An innovative PCM Storage System to enhance Building Energy Autonomy: experimental and numerical characterization

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Abstract. Even if the use of renewable energy sources towards autonomous buildings is promising, it is facing a fundamental issue: the shift between energy production and heating energy demand. We propose in this paper a thermally controlled storage solution using phase change materials integrated in the building walls. Its main advantage lies in the ability to activate on-demand the thermal discharge by ventilating the phase change materials. A test bench has been manufactured. Tests were performed which proved the feasibility of overnight storage with morning discharge allowing an internal air temperature increase of 5°C. Simulations based on experimental results showed that an integration in real buildings with photovoltaic energy production allows to significantly increase the building energy autonomy. If the improvement is important for all types of buildings, it showed larger absolute improvements for weakly insulated buildings than for buildings with an efficient insulation.

Keywords. Phase Change Material, building application, energy autonomy, thermal storage, active discharge, comfort temperature

1. Introduction

If Phase Change Material (PCM) has been successfully used for heat storage and in building temperature stabilization, an air conditioning fully based on PCM has not yet been developed. This is due to low PCM thermal conductivity [1, 2, 3, 4], a lack of simulation tools to optimize heat extraction [5] and in most use cases, the lack of control of the charge and discharge processes [6, 7]. The phase change materials are predominantly used passively with melting and solidification processes occurring once the building temperature is higher, respectively lower than the PCM fusion temperature. As such, on-demand heat discharges are not possible.

To achieve powerful and controllable heat discharges, we propose to ventilate thin PCM layers when required. We developed for that purpose a 4 m^3 testbed including PCM and measured its properties through various charge and discharge processes [6]. The results will be presented in this paper together with simulations of an integration in real buildings. They will also be used to evaluate the potential of PCM heat exchangers to store excess renewable energy during sunny days and to redistribute it as soon as required. As 80% of the building energy needs in central Europe corresponds to thermal energy, the proposed system drastically increases the autonomy of buildings with renewable energy.

2. New PCM active storage system and proof of concept

To actively control the charge, storage and discharge process, thin PCM layers thermally insulated from the rest of the building were placed between a heating circuit and a thin air layer (see figure 1). During the PCM charge and storage phases, the air stays still and the entire system remains thermally insulated. The discharge phase is activated by ventilating the PCM layers and redirecting the heated air towards the building's room.

2.1. Experimental set up

To prove the feasibility of the new methodology, a representative test bench shown in figure 1 has been designed and manufactured [4]. It is characterized by two rooms of 2 m^3 each, separated by a PCM wall and is equipped with a heating system that uses a pumped hot water circuit to load the PCM plates. These ones are made of a mix of limestone and “micronal” paraffin wax. The PCM low thermal conductivity is compensated by its integration in microcapsules, thus increasing the heat exchange surface. The main advantage of this implementation is that it presents no risk of liquid PCM leakage, since the paraffin is contained in a solid envelope. In order to characterize the test bench and obtain quantitative results, we measured the outside, the room and the PCM plates temperature using thermocouple sensors**.**

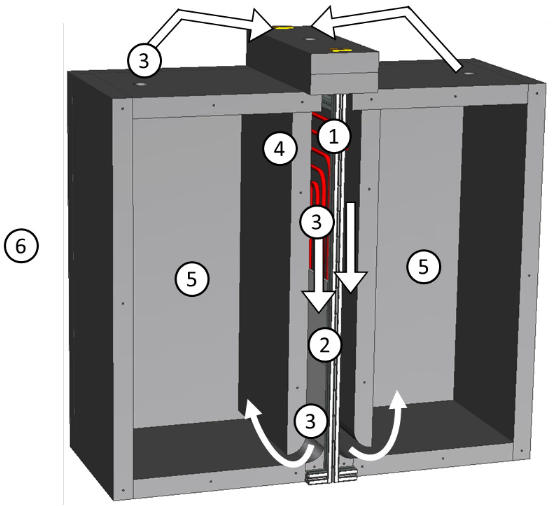

Figure 1. Testbed set up with a central heating circuit (1) and on both sides, PCM plates (2), an air flow path (3), an insulating layer (4) and a room (5). Sensors measure the temperature of PCM plates (2), the inside (5) and the outside ambient air (6).

Measurements of 24 hours with loading, storage and discharge phases have been performed (see figure 2). The PCM plates containing 5 kg micronal per m^2, were firstly heated up to 30°C during the afternoon loading phase. The second phase corresponding to the storage lasted from the evening to the early morning. During that time the PCM lost its temperature but remained liquid. At 5:00 in the morning, the discharge was initiated by ventilating the PCM plates with an air flow velocity of 0.1m/s. Despite the low PCM phase change temperature used in the experiment (23°C), high discharge efficiencies have been achieved. As shown in figure 2 the room temperature increased from about 15°C to 20°C in less than 40 minutes.

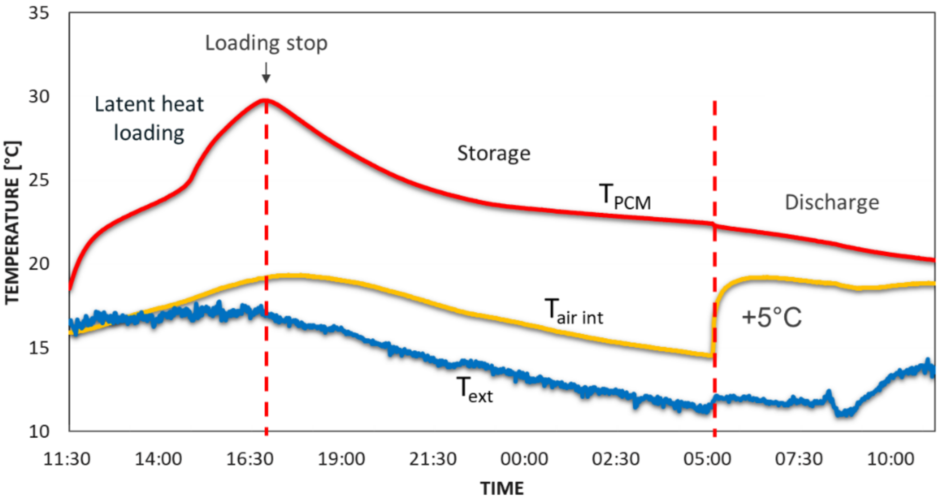

Figure 2. PCM loading, storage and discharge phases for a 24h cycle and temperature behaviour of PCM, indoor $T_{\text{air int}}$ and outdoor air T_{ext}.

2.2. Simulations

To understand the high efficiency achieved despite the low phase change temperature, we performed daily cycle simulations with PCM charge, storage and discharge phases for two different phase change temperatures: 23°C and 26°C. The PCM was integrated in the non-load-bearing walls of a two-floor building. The total PCM wall surface was equivalent to one half of a floor surface and the building had an external wall heat loss of 0.15 W/(m^2·K). As the current analysis concerned administrative buildings, an indoor air comfort temperature of about 20.5°C was maintained between 6:00 and 17:30 with potential lower temperatures overnight. Outside temperatures, T_{ext}, were simulated between -15°C and +10°C and considered constant during 24 hours. The PCM was heated with 12 kW for maximally 6.5 hours during the middle of the day. By using a heat pump with a Coefficient Of Performance (COP) of 3.3, a Photovoltaic (PV) production of 3.6 kW is sufficient. The simulation results are shown in figure 3 for PCMs with both phase change temperatures of 23°C and 26°C. Note that a ventilation of 0.05 m/s was used for the PCM of 23°C and natural convection for the PCM of 26°C.

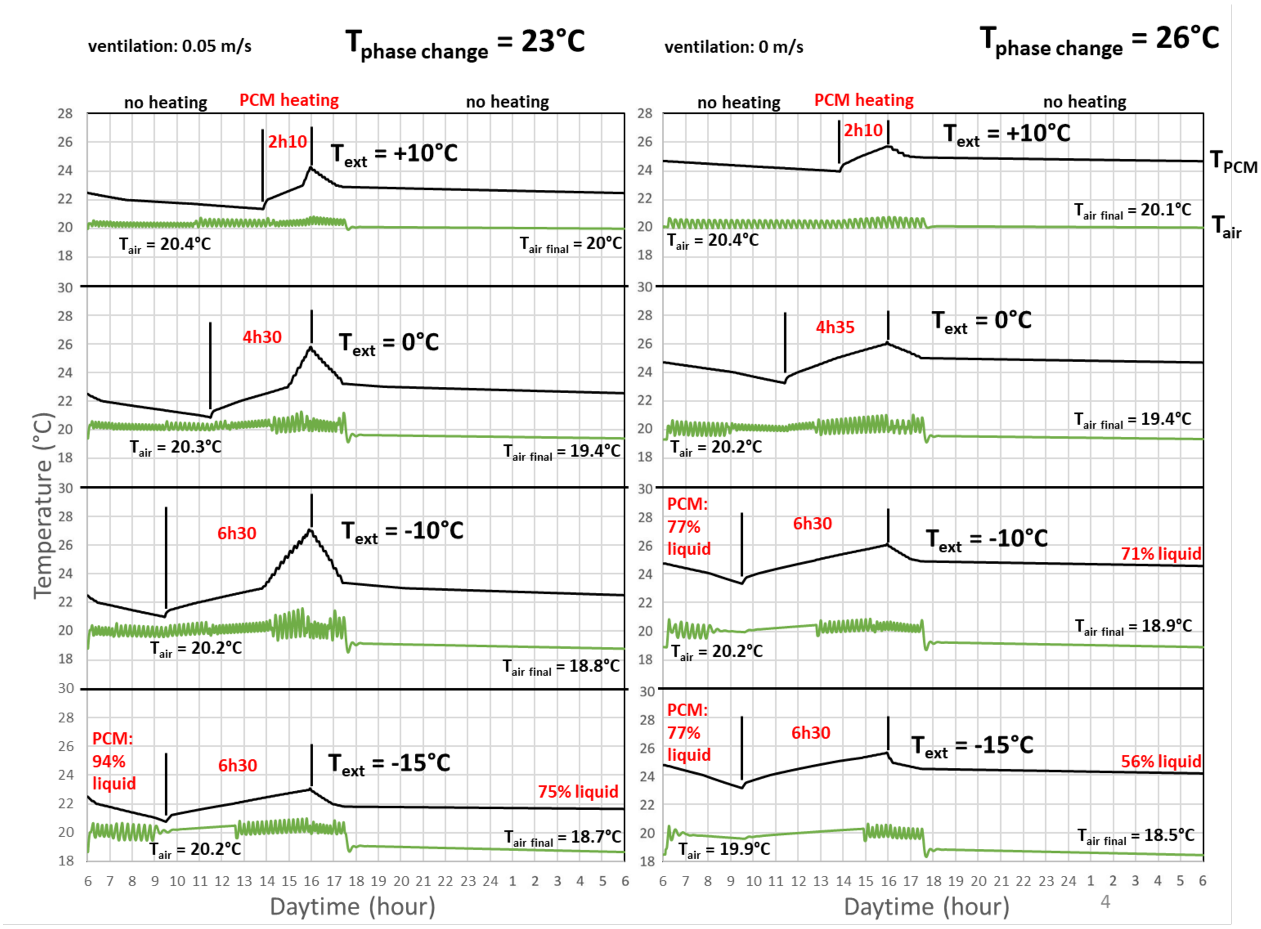

Figure 3. Indoor air and PCM temperatures with PCM loading at midday and discharge taking place between 6:00 and 17:30. The fluctuation of T_{int} is due to the controlled PCM discharge.

Interestingly, the indoor temperature, T_{int}, could be maintained at a comfort temperature for outside temperatures down to T_{ext} = -10°C for the PCM with a phase change temperature, $T_{phase\ change}$ of 23°C. For the PCM with $T_{phase\ change}$ = 26°C, the internal comfort temperature could only be maintained until T_{ext} = -5°C. In this case the building shows a thermal energy autonomy down to -10°C and -5°C with PCMs of 23°C and 26°C, respectively. Even if a larger efficiency for lower phase change temperatures could appear to be contradictory, it can be easily explained. The overnight storage phase is less efficient for PCM with higher $T_{phase\ change}$ due to their larger overnight temperature which is responsible for a larger discharge. In that respect, the bottom graphs of figure 3 with T_{ext}= -15°C show a daily PCM liquid phase loss of only 9% for $T_{phase\ change}$ = 23°C while a liquid phase loss of up to 21% is observed for $T_{phase\ change}$ = 26°C.

3. Enhancement of the building energy autonomy for the Swiss real estate

If the PCM storage leads to large improvements in the energy autonomy of efficiently insulated buildings, it remains interesting to study its effects for less insulated buildings. According to the data of the Swiss Federal Statistical Office, we can distinguish 3 types of buildings shown in Table 1.

Table 1. Swiss buildings types categorized according to their energy efficiency. Half of the buildings correspond to older buildings with an insulation approximatively 3 times weaker than the new energy efficient buildings.

Building	**Heating needs:** building + hot water (KWh/m^2 and year)
built until 1970 (50% of buildings)	150
Medium energy efficiency	80
High energy efficiency (Minergie standard)	45

As shown in the table, most of the energy consumption comes from the older buildings due to their quantity (50% of all buildings) and their weak insulation. These buildings are responsible for nearly 80% of the total real estate energy consumption. It is therefore important to analyse their potential gain in energy autonomy especially in the case photovoltaic energy production is combined with heat storage.

We used for that purpose the “MeteoSwiss data” average monthly temperature over the last 20 years for the city of Bern, and calculated the required heating energy for each building type. We took as reference medium size rental buildings with 300 m^2 PV panels and a heat pump with a COP of 3.3. By using the monthly average solar power of the city of Bern, we found as shown in figure 4, the average solar thermal energy production and the monthly heating energy needs for each building type. The figure 4 displays the total thermal energy needs during the day (from 6:00 to 18:00) and during the day and night (24 hours). Without energy storage, solar power can only be used during the daytime. With PCM heat storage, self-consumption becomes also possible at nighttime and a thermal energy autonomy is achieved if the daily local energy production is sufficient. This is visible in figure 4 when the total required energy (continuous lines for each building type) is below the PV driven heat pump thermal energy production. The buildings with the highest energy efficiency become totally autonomous, while the buildings with medium energy efficiency remain dependent on the grid energy during December and January. The less efficient buildings built until 1970 show an energy autonomy from March to October.

A summary of the energy autonomy with and without heat storage is given in figure 5. For each building type, the thermal energy needs and the self-consumption with and without PCM heat storage are displayed. The gain in energy autonomy due to heat storage is indicated by the arrows. Interestingly the maximal gain is obtained for the old buildings. Even if the most energy efficient buildings becomes autonomous all year long, their absolute energy autonomy gain remains lower.

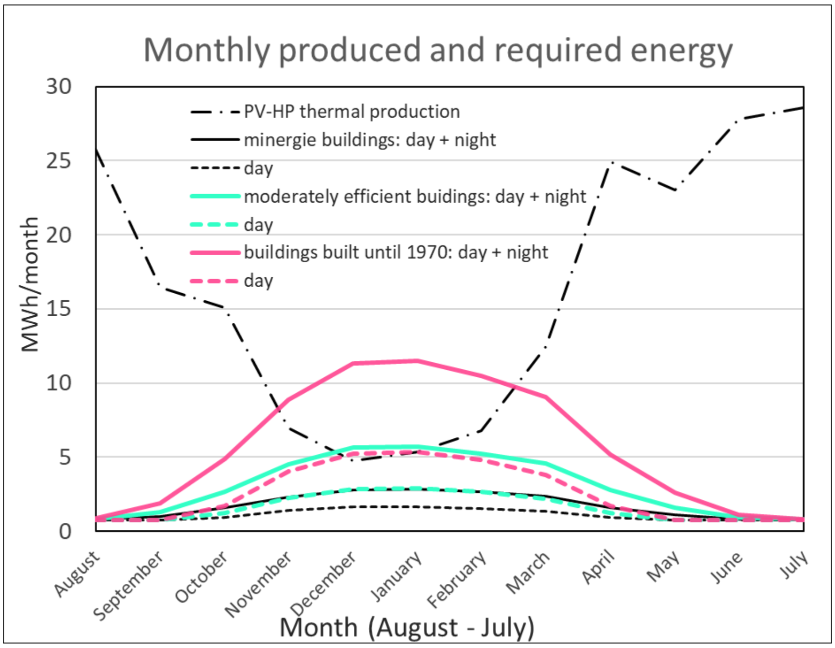

Figure 4. The graph displays the monthly total thermal energy production of a PV driven heat pump (HP) together with the thermal energy requirement of the buildings with low, medium and high energy efficiency. The continuous curves correspond to the total monthly thermal energy requirements while the dashed curves represents the same requirements but only during the day from 6:00 to 18:00.

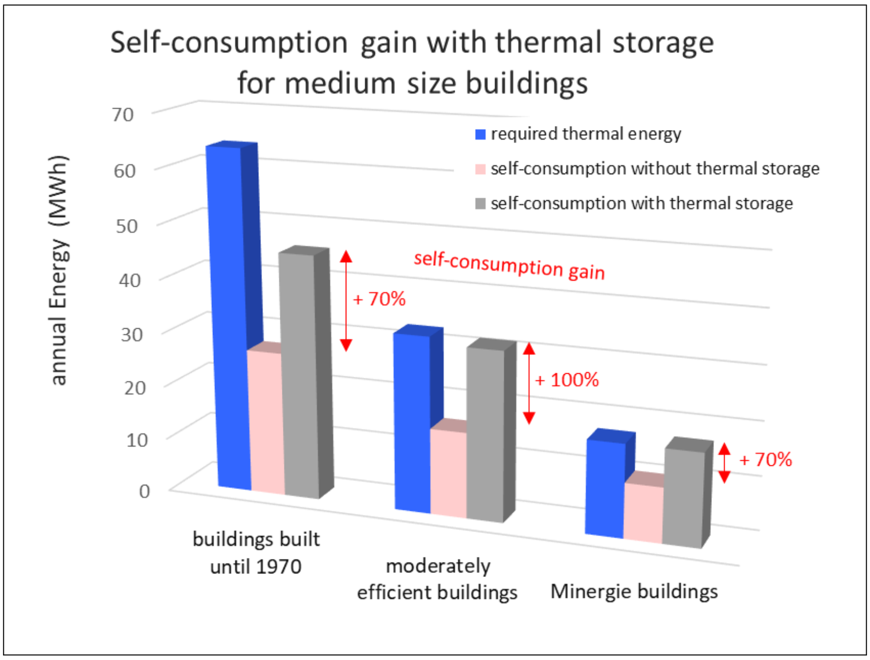

Figure 5. Annual thermal energy requirement for buildings built until 1970, medium and highly energy efficient building described in Table 1. The self-consumptions resulting of the use of photovoltaic energy are given for the three building types without and with heat storage.

4. Conclusion

Phase Change Materials can store a considerable amount of thermal energy and can significantly increase the energy autonomy of buildings with renewable energy production. However to achieve this, a full control of the charge, storage and discharge phases is necessary. This has been proved and accomplished in a 4 m^3 testbed where the heated PCM was thermally insulated and ventilated once required. By applying the testbed results to real buildings it was demonstrated that the PCM storage is sufficient to maintain comfort temperature for more than one day with temperature as low as -10°C. The improvement of energy autonomy has shown to be the most important for old buildings requiring 150 kW/m^2 heating. As those buildings correspond to about 80% of the total real estate thermal energy consumption, their energy autonomy improvement results in major reductions for the total real estate network power consumption. By combining for older buildings thermal storage, the improvement of thermal insulation, and the integration of renewable energy, this effect would be even stronger.

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