PRORAČUN NIVOA BUKE GENERISANE PROTOKOM VAZDUHA U AKTIVNO KONTROLISANOM VAZDUŠNOM KANALU SA USMERIVAČIMA VAZDUHA OBLIKA AEROPROFILA

HEAT TRANSFER ANALYSIS OF A PHASE CHANGE MATERIAL INTEGRATED FLOOR HEATING SYSTEM

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Fazno promenljivi materijali imaju velike prednosti u odnosu na klasične građevinske materijale zato što mogu da skladište i otpuštaju velike količine toplotne energije tokom procesa fazne promene. Pomoću CFD simulacija, ovaj rad ukazuje da smanjenje dnevne potrošnje energije za potrebe grejanja zgrada može biti postignuto integracijom fazno promenljivih materijala u sistem podnog grejanja – putem smanjenja broja dnevnih ciklusa grejanja kroz produženje vremena faze otpuštanja.

Ključne reči: *fazno promenljivi materijal, podno grejanje, energetska efikasnost, CFD*

Phase change materials presents important advantages in comparison to classic construction materials due to their characteristics of being able to store and release higher quantities of thermal energy during the phase change process. This paper highlights through CFD simulations that a reduction in the daily energy consumption for heating demand of buildings can be achieved with the integration of phase change materials into a floor heating system by reducing the number of daily heating cycles and by increasing the discharge phase time.

Key words: *phase change material, floor heating, energy efficiency, CFD*

1 Introduction

Due to the rapidly increase of urbanization, deforestation, global climate change and the increased demand for indoor thermal environments caused by the rise of indoor residence time, the energy consumption of buildings represent 40% of the global energy consumption and accounts to over 30% of the global emissions of CO2 [1].

A large portion of the electric energy demand in the residential sector is caused by heating and cooling. Considering this, the implementation of solutions that have the purpose of increasing the energy efficiency in buildings has become an urgent matter.

Phase change materials (PCMs) can provide the missing link in the supply and demand chain due to their properties of storing heat in time. PCMs are very advanced energy storage materials [2], capable of storing energy in the form of latent heat according to the temperature differences. When the temperature decreases, the material releases the stored energy by switching its phase from liquid to solid in order to reduce the energy demand [3].

The storage of thermal energy using phase change materials has become a pertinent research topic in recent years, being the centre of interest of researchers around the world in very diverse fields, due to the ability to reduce the energy demand.

In the last decade the interest for PCMs has increased, a result to the incorporation of PCMs in construction materials was the increase in the number of publications of research articles, as presented in Fig. 1, in order to meet the concerns regarding energy efficiency, energy consumption and sustainable construction.

The increase in the number of publications related to phase change materials emphasized the goals for Horizon 2020 and proves the interest of the scientific community towards providing modern, reliable, sustainable and affordable energy sources.

The increasingly energy demand throughout the world represents one of the main reasons for the unstable development and the degradation of our planet. The surge in world population and the increase in energy accessibility for more and more people justifies the increase in energy demand. The exploitation and consumption of non-renewable fossil fuels that have a high impact to the environment are currently the main source of energy production, but the major drawback is the greenhouse gas emissions which pose a great threat to the environment. Furthermore, energy demand has a substantial contribution towards the GDP growth of a country, the energy demand is elastic in both the household/services sector and the industrial sector and in the European union electricity and natural gas serve as demand substitutes [4, 5].

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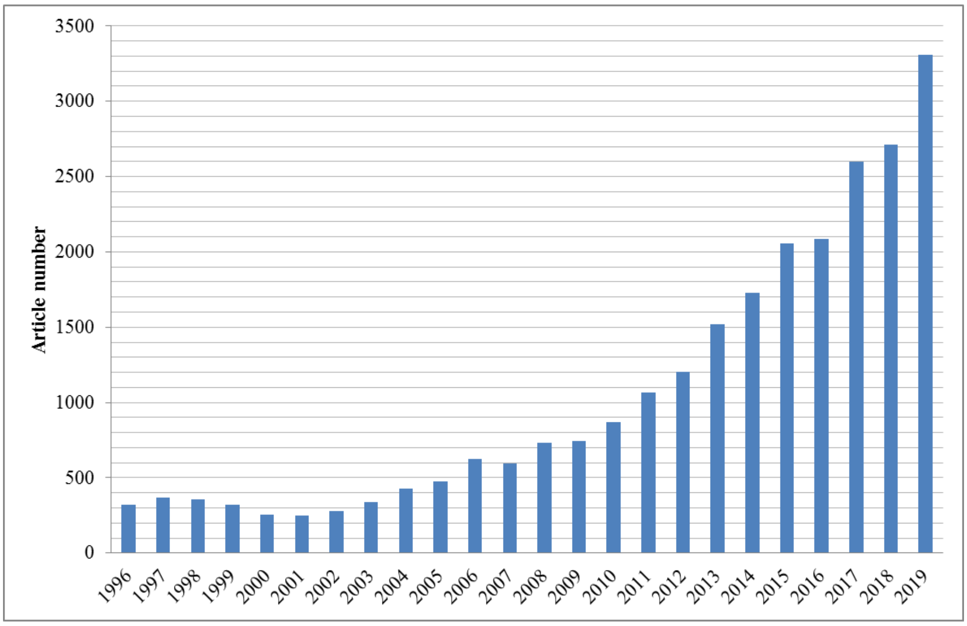

Figure 1. Worldwide PCM research articles between 1996 and 2019

2 Energy efficiency

In the past decades, the interest towards climate change mitigation has increased on an international scale. Following this trend, the EU adopted in 2012 a legislation with the target to reduce the emissions of greenhouse gases until 2020 by 20% compared to the values of 1990. Studies performed in 2017 showed that these conditions would not be met, and as a result the restrictions were increased, the targets for 2030 demanded a decrease of 27% in energy consumption and a reduction of greenhouse gas emissions by 40% [6].

In order to increase the energy efficiency of buildings and reduce their energy consumption modernization is a viable method, this being on the same line as one of the objectives and measures proposed by the United Nations, buildings energy rehabilitation until 2030 [6].

In the last decades, especially after 1990, the construction sector put a high emphasis on increasing the energy efficiency of buildings, this was the case as a result to the strict regulations implemented in the real estate sector. As a result, in the following years the energy consumption decreased, in the year 2002 the reduction reached 24%, but the European renovation rate is less than 2.5% of the existent buildings [6].

Considering these factors, a method of overcoming these shortcomings is the implementation of novel building materials with better thermal energy storage capacities.

3 Phase change materials

Thermal energy storage is a method to increase the energy efficiency of buildings and can be classified in two main categories sensible heat storage and latent heat of storage.

Sensible heat storage can be achieved using a fluid or a solid and increasing their temperature without phase change, utilizing the thermal mass of the materials, this is the case for most conventional construction materials, the amount of sensible heat that is stored is dependent by the material heat capacity and the rate at which the heat can be stored and released (thermal diffusivity) [7].

Latent heat storage is based on the phase transition of a material. The most common use of phase transition is using solid-liquid phase change, through melting and solidification of the material. By melting, the material stores large quantities of heat while maintaining a constant temperature and through solidification this heat is released. The materials that use latent heat storage are called phase change materials (PCM) [7].

In comparison to sensible heat storage, latent heat storage has a much higher energy density.

Scientific research show that there are numerous methods of harnessing thermal energy, but among them phase change materials present objective advantages due to their characteristics of being able to store and release higher quantities of thermal energy during the phase change process, being considered a favourable option [8].

The melting-solidification cycle is presented in Fig.2

In terms of classification, phase change materials can be divided by different properties.

Regarding the type of substance, phase change materials can be characterized as solid–solid PCMs, solid–liquid PCMs, solid–gas PCMs, and liquid–gas PCMs [9]. Among these 4 types of PCMs, the most commonly used are solid-liquid PCMs because these present some advantages in comparison to the other categories, during the phase change this present high latent heat capacity with negligible change in terms of volume.

The solid-liquid PCMs can be furthermore classified based on their chemical properties into organic PCMs, inorganic PCMs and eutectic PCMs, which can be further classified as shown in Fig.3.

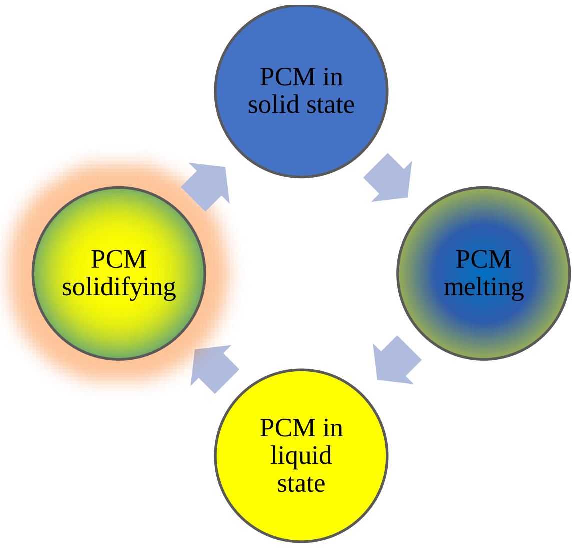

Fig. 2. PCM melting and solidification cycle

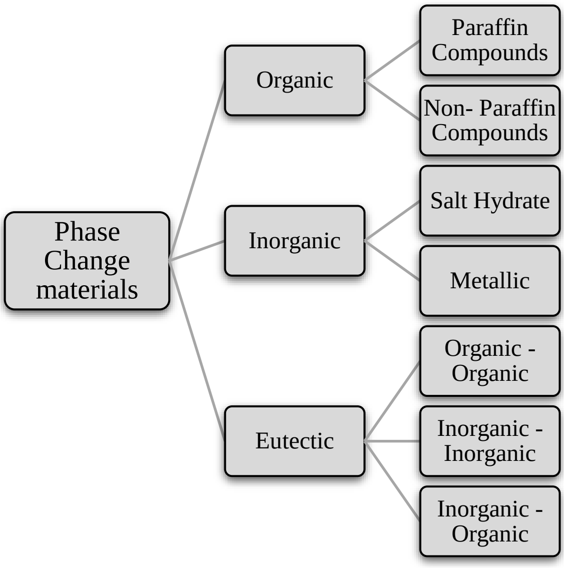

Fig. 3. PCM classification

Not all PCMs are used in practical applications. The most important characteristics of PCMs are: (1) The temperature at which the phase change occurs is within practical operation temperature range. (2) Increased latent heat storage capacity. (3) High thermal conductivity. (4) Stable in terms of thermal chemical and properties. (5) Non–toxic, non–corrosive and harmless to environment. (6) Low cost and easily available. (7) Reduced cost and increased availability. (8) Zero or reduced supercooling.

3.1 Organic PCMs

These types of PCMs present the following advantages: wide range of working temperatures, fusion presents high latent heat, non-reactive, liquid state undercooling capability is low, high nucleation rate, consistent phase change, auto-nucleation properties, non-corrosive, thermally and chemically stable, low segregation, recyclable and can be implemented in buildings.

The main disadvantages consist of high cost, low thermal conductivity, low enthalpy, low density, increased volume variation during phase change and flammable [10].

3.2 Inorganic PCMs

These types of phase change materials are divided in hydrated salts and metallic salts.

Metallic salts are not an appealing research topic for thermal energy storage because of their weigh, but hydrated salts PCMs have been extensively studied due to their properties.

Inorganic PCMs have as main advantages: low cost, reduced volume variation during phase change, high enthalpy, high thermal conductivity, easily accessible, non-flammable, low impact on the environment, compatible with plastic containers and as main drawbacks corrosive to metals, phase subcooling drawbacks, slightly toxic, low thermal stability, phase change presents material separation and incompatible with some construction materials [10].

3.3 Eutectic PCMs

These types of phase change material are obtained by combining two or multiple PCMs, either organic or inorganic or a combination of these two, in order to form a material specially designed to the existing need in terms of transition temperature, in comparison to the base components. The main disadvantage is the high production cost, reaching several times the cost of the base components.

4 Building applications of PCMs

The interest for phase change materials of the scientific community is highlighted by the increased interest towards their applications in buildings and their integration in various building elements such as: walls [11, 12, 13, 14, 15], windows [16, 17], ceilings [18, 19], floors [20, 21, 22, 23, 24, 25].

5 Research methodology

To achieve the objective of the research paper, the studies were performed using the ANSYS Fluent CFD software to simulate the correct operation of both underfloor heating systems.

For the study an electrical dry floor heating mat was considered due to it having superior advantages in comparison to a water based radiant floor heating system, it is implementable on a larger scale in every room and the only drawback of a higher operation cost can be reduced by using green energy sources such as photovoltaic panels both in small residential and large scale industrial applications.

The research addresses multiple numerical simulations performed using ANSYS Fluent CFD as a means to study the heat distribution of both systems during the heating cycle in order to demonstrate the viability of the system in the energy performance improvement of buildings.

The numerical 3D modelling was completed using software 2019 R3 with the same conditions for both models. A section of the models with the electrical heating mat as a heating source is presented in Fig.4-6, the key difference between the first and second model is that in the first one, layer number 2 is representing a PCM that is placed between two layers of concrete in order for it to have shape stabilization during the phase transition process, while in the second model there is no PCM layer.

The analysed models are 500 mm in length and 500 mm width, the height of the models is 35mm as follows:

- first concrete layer 500mm × 500mm × 10 mm
- PCM layer 500mm × 500mm × 10 mm
- second concrete layer 500mm × 500mm × 5 mm
- floor heating mat 500mm × 500mm × 10 mm
- concrete floor 500mm × 500mm × 50 mm

In terms of mesh initialization, sizing and quality, linear element order with a 5 mm element size were imposed, and for the mesh quality a target skewness of 0.8 was set.

To have an accurate representation CFD simulation for the models in the case of the PCM model apart from the energy equation, the solidification/melting model was used.

For the phase change material, a paraffin, RT 21 HC produced by Rubitherm Technologies GmbH [29] was considered because it presents impressive purity and specific composition, which translates to increased latent heat capacity with a small temperature range, the performance of the material remaining high for the phase change cycles as a result of the long lifetime of the material. The paraffin properties are shown in Table 1.

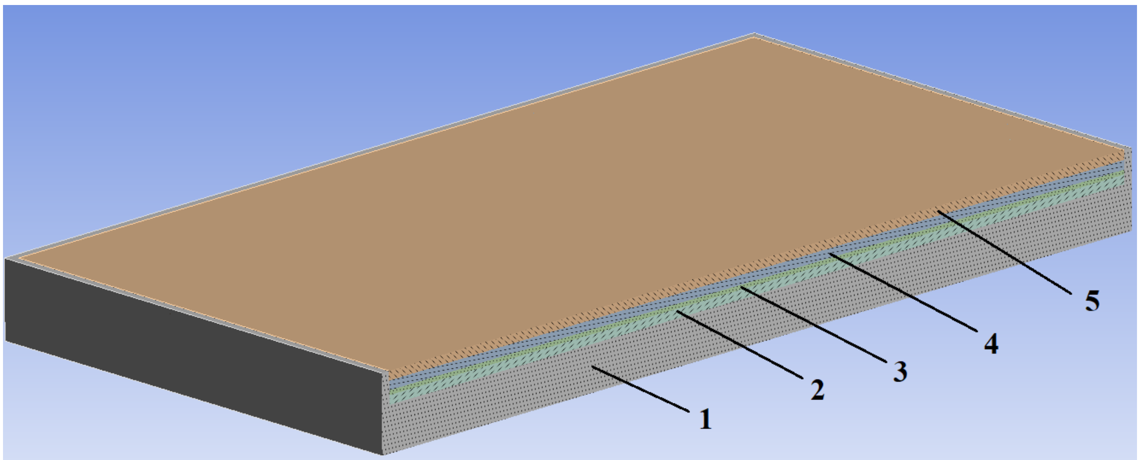

Fig. 4 − A section of the models

1.Concrete layer 1 2. PCM 3. Concrete layer 2 4. Electrical heating mat 5. Concrete floor

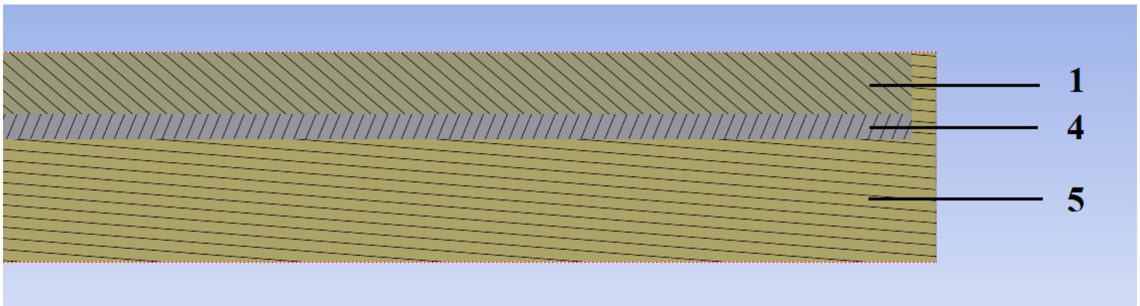

Fig. 5 − A section of the electrical floor model

1.Concrete layer 4. Electrical heating mat 5. Concrete floor

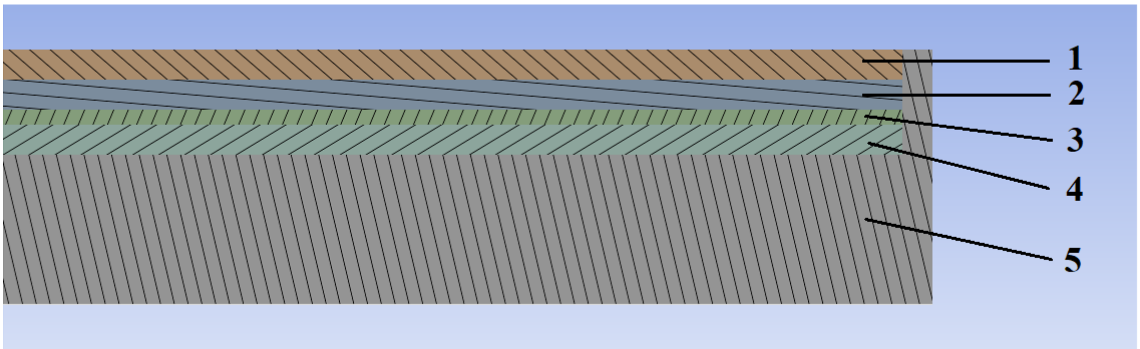

Fig. 6 − A section of the PCM integrated electrical floor model

1.Concrete layer 1 2. PCM 3. Concrete layer 2 4. Electrical heating mat 5. Concrete floor

Table 1. RT 21 HC Material properties

Characteristics	*Value*	*Units*
Melting area	20-23	[°C]
Solidification area	21-19	[°C]
Heat storage capacity	190	[kJ/kg]
Specific heat capacity	2	[kJ/kg·K]
Density solid (at 15°C)	0.88	[kg/l]
Density liquid (at 25°C)	0.77	[kg/l]
Heat conductivity	0.2	[W/(m·K)]
Max. operation temperature	45	[°C]

The reference temperature for the electric heating mat and the water inlet was considered to be 35 °C, this being a recommended operating temperature for the heating source in a floor heating system.

The initial room temperature for the system was considered 10°C.

In terms of the cooling phase, the temperature of 10°C was imposed on the upper surface.

For both cases the heating and cooling time was recorded in order to have an accurate representation in time of the charge/discharge cycle.

6 Results and Discussion

The numerical simulation highlighted the fact that when a layer of PCM was introduced in the floor heating system, the heating phase required more time for the floor to be fully heated but at the same time, during the discharge phase the properties of the phase change material are highlighted, the floor retaining the thermal energy for much higher quantities of time.

An analysis can be performed considering a complete heating and cooling cycle in order to analyse the thermal storage capabilities of both systems.

The temperature distribution of the electrical floor heating system during the charging/ discharging phases emphasises that the required time for the floor to be fully heated is around 20 min and after the heating source was turned off the floor discharged the stored heat over a period of 45 min (Fig.7)

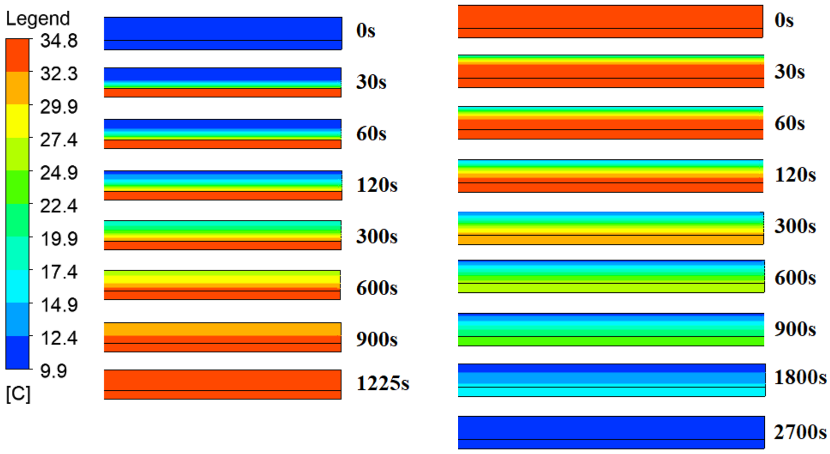

Fig. 7 Electrical heated floor temperature profile throughout the heating and cooling phases

Through adding a layer of PCM, both the heating phase and the cooling phases are prolonged, this is emphasised by the numerical analysis, in the beginning of the heating phase, the temperature of the PCM rises rapidly up to the melting point, than the PCM starts to melt and the temperature variation continues at a reduced rate until the material is fully melted, storing high quantities of thermal energy in this time during the phase transition process. After the PCM has changed to a fluid phase the floor temperature rises quickly until it reaches a convergence state after 98 minutes (Fig. 8).

During the discharge phase, as was the chase for the heating phase the PCM properties are highlighted in the increase in the time it is required for the floor to be fully cooled. The PCM properties can be viewed even from the first few minutes, after 10 min the PCM starts to solidify and release the heat that was stored during the melting process. The systems cooling phase lasted for over 3 and a half hours highlighting the increased capacity of thermal storage of a PCM integrated floor (Fig. 8).

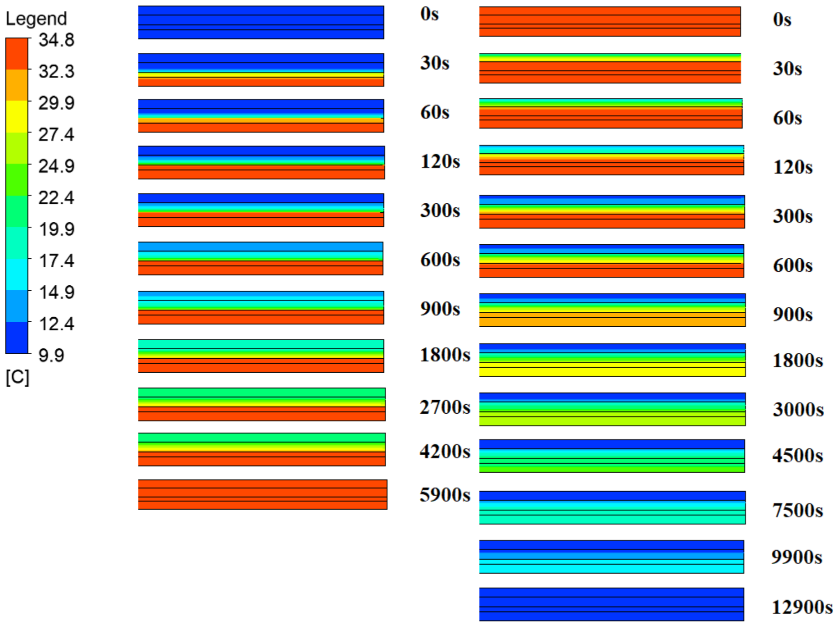

Fig. 8 − PCM integrated electrical heated floor temperature profile throughout the heating and cooling phase

After recording the time, it required for both systems to heat and cool down, in order to make a pertinent comparison a fixed unit of time was imposed, 24 hours, and the number of uninterrupted heating and cooling cycles was determined. Considering the number of daily cycles and the required operation time for the heating source the number of daily hours of operation was determined.

Table 2. Results of a complete charge/discharge cycle

	Classic floor	*PCM floor*	*Unit*
Heating	0.34	1.64	[h]
Cooling	0.69	3.58	[h]
Daily cycles	23.19	4.6	
Daily heating time	7.83	7.53	[h/day]

7 Conclusions and further improvements

Due to their characteristics to store and release high quantities of thermal energy, phase change materials provide a good potential in the buildings sector to achieve significant energy savings. Through the integration of a PCM in the elements of buildings, passive energy savings can be achieved.

The numerical simulation highlight that through the integration of a PCM in a building with an electrical based heating system, a reduction in the heating costs is achieved through a reduction in the number of daily hours of operation for the heating source. Furthermore, due to the longer discharge cycles the PCM floor heating system can benefit from the reduced price in electricity during the off-peak load times, resulting in further reduction in the heating cost.

As further improvements, different types of PCMs and other types of heating systems can be considered as well as the validation of the results through experimental tests in order to have a more comprehensive solution to integrate PCMs in buildings in order to maximize the energy savings capacity.

8 References

[1] **X. Cao, X. Dai and J. Liu,** "Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade," *Energy and Buildings*, vol. 128, p. 198–213, 2016.

[2] **F. Guarino, A. Athienitis, M. Cellura and D. Bastien,** "PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates," *Applied Energy,* vol. 185, pp. 95-106, 2017.

[3] **S. S. Magendran, F. S. A. Khan, N. M. Mubarak, M. Khalid, R. Walvekar, E. C. Abdullah, S. Nizamuddin and R. R. Karri,** "Synthesis of organic phase change materials by using carbon nanotubes as filler material," *Nano-Structures & Nano-Objects,* vol. 19, p. 100361, 2019.

[4] **E. Akalpler and M. E. Shingil,** "Statistical reasoning the link between energy demand, CO2 emissions and growth: Evidence from China," *Procedia Computer Science,* vol. 120, p. 182–188, 2017.

[5] **P. Fotis, S. Karkalakos and D. Asteriou,** "The relationship between energy demand and real GDP growth rate: The role of price asymmetries and spatial externalities within 34 countries across the globe," *Energy Economics,* vol. 66, pp. 69-84, 2017.

[6] **F. P. Cambeiro, J. Armesto, G. Bastos, J. I. P. López and F. P. Barbeito,** "Economic appraisal of energy efficiency renovations in tertiary buildings," *Sustainable Cities and Society,* vol. 47, p. 101503, 2019.

[7] **K. Belz, F. Kuznik, K. F. Werner, T. Schmidt and W. Ruck,** "Thermal energy storage systems for heating and hot water in residential buildings," in *Advances in Thermal Energy Storage Systems,* Woodhead Publishing Series in Energy, 2015, pp. 441-465.

[8] **S. S. Magendran, F. S. A. Khan, N. M. Mubarak, M. Vaka, R. Walvekar, M. Khalid, E. C. Abdullah, S. Nizamuddin and R. R. Karri,** "Synthesis of organic phase change materials (PCM) for energy storage applications: A review," *Nano-Structures & Nano-Objects,* vol. 20, p. 100399, 2019.

[9] **Y. Lin, Y. Jia, G. Alva and G. Fang,** "Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage," *Renewable and Sustainable Energy Reviews,* vol. 82, no. 3, pp. 2730-2742, 2018.

[10] **S. R. L. Cunha and J. L. B. Aguiar,** "Phase change materials and energy efficiency of buildings: A review of knowledge," *Journal of Energy Storage,* vol. 27, p. 101083, 2020.

[11] **X. Kong, L. Wang, H. Li, G. Yuan and C. Yao,** "Experimental study on a novel hybrid system of active composite PCM wall and solar thermal system for clean heating supply in winter," *Solar Energy,* vol. 195, p. 259–270, 2020.

[12] **H. Wang, W. Lu, Z. Wu and G. Zhang,** "Parametric analysis of applying PCM wallboards for energy saving in high-rise lightweight buildings in Shanghai," *Renewable Energy,* vol. 145, pp. 52-64, 2020.

[13] **P. K. S. Rathore and S. K. Shukla,** "Potential of macroencapsulated pcm for thermal energy storage in buildings: A comprehensive review," *Construction and Building Materials,* vol. 225, p. 723–744, 2019.

[14] **T. Pirasaci,** "Investigation of phase state and heat storage form of the phase change material (PCM) layer integrated into the exterior walls of the residential-apartment during heating season," *Energy,* no. 207, p. 118176, 2020.

[15] **A. S. Bejan and T. Catalina,** "The implementation of Phase Changing Materials in energy-efficient buildings. Case Study: EFdeN Project," *Energy Procedia,* no. 85, pp. 52-59, 2016.

[16] **S. Li, K. Zou, G. Sun and X. Zhang,** "Simulation research on the dynamic thermal performance of a novel triple-glazed window filled with PCM," *Sustainable Cities and Society,* vol. 40, pp. 266-273, 2018.

[17] **Y. Hu and P. K. Heiselberg,** "A new ventilated window with PCM heat exchanger—Performance analysis and design optimization," *Energy and Buildings,* vol. 169, pp. 185-194, 2018.

[18] **H. Weinläder, F. Klinker and M. Yasin,** "PCM cooling ceilings in the Energy Efficiency Center – Regeneration behaviour of two different system designs," *Energy and Buildings,* vol. 156, pp. 70-77, 2017.

[19] **M. Yasin, E. Scheidemantel, F. Klinker, H. Weinläder and S. Weismann,** "Generation of a simulation model for chilled PCM ceilings in TRNSYS and validation with real scale building data," *Journal of Building Engineering,* vol. 22, pp. 372-382, 2019.

[20] **B. Y. Yun, S. Yang, H. M. Cho, S. J. Chang and S. Kim,** "Design and analysis of phase change material based floor heating system for thermal energy storage," *Environmental Research,* vol. 173, pp. 480-488, 2019.

[21] **S. Lu, B. Xu and X. Tang,** "Experimental study on double pipe PCM floor heating system under different operation strategies," *Renewable Energy,* vol. 145, pp. 1280-1291, 2020.

[22] **K. Faraj, J. Faraj, F. Hachem, H. Bazzi, M. Khaled and C. Castelain,** "Analysis of underfloor electrical heating system integrated with coconut oil-PCM plates," *Applied Thermal Engineering,* vol. 158, p. 113778, 2019.

[23] **J. Guo, Y. Jiang, Y. Wang and B. Zou,** "Thermal storage and thermal management properties of a novel ventilated mortar block integrated with phase change material for floor heating: an experimental study," *Energy Conversion and Management,* vol. 205, p. 112288, 2020.

[24] **A. E. Mays, R. Ammar, H. Mahamad, M. A. Akroush, F. Hachem, M. Khaled and M. Ramadan,** "Using phase change material in under floor heating," *Energy Procedia,* vol. 119, pp. 806-811, 2017.

[25] **P. Devaux and M. M. Farid,** "Benefits of PCM underfloor heating with PCM wallboards for space heating in winter," *Applied Energy,* no. 191, p. 593–602, 2017.

[26] **D. A. Reay, R. J. McGlen and P. A. Kew,** Heat Pipes, 6th Edition, Theory, Design and Applications, Elsevier Ltd., 2014.

[27] **A. Burlacu, C. D. Lăzărescu, V. Ciocan, M. Verdeș, M. C. Balan and A. A. Şerbănoiu,** "CFD Heat Transfer Analysis for Heat Pipes Integration into Buildings with Glazed Façades," *Procedia Engineering,* vol. 181, pp. 658-665, 2017.

[28] **A. Burlacu, G. Sosoi, R. Ș. Vizitiu, M. Bărbuță, C. D. Lăzărescu, V. Ciocan and A. A. Șerbănoiu,** "Energy efficient heat pipe heat exchanger for waste heat recovery in buildings," *Procedia Manufacturing,* no. 22, p. 714–721, 2018.

[29] [Online]. Available: https://www.rubitherm.eu/en/index.php/productcategory/organische-pcm-rt.