# ANALYSIS OF SIMULATION MODELS OF PCM IN BUILDINGS UNDER LATVIA'S CLIMATE CONDITIONS

**Janis Kazjonovs[*], Diana Bajare[**], Aleksandrs Korjakins[***], Ansis Ozolins[* **], Andris Jakovics[** *]**
Riga Technical University, Chair of building materials and wares, Kalku Street 1, LV-1658, Riga, Latvia,
Phone: +371-67089132,
e-mail: [*]janis.kazjonovs@rtu.lv, [**]diana.bajare@rtu.lv, [***]aleks@latnet.lv,
[* **]ansiso@inbox.lv, [** *]ajakov@latnet.lv

## ABSTRACT

*This paper reviews a simulation study about Phase Change Materials (PCM) incorporated in building materials, particularly in passive applications. Due to the phase change these materials can store higher amounts of thermal energy than traditional building materials and can be used to add thermal inertia to a lightweight construction without adding physical mass. Thermal and mechanical properties of the used PCMs are presented in the paper. Thermal simulations were performed to study the optimal distribution of this material inside a building. A simulation study using WUFI®plus and EnergyPlus was carried out on PCM plaster, investigating various fusion temperatures of the PCM during day and night in hot weather conditions. The PCM effect during the heating season is also investigated. It was shown that the use of PCMs have advantages for cooling demand and building applications stabilizing room temperature variations during summer days, provided sufficient night ventilation is available. Another advantage of PCM usage is stabilized indoor temperature during the heating season.*

. **Key words:** Phase change materials, cooling, thermal simulations, thermal inertia

## INTRODUCTION

Demand for higher thermal comfort and climate changes have brought new challenges for designers of cooling systems, because of an increased usage of air conditioning in a building environment, resulting in higher electricity demand and $CO_2$ emissions. Today the thermal energy storage plays an important role in building energy conservation, which can be achieved by the incorporation of PCM into the building envelope. PCM incorporated in the building envelope, for example, in walls with plasters, absorb redundant heat, which leads to improved thermal inertia of the building, lower and shifted in time temperature peaks. References have been found for improving the thermal properties of concrete and plasters containing PCM (Cabeza, 2006; Romero et al., 2010; Schossig et al., 2005; Tyagi et al., 2011; Kuznik et al., 2011; Zamalloa et al., 2006).

PCMs can be used for cooling a building in three conventional ways (Kendrick, Walliman, 2007):

• Passive cooling: Cooling through the direct heat exchange of indoor air with PCMs incorporated into the existing building materials such as plasterboards, floorboards and furniture

• Assisted passive cooling: Passive cooling with an active component (for example, a fan) that accelerates heat exchange by increasing the air movement across the surface of the PCM

• Active cooling: Using electricity or absorption cooling to reduce the temperature and/or change the phase of the PCM

As active cooling, and supportive passive cooling, require the use of additional energy (refrigeration and fans). It is likely that the simplest, most cost-effective and environmentally friendly usage of PCM is in a purely passive way. The focus of this paper is on the use of PCMs for passive cooling, although the PCM effect during the heating period is also investigated.

The simulation models are based on five polygon test stands which have been built for the first time in Latvia. The goal of these test stands is to verify the energy efficiency and sustainability of the developed solutions for external bounding constructions, which are produced from local raw materials (ceramic blocks, foam concrete, wood, plywood, fibrolite, granules, sawdust etc.), in the conditions of the Latvian climate and, at the same time, to ensure the interior thermal comfort. Also, PCM could be incorporated in a building envelope for one stand to analyze PCM applications for Latvian climatic conditions.

Test stands are equipped with a full system for monitoring, collection and storage of data. Slightly similar polygon investigations were carried out at the Technical University of Tampere in Finland (*Vinha J., 2007*). However, the stands in Tampere were designed for different goals, they are smaller and without windows, which is important to ensure a sufficient level of thermal comfort. Instead of a heat pump, which will be used in the present project to reduce the consumption of fossil energy, the Tampere stands used electrical heaters. Moreover, the initial measurement data from those stands are not available for detailed analysis, only specific results can be found in certain scientific publications. The significance of those results are also decreased for the Latvian situation due to climatic differences.

The polygon with test stands, to compare the efficiency of PCMs, are built in Lleida Technical University, Spain. The main goal of that research is to create the solution of minimal energy consumption for air conditioning systems in hot climate conditions. However, Latvian climate conditions differ significantly from Spain's climate. Moreover, the stands which are presented in Lleida do not take into account the solar energy, which comes through the window. Thereby, legacy investigations are not duplicated, and this fact substantiates the scientific and practical value of the current research in Latvian climate conditions.

## MATERIALS AND METHODS

### 1D Integral Model

To model the heat and moisture transport in the multi-layer wall of a building, the following set of partial differential equations is used (Kunzel, 1995; Zhong, Braun, 2008):

$$\begin{aligned} &\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+h_v\frac{\partial}{\partial x}\left(\delta_p\frac{\partial(\varphi P_{sat})}{\partial x}\right)= \\ &\quad=\rho(c+wc_w)\frac{\partial T}{\partial t} \\ &\frac{\partial}{\partial x}\left(D_\varphi\frac{\partial \varphi}{\partial x}\right)+\frac{\partial}{\partial x}\left(\delta_p\frac{\partial(\varphi P_{sat})}{\partial x}\right)= \\ &\quad=\rho\frac{dw}{d\varphi}\frac{\partial\varphi}{\partial t}\end{aligned} \qquad (1)$$

where $\lambda$ – thermal conductivity, W/(m·K);
$T$ – temperature, °C;
$x$ – wall thickness, m;
$h_v$ = 2260000 J/kg – the heat of vaporization;
$\delta_p$ – the water vapour permeability of a material, kg/(m·s·Pa);
$\varphi$ –relative humidity;
$P_{sat}$ –saturation vapour pressure, Pa;
$\rho$ – bulk density of dry building material, kg/m$^3$;
$c$ – specific heat capacity of dry building material, J/(kg·K);
$w$ – dry basis moisture content, kg/kg;
$c_w$ = 4187 – the specific heat capacity of water, J/(kg·K);
$D_\varphi$ – liquid conduction coefficient, kg/(m·s).

The above equations are non-linear (due to variable properties $\lambda$, $\delta_p$ and $D_\varphi$ values), strongly coupled and have time-varying boundary conditions.

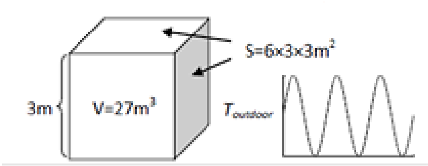


**Figure 1.** The integral mathematical model: graphical illustration

The simple model is created for estimating the indoor temperature variance due to varying outdoor temperatures taking into account the energy flow that crosses the wall (see Fig. 1). A similar model is inspected in (Ozolinsh, Jakovich, 2013). It is assumed that the inner load is constant $q_0$. The heat amount variation indoors due to indoor temperature variation during a short time interval $\Delta t$ is:

$$\Delta Q_1 = Vc_{air}\rho_{air}\left(T_{indoor}(t+\Delta t)-T_{indoor}(t)\right)$$

and the variation dependent on the difference with the outdoor temperature is:

$$\Delta Q_2 = \left(\sum_i S_i q_i(t+\Delta t) - q_0\right)\Delta t$$

where $S_i$ is the surface area of one wall, roof or floor, $q_i$ is the heat flux corresponding to the surface with the area $S_i$.
From (1) and (2) it can be concluded that

$$\Delta Q_1+\Delta Q_2=0 \Rightarrow \lim_{\Delta t\to 0}\left(\frac{\Delta Q_1+\Delta Q_2}{\Delta t}\right)= \\ = Vc_{air}\rho_{air}\frac{dT_{indoor}}{dt}+\sum_i S_i q_i - q_0 = 0.$$

For calculation of the temperature and relative humidity profiles in the construction, the set of equations (1) used. From this, heat fluxes $q_i$ on the inner surfaces are obtained.
Assuming, that indoor temperature is constant, but heating, that is necessary to ensure a constant indoor temperature, is changing, the following equation is obtained:

$$q_h = \sum_i S_i q_i$$

### Simulation Methods

For calculating room climate and energy demand, two different models are used: 1D model, described on previous subsection, and 3D model which takes into account the whole building, windows etc.
For calculating room climate and energy demand, using the 3D model, the commercial software

WUFI®plus and free available software Energypluss are used.

WUFI®plus is a room climate model which connects the energetic building simulation and the hygrothermal component calculation. With the building simulation software WUFI®plus the hygric and thermal ratios in a building, in its perimeter and their interaction can be calculated and quantified as well as the energy demand and the consumption of system engineering. WUFI®plus focuses on calculating the thermal behavior of the building taking into account hourly outdoor climate values, interior thermal loads, various set-point temperatures and ventilation strategies as well as the adjusted system technology.

Energypluss is a whole building energy simulation program that engineers, architects, and researchers use to model energy and water use in buildings. EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use. EnergyPlus includes many innovative simulation capabilities: time-steps less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.

**Simulation Model**

PCM can be impregnated into building materials such as plasters, either directly or as impregnated pellets. In the presented simulation model PCM was applied on the inner side of the building wall varying with the thickness of 2 mm, 4 mm and 6 mm. The building was a 3 x 3 m cubicle with a height of 3 m. Commercially available PCMs were used and their main properties are shown in Table 1. The most important properties of PCM are the thermodynamic properties, like transition temperature ΔT (°C) and latent heat H (kJ/kg). Heat flows of PCM are shown in (Puretemp tehnical data…,Rubitherm…).

**Table 1**

Main properties of PCM

| PCM | λ, (Conductivity) | ρ, (Density) | ΔT, (Transition range) | H, (Latent heat) |
|---|---|---|---|---|
| | W/(m·K) | kg/m3 | °C | kJ/kg |
| PT 23 | 0.2 | 830 | 20..24 | 203 |
| PT 24 | 0.2 | 860 | 21..24 | 185 |
| SP25 | 0.6 | 1380 | 25..29 | 180 |

**Table 2**

Constructions used for modeling

| *Construction* | Thickness mm | Conductivity W/(m·K) | Specific heat J/(kg·K) | Density kg/m$^3$ |
|---|---|---|---|---|
| **Wall** | | | | |
| Outside | | | | |
| Plywood | 20 | 0.17 | 1500 | 500 |
| Mineral wool | 200 | 0.036 | 850 | 40 |
| Vapour retarder | 0.25 | 0.15 | 1700 | 290 |
| Plywood | 20 | 0.17 | 1500 | 500 |
| Fibrolite | 75 | 0.068 | 2100 | 360 |
| Lime plaster | 15 | 0.49 | 840 | 1530 |
| **Roof** | | | | |
| Plywood | 12 | 0.17 | 1500 | 500 |
| Mineral wool | 254 | 0.036 | 850 | 40 |
| Plywood | 9 | 0.17 | 1500 | 500 |
| **Ground floor** | | | | |
| Plywood | 21 | 0.17 | 1500 | 500 |
| Mineral wool | 271 | 0.036 | 850 | 40 |
| Plywood | 21 | 0.17 | 1500 | 500 |

Thermal discomfort problems may arise due to outside temperature fluctuations to buildings with low inertia and large glazing areas. Using PCM as an inner layer for the building's wall may mitigate the problem. The absorbed latent heat increases the thermal inertia of the construction while maintaining a near constant temperature.

The test stand of plywood in Fig. 2 was chosen for the simulation due to the lowest thermal inertia of the test polygon of five stands. The aim of the plywood test stand was to verify PCM usage.

The thermo physical properties and layers of the constructions were created according to the best practice guidelines. All the layers of the constructions are presented in Table 2. The heat transfer coefficient for wall was set to 0.154 $W/m^2K$, floor 0.170 $W/m^2K$, roof 0.158 $W/m^2K$ and triple glazed windows 1 $W/m^2K$. The window is added on the South side.

Main parameters of the described building zone are:

- Total volume ($m^3$) 27.0
- Floor area ($m^2$) 9.0
- External wall area ($m^2$) 34.2
- External transparent area ($m^2$) 1.8
- Total PCM area ($m^2$) 34.2
- Floor area/PCM area 0.26
- PCM relative thickness (mm) 2/4/6

To define the outside conditions, weather data for Riga, Latvia, were taken and average temperatures were used by the time step 1 hour. Summer and winter periods of the year were selected for detailed analysis.

To simplify the model, no inner heat gains from people, lightings were selected. An exception was allowed only in Fig. 5.

However, it was noted that the main factor for effective usage of PCM is night cooling for PCM solidification. Free cooling by opening the window was applied to cool and solidify the PCM.

**Figure 2.** Polygon of stands - in the centre: stand of plywood

**PCM Application on the real test stand**

The base cases were simulated with PCM usage on different places on the building wall to compare the results with standard construction without PCM usage. The base cases are given in Table 3 below.

For analyzing the influence of the window, the cases without windows were also inspected.

EnergyPlus was used for the summer period simulation, where free cooling night ventilation was applied and the window was opened at 30% by an area from the time of 20:00 to 8:00. Two temperature conditions were selected for this analysis:

1. Free floating conditions, where no temperature control is applied.
2. Controlled temperature of 25°C was selected from the time of 8:00 to 20:00. Cooling loads were measured.

For base cases it is assumed that PCM is incorporated into the lime plaster or roof. Default thickness of PCM is 6 mm, but cases with thickness of 2 and 4 mm are also inspected.

**Table 1**

Different cases of PCM usage on the test stand

| Case | Description |
|---|---|
| A | without window, no PCM is added |
| A1 | without window, PCM is added to the inner surface of each wall, |
| A2 | without window, PCM is placed after lime plaster |
| A3 | without window, PCM is placed throughout lime plaster |
| B | without window, PCM is added to the inner surface of one wall |
| C | without window, PCM is added to the inner surface of roof |
| WA | case A, window is added |
| WA1 | case A1, window is added |
| WC | case C, window is added |

**RESULTS AND DISCUSSIONS**

**24h periodicity outdoor winter conditions**

The aim of this subsection is to analyze thermal inertia for different cases of PCM PT23 usage. Simulation was done with a 1D integral model.

It is assumed that the temperature outdoors is changing periodically as a sinusoidal function within a 24-h periodicity. For analyzing thermal inertia, the inside temperature amplitude fraction was taken between case A and other cases, when PCM, with a total thickness 6 mm was added. It is assumed that the average outdoor temperature is +5°C and the temperature amplitude is 10°C, and a constant heat load is applied inside the room. Initial indoor temperature was taken to ensure maximal effect of PCM, and a simple integral model, described in subsection “1D integral model”, was used. The results are summarized in Table 4.

**Table 2**

The ratio of the temperature amplitude for case A and given case, when PCM is used

| Case | A1 | A2 | A3 | B | C |
|---|---|---|---|---|---|
| Amplitude fraction | 3.1 | 2.9 | 3.1 | 1.5 | 1.9 |

The results show, that the thermal inertia of the building insignificantly depended on the position of PCM (case A1, A2 and A3) in lime plaster, but PCM which was added on the floor is a better solution than case B, when PCM was added only on one wall. It could be explained by the fact that the thermal inertia of the roof is lower than that of the wall, therefore the effect of PCM usage is higher in this case. Based on these data, for a better effect and PCM placement position in the wall construction, it was selected that for further simulation analysis PCM is placed on all inner surfaces of the walls.

### PCM application on heating season

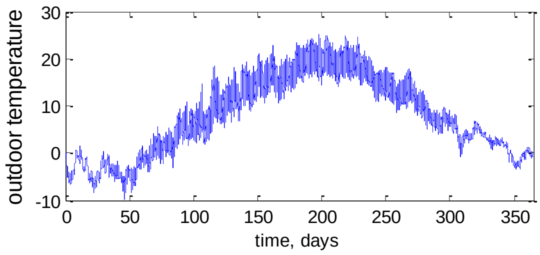


**Figure 3.** Annual temperature cycle in Latvia

Annual cycle (Fig. 3) was taken to analyze the yearly heat demand. Climate data for Latvia, Riga was taken by a time step of one hour as an average from the last 6 years. Data was taken from (Latvian Environment…). It is assumed, that the indoor temperature was a constant of +23,5°C during the whole year. Only the heating energy changed. For calculating the heating demand, commercial software WUFI®plus was used.

**Table 3**

Yearly heating demand.

| Heating demand (kWh) | Without window | Window is added |
|---|---|---|
| No ventilation | 1646 | 1353 |
| Ventilation (0,7 1/h) | 2508 | 2191 |

The data (see Table 5) show, that the ventilation absolutely changed the yearly heating demand. However, PCM did not effect the yearly heating demand by assumption that the inside temperature is constant. It is because PCM only helps to increase thermal inertia and there are no temperature fluctuations inside the room. A similar analyze of the yearly heating demand saving was made in (Shrestha, 2012). In this work, the yearly heating demand savings was about 1 % due to PCM usage. However, the reason for this saving was not PCM high heat of fusion, but only thermal conductivity.

However, PCM could be useful during the heating season in the following ways:

a) PCM can stabilize indoor temperature by constant heat load

b) In transient case from summer season to the heating season. PCM could help to increase time when the indoor temperature is decreasing below the comfort temperature.

c) In specific cases, e.g., heating is switched off for brief time period. PCM application could ensure, that the inside temperature does not decrease below the optimal temperature during the brief time.

Average January temperature in Latvia is taken to analyze temperature fluctuations indoors (Fig. 4).

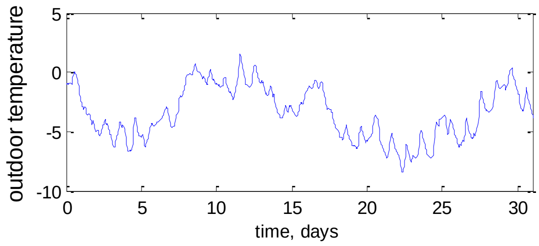


**Figure 4.** Outdoor temperature in January

It is assumed, that a constant heat load is applied indoors, and the indoor temperature changes are by the integral model. To see maximal effect of PCM usage, inner heat load, that ensure a maximal PCM effect, is taken.

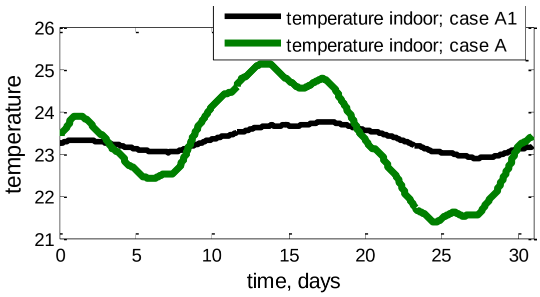


**Figure 5.** Indoor temperature in January

Figure 5 shows that PCM usage on walls significantly helps to stabilize indoor temperature. Without PCM the indoor temperature amplitude is about 4°C, however using PCM it is only 1°C.

Due to low solar radiation during January in Latvia, the results are not significantly increased by solar radiation through the window.

### PCM application on summer

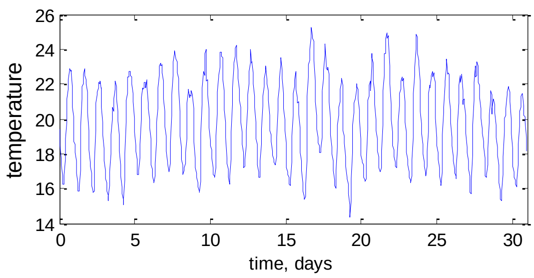


**Figure 6.** Outdoor temperature in July

July, which is the warmest month in Latvia, was taken for analysis (see Fig. 6).

To see the maximal effect, a constant heat load was taken indoors to ensure the maximal effect of PCM applications in this example.

1D Integral model was applied.

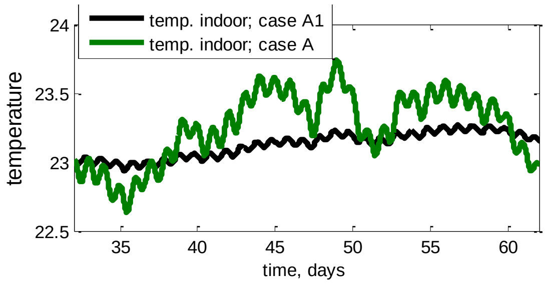


**Figure 7.** Indoor temperature in July

Figure 7 shows the maximal effect, when PCM's melting temperature is in the correct range. PCM usage on walls significantly helps stabilize indoor temperatures. However, the indoor temperature amplitude is relatively low without PCM usage in the building. However, the ventilation and window that were not taken into account in Figure 7 were important aspects that influenced temperature fluctuations indoors.

Also the indoor temperature fluctuations were analyzed without PCM. The air change coefficient was constant 0.7 1/h. Different cases were compared. Software WUFI®plus was used.

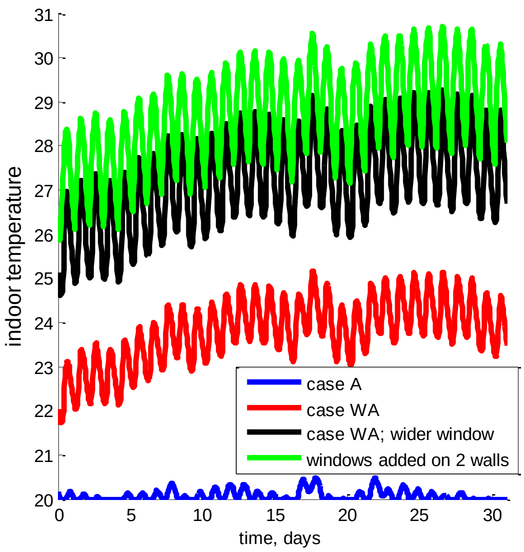


**Figure 8.** Indoor temperature in July. Blue curve corresponds to the real test stand of plywood. Black curve is the case, when the standard window (width 1.2m) is replaced with a wider window (2,2m). Red curve is the case, when a new window is added on the east side of the wall

Figure 8 shows that the temperature significantly differs, if window and solar radiation are taken into account. The width of a window is also an important factor that influences temperature fluctuations indoor. Also PCM could be necessary for cooling the room, especially in cases when the influence of a solar radiation is sufficiently large, and therefore the inside temperature is relatively high inside the room.

Next, the effect of PCM usage was analyzed by the assumption that the air change is constant 0,7 1/h.

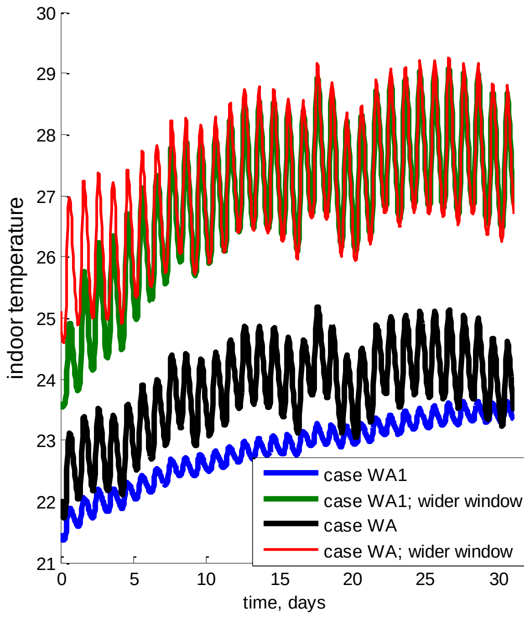


**Figure 9.** Indoor temperature in July

Figure 9 shows that PCM insignificantly helps to decrease the inside temperature, if the inside temperature differs too much from PCM melting temperature, because inside, the temperature does not decrease at night. This could be improved, if free cooling is applied, for example if the window is opened during the night. This situation is analyzed at the next subsection.

EnergyPlus was used for the summer period simulation, where free cooling night ventilation was applied and the window was opened at 30% by an area from the time period of 20:00 to 8:00. Two temperature conditions were selected for this analysis:

1. Free floating conditions, where no temperature control is applied.
2. Controlled temperature of 25°C was selected from the time period of 8:00 to 20:00. Cooling loads were measured.

**Free floating conditions**

From Figure 10 to 12 indoor temperatures with different PCMs used are shown: PT23, PT24 and SP25 with different thickness of the layer. During 5 days of July, from 05.07 to 09.07 were selected for analysis. It is seen that only PCM SP25 had some significant effect for stabilizing the temperature fluctuations and reducing the peak temperatures. Using SP25 with a thickness of 2 mm the maximum peak temperature can be reduced by 2°C, but with a 6 mm layer 3°C. Also there is a trend that proportionally increasing the thickness of the PCM layer, the maximum temperature reduction does not reduces proportionally, but reduces less. It means that it is not reasonable to increase the PCM layer to

4 or 6 mm. It is explained by less effective melting and solidification in the PCM layer.

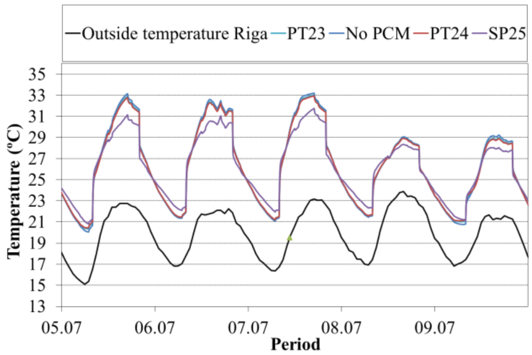


**Figure 10.** Indoor temperature for Free Floating conditions (PCM layer – 2 mm)

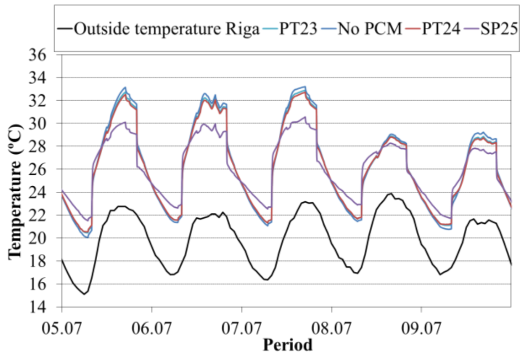


**Figure 11.** Indoor temperature for Free Floating conditions (PCM layer – 4 mm)

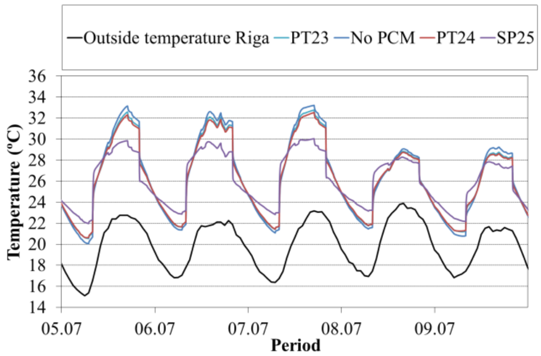


**Figure 12.** Indoor temperature for Free Floating conditions (PCM layer – 6 mm)

**Controlled temperature conditions**

To estimate the reduction in cooling loads during summer due to the usage of PCM, summer months, June, July and August were simulated. From Table 6 and Figures 13 to 16, the effects of PCMs can be seen. All three PCMs act similarly with a layer thickness of 2 mm, and reduce the cooling loads maximum to 14.4%. Maximum cooling load reduction can be observed for SP25 with a layer of 6 mm (23.1 %). From Figure 16, it can be seen that a PCM layer of up to 3 mm is the most advisable for a good and effective usage of the PCM material.

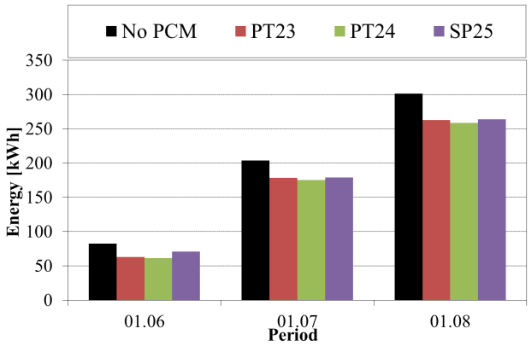


**Figure 13.** Cooling load for different PCMs (2 mm layer)

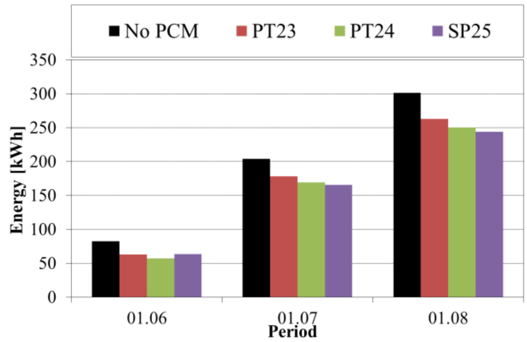


**Figure 14.** Cooling load for different PCMs (4 mm layer)

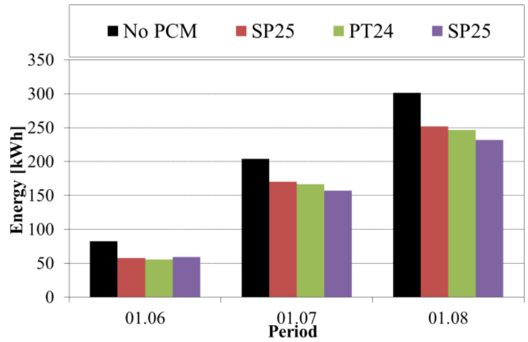


**Figure 15.** Cooling load for different PCMs (6 mm layer)

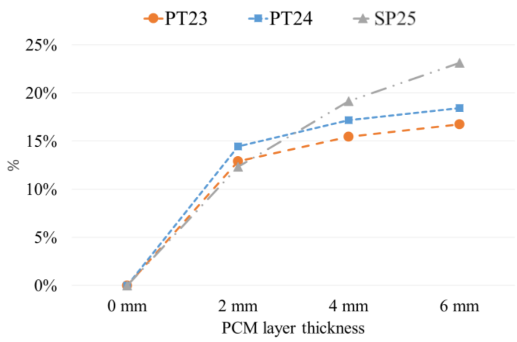


**Figure 16.** Cooling load decrease for different PCMs and their layer thickness

**Table 6**

Cooling demand for different PCMs

| PCM thickness | No PCM | PT23 | | PT24 | | SP25 | |
|---|---|---|---|---|---|---|---|
| | kWh | kWh | % | kWh | % | kWh | % |
| 2 mm | 303.12 | 263.94 | 12.9% | 259.32 | 14.4% | 265.73 | 12.3% |
| 4 mm | 303.12 | 263.94 | 15.5% | 251.03 | 17.2% | 245.05 | 19.2% |
| 6 mm | 303.12 | 252.32 | 16.8% | 247.20 | 18.4% | 232.97 | 23.1% |

## CONCLUSIONS AND FURTHER WORK

The aim of this work was to verify PCM usage on a real plywood test stand of polygon using theoretical simulation software. The results show, that PCM could be useful for Latvian climatic conditions for passive cooling. PCM usage significantly helps increase thermal inertia of building.

During the summer days in free cooling conditions, using PCM together with night ventilation, a significant indoor temperature peak decrease to 3°C can be achieved.

During the summer days in a controlled temperature of 25°C, conditions using PCM together with night ventilation, a significant cooling load demand decrease to 23.1% can be achieved.

To make the PCM work more effective a layer of 3 mm is the most advisable.

Different PCMs with different peak temperatures can be incorporated in a building envelope to ensure thermal comfort for different indoor temperatures. Since the summer season is relatively short for Latvian climatic conditions, a detailed analysis of PCM usage during the heating season is required.

The next step would be comparison of the results obtained in experiments on similar constructions with theoretical calculations. Such experiments are planned to be carried out in the future for the test of poligon stands.

## REFERENCES

Cabeza L.F., et al., Use of microencapsulated PCM in concrete walls for energy savings, Energy and Buildings, 39 (2006), pp. 113-119.

Kuznik F. et al., A review on phase change materials integrated in building walls, Renewable & Sustainable Energy Reviews, 15 (2011), pp. 379-391.

Kendrick C., Walliman N., Removing unwanted heat in lightweight buildings using Phase Change Materials in building components: simulation modelling for PCM plasterboard, Architectural Science Review Volume 50.3 (2007), pp 265-273.

Kunzel, M., (1995) Simultaneous Heat and Moisture Transport in Building Components. PhD thesis. Wiley IRB Verlag, Stuttgart.

Latvian Environment, Geology and Meteorology Centre. (2012) Relative, humidity and temperature database. http://www.meteo.lv/meteorologija-datu-meklesana/?nid=461

Ozolinsh A., Jakovich A. (2013) Heat and Moisture Transport in Multi-Layer Walls: Interaction and Heat Loss at Varying Outdoor Temperatures, Latvian Journal of Physics and Technical Sciences. Vol. 49, No. 6, p. 32-43.

Puretemp technical data. Allowed online: http://www.puretemp.com/technology_docs/PureTemp%2023%20Technical%20Data%20Sheet.pdf

Puretemp technical data. Allowed online: http://www.puretemp.com/technology_docs/PureTemp%2024%20Technical%20Data%20Sheet.pdf

Romero M.D – Sánchez et al., Phase Change Materials as thermal energy storage incorporated to natural stone. Global Stone Congress (2010).

Rubitherm technical data. Allowed online: http://www.rubitherm.de/english/pages/02f_latent_heat_blend.htm

Schossig P. et al., Micro-Encapsulated Phase-Change Materials Integrated Into Construction Materials, Sol. Energy Mater. Sol. Cells, 89 (2005), pp. 297–306.

Shrestha M. (2012) PCM Application-Effect on Energy Use and IA temperature, Norwegian University of Science and Tehnology.

Tyagi  V.V et al., Development of phase change materials based microencapsulated technology for buildings: a review, Renewable & Sustainable Energy Reviews, 15 (2011), pp. 1373–1391.

Zamalloa A. et al., PCM containing indoor plaster for thermal comfort and energy saving in buildings, Vitioria, Spain, 2006.

Zhong, Z., Braun, J. E. (2008) Combined heat and moisture transport modelling for residential buildings. Purdue University, Indiana.