildings of this type on the territory, to ascertain to what extent the placement of PCM in the ceiling of a residential building would contribute to the indoor temperature decrease without use of additional energy.

The thermal behavior of a typical building was simulated from July 1 to 8, and the paper shows the air temperatures in the zone under the attic for the basic building and the building with added commercial PCM material ENRG BlanketTM-Q25 manufactured by Phase Change Energy Solutions placed between the second floor and the attic.

It has been shown that by incorporating PCM material into the already-existing ceiling construction, indoor temperature can be decreased without the use of energy in order to lower the amplitude of the air temperature in buildings on hot summer days, particularly during heat waves, which have become more frequent in recent years. Using a phase-change material with a melting temperature of 25 °C can lower the air temperature by almost 2 °C at a temperature of about 30 °C outside, and even more when night ventilation is combined with.

The use of labor, or the presence of tenants and their actual behavior, the economic viability of various solutions, and the effects of various PCM on the environment and human health are additional factors that must be taken into account in future numerical and experimental research. Furthermore, it is necessary to include actual weather conditions for Belgrade in the simulations, which will display periods of heat waves, because the ambient temperature in the used Weather file, which represents a typical meteorological year, is lower than the actual recorded temperatures.

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