Application of PCM in Building's Envelope of Lightweight Prefabricated Houses as an addition to a PV driven renovation cooling system by EU project HEART

Eva Zavrl[1], Gašper Zupanc[2], Uroš Stritih[1] and Mateja Dovjak[2]

[1] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana (Slovenia)

[2] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana (Slovenia)

Abstract

Countries with moderate climate have heat gains during the year smaller compared to the heat losses. Therefore, most of the attention on lightweight prefabricated houses is given for thermal insulation (nZEB). Thermal capacity of such envelopes is very low, which can result in overheating of the indoor spaces over the summer months. As a result, the energy needed for mechanical air-conditioning can even exceed the needs for heating. The envelope coupled with PCM layer is introduced. Different types of envelopes applied on residential building are simulated with Energy plus and compared. The results showed that the performance of several variations of PCM are comparable to the heavyweight structure. Also, the mechanical ventilation driven on photovoltaics can efficiently cover the remaining amounts of energy needed for additional cooling. It shows that when the PCM strategy, melting point and capacity are chosen correctly, the produced electrical energy in total can be used for other purposes. This means that a large variety of the products must be available for the building's installation. To satisfy the low energy consumption and thermal comfort (by decreasing inner operative temperatures), the holistic approach (the combination of the active and passive system) is the best solution.

Keywords: Overheating, heavyweight, lightweight structure, PCM, PV mechanical cooling

1. Introduction

The heat gains during the year in countries with moderate climate are smaller compared to the heat losses Therefore, most of the energy consumption in building's sector is used for heating. Lightweight structures improved with low heat transfer insulations enabled the construction with thin wood load-bearing walls (Pajek et al., 2017). However, the lack of thermal mass or heat capacity results in buildings' overheating (Adekunle and Nikolopoulou, 2016). The consequences are low thermal stability and decreased thermal comfort in summer. As a result, the yearly energy consumption for the mechanical air-conditioning (active cooling) can even exceed the energy needed for heating. To improve the heat capacity of the structures' envelope, the phase change materials (PCM) are introduced. PCMs can store or release the energy by changing the phase of the material. By adding the PCM in the lightweight structure where the environmental temperature fluctuations occur, the thermal stability of the building is improved. The standards and requirements on the topic of overheating are limited. Some of the standards focus on the acceptable temperature ranges based on the health aspects and thermal comfort requirements (ANSI/ASHRAE 55-2013 and CEN CR 1571:1998). The other aspect is the annual energy required for cooling building, calculated per unit of cooled area of the building and it shouldn't exceed 50 kWh/m^2 (Directive 2010/31/EU, 2010). Another alternative to the envelope enriched with PCM is mechanical ventilation for cooling powered by the Photovoltaics (PV), as the amount of sun radiation during the overheating periods is usually high. Similar solutions coupled with heating and cooling systems are currently investigated in Horizon2020 project HEART (HEART, 2017). The aim and the scientific contribution of this investigation is: to test the effect of overheating among two different types of envelopes calculated with ID DesignBuilder™ (DesignBuilder Software Ltd., 2017); to study the holistic approach for overheating reduction including active (air-conditioning coupled with PV) and passive systems (envelope enriched with PCM); to assess the overheating based on energy needed for cooling and thermal comfort (including operative temperatures). The passive systems were installed in the lightweight wooden structure with two different strategies. Further on various capacities and melting points were investigated. In order to have more accurate evaluation of the results, additional melting point variations were established. Afterwards, the evaluation based on the thermal comfort in the building with the amount of cooling demand for each method investigated.

doi:10.18086/eurosun2018.04.02 Available at http://proceedings.ises.org

2. Method

Figure 1 shows the concept of the renovation approach. The figure shows the solar assisted active cooling system (active) and the passive heat accumulation system (passive) cooling strategy. The active strategy consumes electrical solar/energy for its operation. The active approach system is currently investigated within Horizon2020 project HEART (HEART, 2017). It can be used for single or multiple family houses. The system has the photovoltaics (PV or BIPV) installed on the optimum location of the building's envelope, which powers the heat pump (HP). The air to water HP is used for both, heating and cooling, so it runs also through the heat and cold storage tank. The water from the heat storage continuous to the smart fan-coil. The smart fan-coil blows the cool air into the space. The connotation 'smart' is added, because the unit includes a local heat pump in it, which can enable a fine regulation of the inlet air temperature for every smart fan-coil in the apartment (normally, one per room).

In order, to reduce the energy consumption, the active system is coupled with the passive one. The passive system accumulates the excess heat. In this way, the remaining energy needed to decrease the room air temperatures generated by the PV can be used for other purposes.

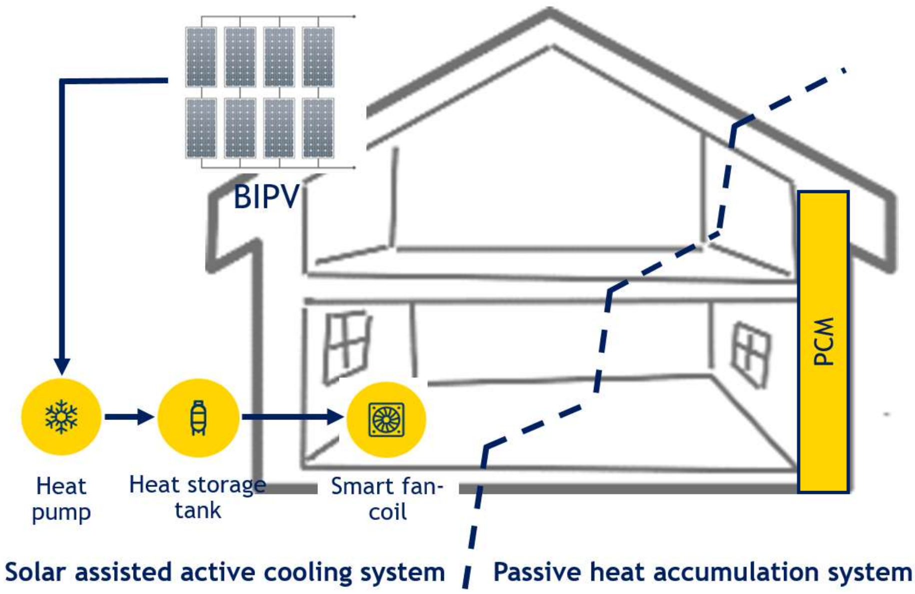

Fig. 1: The holistic cooling approach (active and passive system)

The passive system consists of the lightweight timber envelope which has additional layer of the phase change material (PCM) installed in its walls. When the building's interior is warmed up and the air temperature exceeds the comfortable level the temperature has to be reduced. It can be reduced by adding cool air to the space or by accumulating the excess heat by changing the phase of the material installed in the walls (PCM). PCMs start to melt at certain temperature called melting point. The PCM type should be determined based on its purpose (temperature ranges). So, for the reduction of overheating the melting point should be somewhere within the last acceptable range.

Fig. 2a: Front of the building

Fig. 2b: Back of the building

The purpose of this research was to evaluate the energy saving potential of this passive system, based on the operative temperatures obtained over the first week of August (the hottest week) and through the entire test reference year in Ljubljana (Slovenia). Also, the hours during which the space is overheated and the weekly and yearly amount of electrical energy needed for cooling are calculated.

DesignBuilder™ (Design Builder software Ltd, 2017) is a calculation tool used by designers and researchers for calculation of energy consumption (for HVAC, lighting and operation) and use of water in buildings (Energy Plus, 2017). The geometry was inserted following the layout of the building with area of 167 m^2 shown in Figures 2a and 2b.

The heavyweight (HW) and lightweight wooden frame (LW.WF) structures were investigated The PCM was applied only to the external walls of the LW.WF structure. The passive PCM system was investigated by variation of the strategy (added layer of BioPCM ™ or microencapsulated PCM in gypsum boards), melting points and the PCM thicknesses. The list of investigated cases:

- HW;
- LW.WF (the reference case of the building that needs to renovated in order to reduce the operative temperatures in its interior);
- PCM23.a: M182/Q23;
- PCM25.a: M182/Q25, M91/Q25, M51/Q25 and M27/Q25;
- PCM24.a: M182/Q24, M91/Q24, M51/Q24 and M27/Q24;
- PCM26.a: M182/Q26;
- PCM23.in: two thicknesses of 1.25 cm and 2.50 cm and
- PCM25.in: thickness of 1.25 cm.

The graphical investigation approach is explained in Figure 3.

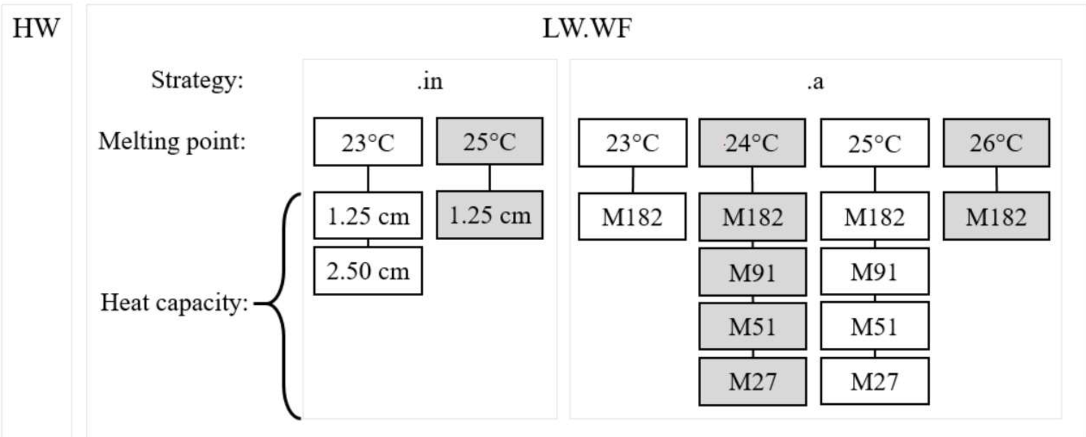

Figure 3: The systematic scheme of the passive system variations investigated

HW structure is chosen for the comparison to the traditional building type with high heat capacity of the building envelope. It has a brick wall with heat transfer (U) of 0.201 W/(m^2K). In this case, also the roof and floor are massive, where the U-value of the roof is 0.182 W/(m^2K) and floor 0.260 W/(m^2K). LW.WF building without the PCM is chosen as a reference case of the building that gets overheated during the summer. The timber envelope with mineral wool panels has the U-value of the external of 0.139 W/(m^2K), of the roof 0.111 W/(m^2K) and of the 0.260 W/(m^2K) floor.

The PCM23.a is the PCM in the building's envelope. Symbol 'a' designates the strategy type, which is a layer of BioPCM ™ added to the buildings envelope. It's has melting point of 23°C and thickness of 7.4 cm, which corresponds with it capacity (M182/25Q). Its latent heat storage is 85 Wh/m^2 (BioPCM ™, 2017). The PCM25.a has melting point of 25°C and thickness of 7.4 cm (M182/25Q) with latent heat storage of 574 Wh/m^2 (BioPCM ™, 2017).The PCM24.a is not an existing product, which means that is not commercially available under this brand's name. It was manually designed by knowing the characteristics of the BioPCM ™ with melting point at 23°C (M182/23Q) in order to find the optimum melting point. Also, the PCM26.a is not an existing product, since it was designed on the basis of characteristics from BioPCM M182/Q27 (BioPCM ™, 2017). The PCM23.in has a different type of the envelope's strategy. The product's name is COMFORTBOARD ™ (Knauf, 2016). The PCM capsules are integrated in the gypsum boards, so they are adjusted to the inner side of the envelope. They melt 23°C and have a thickness of 1.25 cm. It's thermal conductivity is 0.23 W/(mK), density: 880 kg/m³, weight: 11 kg/m^2 where PCM weights 2 kg/m^2, c_p: 12.76 and 1.17 kJ/(kgK). It is sensible to add only 1 or 2 layers of gypsum boards due to its mechanical adjustment possibilities.

Operative temperature is determined based on (ISO 7726:1998(E)):

$$To = (hc * Tai + hr * \overline{Tr})/(hc + hr) \quad \text{(eq. 1)}$$

where Tai - inner air temperature, $\overline{Tr}$ - (mean radiant temperature), hc - heat-transfer coefficient by convection and hr - heat-transfer coefficient by radiation.

The operative temperatures in this article were used to indicate the thermal comfort following the EN 15251:2007 (EN 15251:2007, 2007). The third (the least tolerable) category was used in order to show the worst-case scenario, where 22°C is the lower and 27°C the higher limit of the operative temperature in the residential buildings in summer.

Thermal capacity of the building materials is used for determining the heat accumulation capability of the building.

Thermal capacity C [J/(m³K)]:

$$C = \rho \cdot c \quad \text{(eq. 2)}$$

ρ - density [kg/m³], c - specific heat of the material [J/(kgK)]

The phase delay is calculated based on the number of hours after the outdoor air temperature peak occurred in the building.

3. Results and discussion

The figures below present the results of this study.

Figure 4 presents the daily outdoor air temperatures and the operative temperatures obtained in the space with heavyweight structure (HW) and lightweight wooden frame structure (LW.WF). The dark pink dash line designates the upper limit of the operative temperature (27°C) and the light pink dash line the lower limit of 22°C.

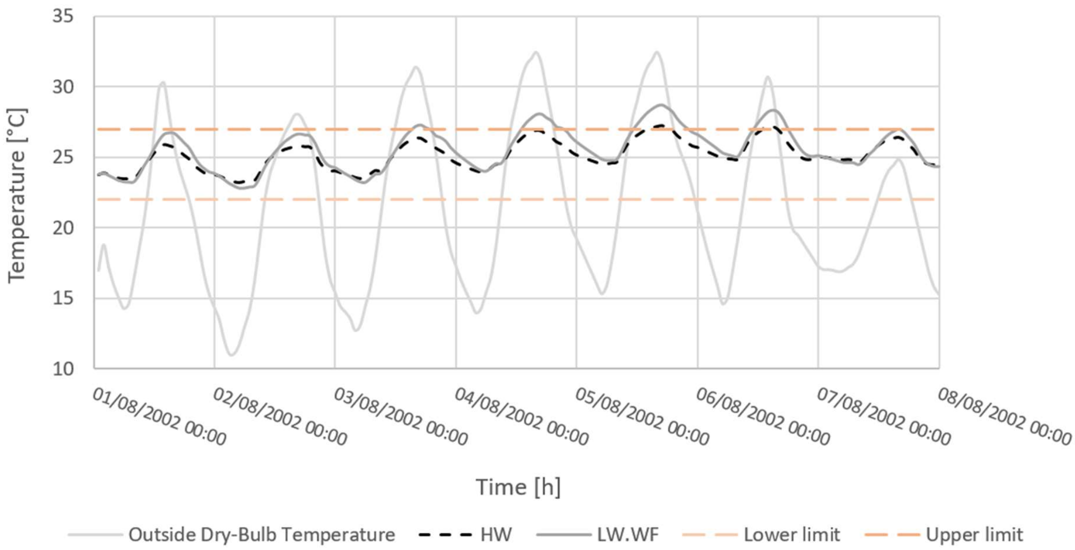

Figure 4: The temperatures obtained with HW and LW.WF structure during the 1st week of Aug

In Figure 4, the light grey line designates the outdoor air temperature fluctuations. The results show that the operative temperatures (hereinafter temperatures) of the HW structure only in minor (max. +0.2°C) exceeds the upper limit of 27°C on 5th of Aug (14:00 - 18:00 h) and 6th of Aug (13:00 - 16:00 h), respectively. The LW.WF structure reaches the maximum temperatures of 28.7°C on the 5th of Aug at 17:00, although the temperatures are cross the upper limit from 12:00 – 22:00.

The first series of solutions are shown in Figure 5. The strategy chosen is the microencapsulated PCM (.in) with melting points at 23°C (1.25 cm and 2.50 cm) and 25°C (1.25 cm).

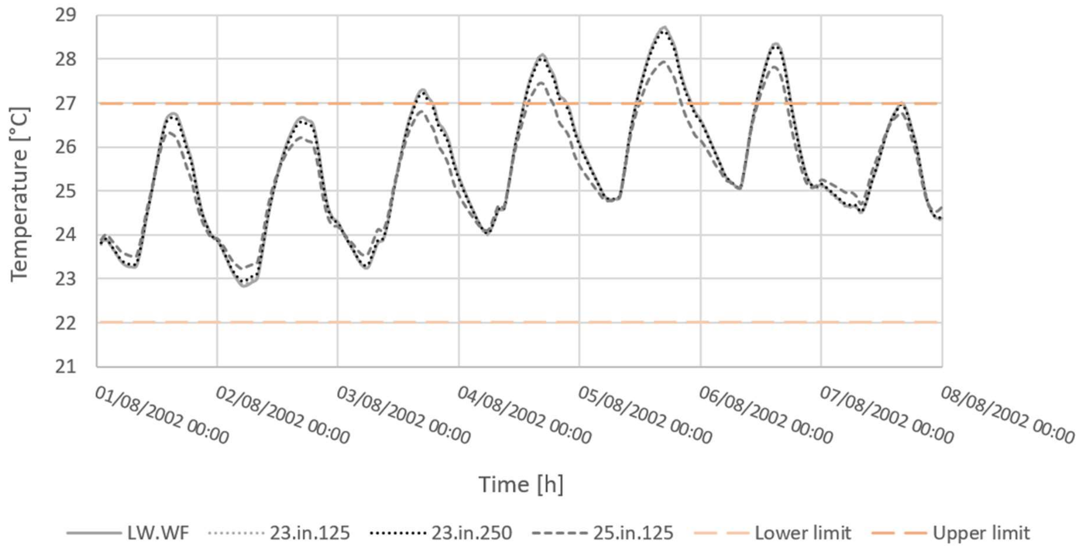

Figure 5: The temperatures obtained with microencapsulated (.in) strategy during the 1st week of Aug

In comparison to LW.WF the microencapsulated PCM with melting point of 23°C and thickness of 1.25 cm (PCM23.in.125) doesn't change the temperature fluctuations. The peak temperature is 28.8°C at 17:00 (5th of Aug). Similarly, PCM23.in.250 neglectingly softens the main temperature peak to 28.6°C. When using PCM25.in.125 the fluctuations slightly dropped compared to LW.WF. The main peak from 5th of Aug was reduced for 0.8°C (to 27.9°C). None of the scenarios showed any phase delay.

Figure 6 shows the results obtained using the BioPCM adding strategy (.a) with melting points of 23°C (M182), 24°C (M182, M91, M51 and M27), 25°C (M182, M91, M51 and M27) and 26°C (M182).

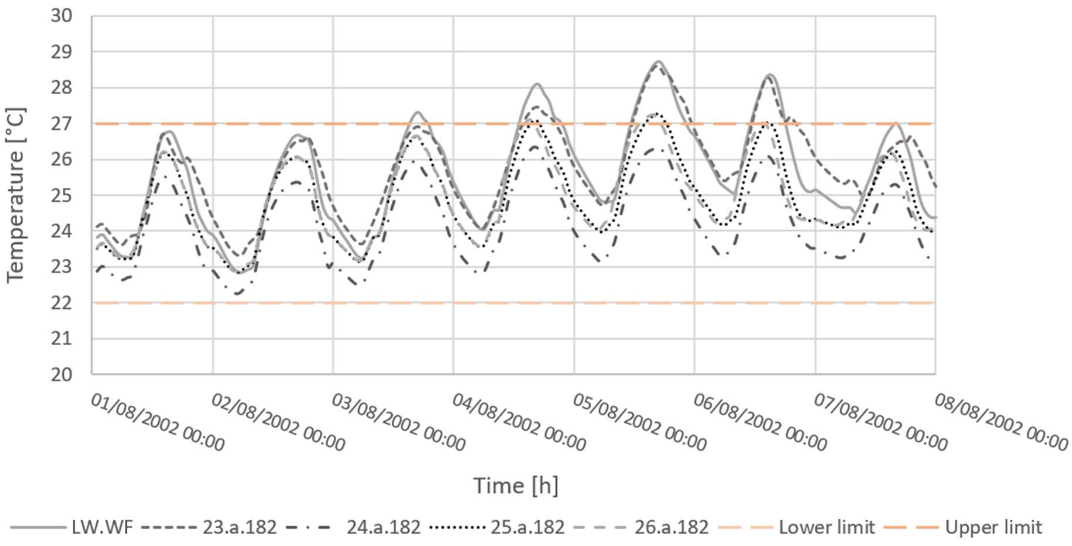

Figure 6: The temperatures obtained with BioPCM ™ (.a) strategy during the 1st week of Aug

Comparison to LW.WF the BioPCM strategy with melting point of 23°C and capacity label of M182 (PCM23.a.182) reduced the temperatures during the first peak (4th of Aug at 17:00). The temperature was reduced for 0.6°C (from 28.1°C to 27.5°C). However, the PCM23.a.182 didn't affect the second and the third peak (5th of Aug (17:00 h) and 6th of Aug (15:00 h)).

The comparison between three strategies within the melting point of 23°C is shown in Figure 7. The PCM23.a.182 has the highest capacity among all, however due to its accumulation capabilities it softens only the highest peak but not the latest two (5th and 6th of Aug). From this it could be concluded that, the mis-determination of the melting point cannot be corrected by the addition of the thermal capacity (PCM mass).

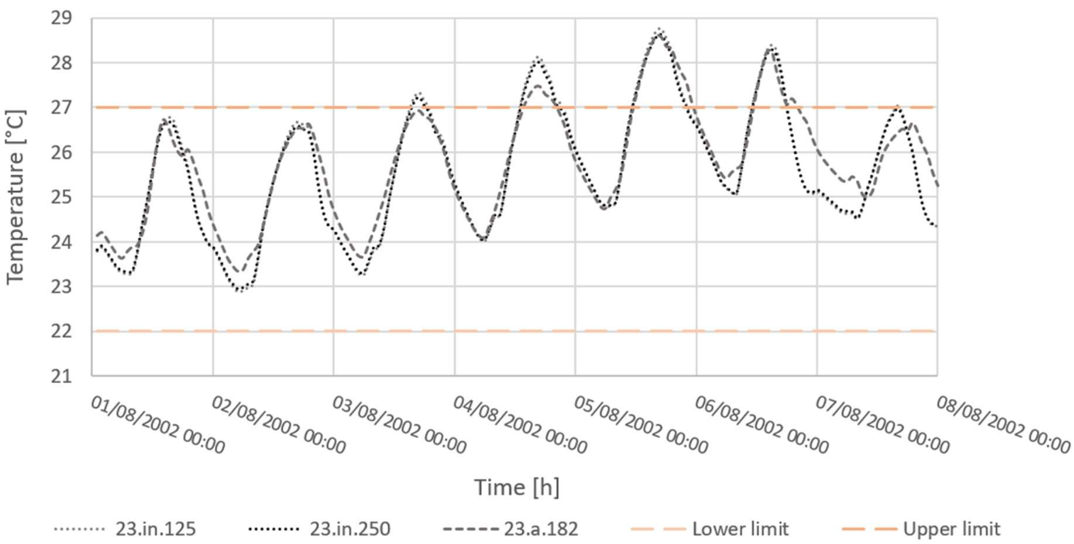

Figure 7: The temperatures obtained with both PCM strategies with melting point of 23°C during the 1st week of Aug

In Figure 6 the PCM25.a.182 and PCM26.a.182 showed similar behavior of the fluctuation. Although it is visible that the PCM26.a.182 moves its peaks before peak of LW.WF and PCM25.a.182. The maximum temperature obtained was close to the upper limit. In both cases was on 5th of Aug (17:00 h), is size of 27.3°C (-1.5°C) and 27.0°C (-1.8°C) for PCM25.a.182 and PCM26.a.182, respectively.

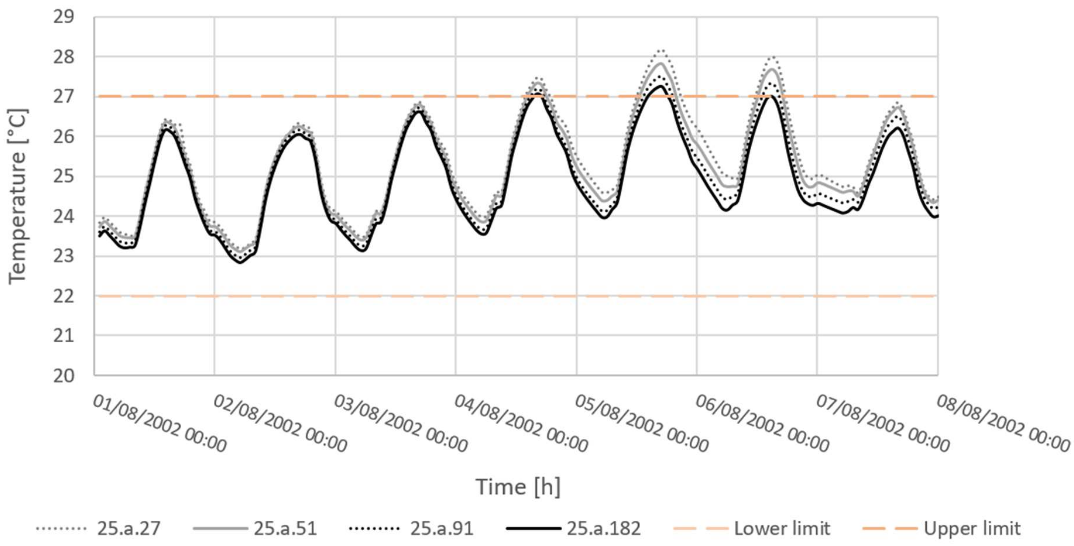

Figure 8: The temperatures obtained with PCM25.a and various heat capacities during the 1st week of Aug

Since the PCM25.a.182 is an existing product, other capacity cases were investigated (M91, M51 and M27) (Fig. 8). It is visible that lower capacity abilities would affect the performance of such case. All of the peaks from 4th to 7th of Aug would increase. Mainly, the highest peak from 5th of August would increase from 27.3°C to 27.5°C, 27.8°C and 28.2°C for M91, M51 and M27, respectively. The performance of the PCM25.a.91 is similar to the thermal performance of HW.

In Figure 6, the PCM24.a.182 was the most keen on reducing the temperatures, which makes is it the most appropriate choice for this study case. It kept the temperatures below the upper limit during the entire week. On 5th of Aug (17:00 h) it reduced the maximum peak of LW.WF for 2.4°C (from 28.7°C to 26.3°C).

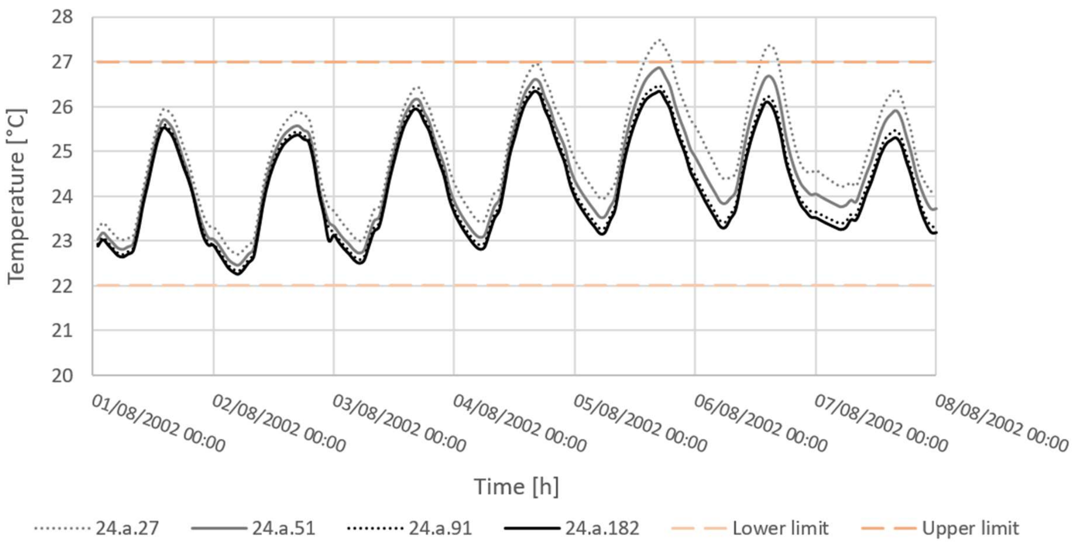

Figure 9: The temperatures obtained with PCM24.a and various heat capacities during the 1st week of Aug

Figure 9 shows, that in comparison to PCM25.a, PCM24.a can keep the temperature peaks below the upper limit in all studied cases but the case with the lowest capacity (M27). This is an indicator of the well chosen melting temperature. In this way, also the costs of the material could be reduced. When using the PCM24.a.M91, the temperature fluctuations remain almost the same, as in case of M182. Its maximum temperature is 26.5°C, which is only 0.2°C higher compared to M182. With PCM24.a.M51, the temperatures remain below the upper limit, but the maximum increases to 26.9°C. The capacity of PCM24.a.M27 wouldn't be high enough to hold the temperature below the limit and thus the maximum exceeds up to 28.2. In both cases (MP 25 and 24°C), all of the fluctuations are very similar without the phase delays.

On 4th of Aug, the temperatures jumped above the upper limit in most of the cases. Fig. 7, 8 and 9 show the performance of the cases within the same melting point. From the figures, it is possible to observe that on that day the maximum temperatures among cases differ the most. This is probably due to the heat accumulation in the entire building's envelope. As a consequence, the PCM have the time to solidify during the night time. Comparing this case to the following three cases – in their peaks on 5th, 6th and 7th of Aug, it is possible to observe that the deviations between the maximum temperatures in the peaks are higher. This shows that the material was not completely solidified over the night.

In all of the cases, the phase delay was observed in one hour after the outer temperature changed, with exception of PCM26.a.182. The temperature change occurred instantly with the outer temperature change. It might be, that when the temperature reached 26°C the PCM started the accumulation. Before the PCM could started receiving a high amounts of sensible heat, the temperature already started dropping.

In general, the solutions PCM26.a.182, PCM25.a.182 and PCM24.a.182, 91 and 51 performed well enough to be implemented as a support to the earlier presented active system.

In Table 1, the hours above which the upper air and operative temperatures limit was crossed.

Tab. 1: The number of hours of overheating OH [h] based on Tai in To (1st week of August)

Type	HW	LW.WF	PCM25.a182	PCM23.in.125
Tai, 26°C	51	66	48	66
To, 27°C	6	30	6	30

In the table also the air temperature is given, because the limit within this study is chosen for the 3rd Category. In some residential buildings inhabitants (elderly) might have non-standard or more demanding threshold (upper limit). Thus, the evaluation of the performance should be treated with higher demand (category) or individually. As visible from the table, the overheating occurred in many of the cases (but PCM24.a.182, 91 and 51) and as a consequence the building's interior was overheated. At this point it is important to stress out, that the PCM24.a.182, 91 and 51 are only theoretical and do not represent existing products. To reduce this numbers, it is the additional cooling with active system is required.

The amount of electrical energy needed to cool the rest of the existing products (PCM23.in.125 and PCM25.a.182) is shown in Table 2.

Tab. 2: The amount of energy needed for cooling [kWh/m^2]

Type	HW	LW.WF	PCM25.a182	PCM23.in.125
Q1st.A	1.4	1.5	1.3	1.5
Qy	7.4	9.7	8.4	9.6
Q1st.A-Qy	19 %	16 %	15 %	16 %

The table shows the energy needed for the 1st week of Aug (Q1st.A) and for the entire year (Qy) calculated for the m^2 of the building. The table also shows the percentage of the amount of energy needed to cool the building during the 1st week of August, which represents up to 19 % of the cooling demand in comparison to the entire year. The correct choice of the passive system (PCM24.a.182, 91 and 51) could reduce this amount for at least 16 %, which is the hottest week in August. In this way, lightweight buildings can be renovated and both the overheating and energy consumption can be reduced. To find a perfect synergy between the passive and the active system, a detailed investigation of the active systems will be a subject of the future research.

4. Conclusions

Based on the research it can be concluded that the passive system is a good alternative to the active solar cooling system, as it can reduce the cooling demand. Thus, the produced power can be used for other heat reduction purposes in the building, such as an electrical control of the window shutters. The best passive system is chosen based on the outer conditions, such as outdoor air temperature. It is also very important to know what are the characteristics of the building and the ventilation system installed. Lightweight buildings with very little accumulation can be renovated with such systems. In this way, the energy consumption for cooling could be reduced. Thus, when the hours of high solar radiation occur, the energy can be used for other purposes.

It is important that the market offers a wide variety of the products with fine deviations in characteristics, such as melting points. Their availability is crucial for the efficient performance of the passive solution. They might even reduce the amount/capacity of the PCM needed, which can drastically reduce the renovation/installation costs. To guarantee and obtain their full potential, the PCM has to be completely solidified over the night time. The night time solidification has to be a subject of the further investigation. If not passively, the preferred active system for solidification purpose is the studied one. However, the energy consumed has to be minimal.

Another promising investigation is coupling the PCM layers in different combinations. The materials with different melting points combined on the same wall could benefit to the thermal performance of the PCM over the entire year (during the night time in summer and even during the heating season). Moreover, a detailed study of the active/passive system combinations has to be performed in order to find the algorithm for the optimum application of both systems.

5. References

Adekunle, T.O., Nikolopoulou, M., 2016. Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. Build Environment, 103, 21-35. DOI: 10.1016/j.buildenv.2016.04.001

Approved American National Standard and American Society of Heating and Air-Conditioning Engineers, 2013. ANSI/ASHRAE Standard 55-2013. Thermal Environmental Conditions for Human Occupancy. Atlanta: ANSI/ASHRAE.

British Standards, 2007. BS EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London: BSI.

DesignBuilder Software Ltd., 2017. Official webpage. [Online]. [Accessed 10 July 2017]. Available from: https://www.designbuilder.co.uk/

European Committee for Standardization, 1998. CEN CR 1752:1998. Ventilation for buildings – Design criteria for the indoor environment. Brussels: CEN.

European Parliament and Council, 2010. Directive 2010/31/EU of the EU Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union. Available from: https://eur-lex.europa.eu/eli/dir/2010/31/oj

HEART Horizon2020, 2017. [Online]. [Accessed 17 January 2018]. Available from: http://cordis.europa.eu/project/rcn/211645_en.html

Knauf Gips KG, 2018. Product Data Sheet Knauf Comfortboard 23: [Online]. [Accessed 10 July 2017]. Available from: http://micronal-pcm-app.de/files/2016-04-16_-_generic_heat_storage_capacity_comfortboard_23.pdf

Pajek L., Hudobivnik B, Kunič R., Košir M., 2017. Improving thermal response of lightweight timber building envelopes during cooling season in three European locations. Journal of Cleaner Production. 156, 939-952. DOI: 10.1016/j.jclepro.2017.04.098

Phase change Energy Solutions Inc., 2016. BioPCM. [Online]. [Accessed 10 July 2016]. Available from: www.phasechange.com/

Stropnik, R., Stritih, U., 2016. Increasing the efficiency of PV panel with the use of PCM. Renewable Energy 97, 671-679. DOI: 10.1016/j.renene.2016.06.011