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A new heat and cold storage system to enhance the thermal autonomy of residential buildings

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Abstract. We integrated 18 kg of PCM in 80 cells of a plate heat exchanger which were placed between a water charge and an air discharge circuit fed by the air renewal. The 0.1 m^3 thermal battery can replace radiators to heat and cool, store heat and cold and perform air renewal independently for each room. The narrow PCM cells and the relatively large temperature difference between the PCM with fusion temperature of 25°C and the renewed air allowed to achieve average discharge powers of 300W and 440W for heating and cooling respectively. The integrated total heat and cold storage capacities were found to be 1.5 kWh and 1.8 kWh respectively. By replacing each radiator of a house with such a battery substantial thermal storage can be achieved. The liquid thermal battery, cooled with outdoor air of 17°C, completely solidified in less than 7h. This means that cool summer nights can charge the PCM to cool the room the following day.

1. Introduction

Renewable energies can be the solution to reduce fossil fuel consumption, but their maximum production is out of phase with the thermal energy demand of residential buildings (typically of one to three flats), which represents ~80% of their energy consumption in Central and Northern Europe. Thermal storage is one solution to compensate this energy production-consumption phase shift. We propose to combine Phase Change Material (PCM) [1, 2, 3, 4] with the air renewal [5, 6, 7] to store heat and cold and to increase the heating or cooling efficiency, respectively. The resulting thermal battery with dimensions of 0.8 x 0.5 x 0.25m can take the place of standard radiators and be connected to a dedicated small air renewal system. It can increase the thermal autonomy of a building equipped with solar power by decreasing its dependance on the grid or fossil fuel at night and during cloudy days.

2. Thermal storage state of the art

Even if thermal storage can be considered as the optimal solution for thermal needs, it faces important challenges. Heat loss is one of the major challenges of long-term storage systems. It can only be reduced with large dimensions, low temperature difference or high insulation. Depending on the solution chosen, the storage material may have low thermal conductivity which makes it difficult to achieve at the same time high storage density, high power extraction and low thermal loss.

Table 1 gives a summary of the most used thermal storage technologies with their advantages and drawbacks. Water thermal storage of various dimensions are compared with the building thermal inertia, thermochemical storage and PCM. Water storage is the most used solution is due to its price, low corrosion, high specific heat, easy heat transfer, fast heating responsiveness and maturity of the technology. However, it requires large volumes for seasonal storage and high temperatures for domestic hot water, forcing Heat Pumps (HP) to operate with a low Coefficient of Performance (CoP).

Heat storage with the building materials of the walls, slabs or ceilings can be considered as the cheapest one. It is however a passive solution that can counteract temporary fast heating/cooling needs and slow down the temperature reduction at night or when the building is unoccupied.

The thermochemical storage, still in the phase of basic research, has the highest storage density potential and relies either on sorption processes or on reversible chemical reactions [8]. The sorption processes require complex systems of condensers, evaporators, absorbate and solution storage tanks. The chemical reactions, used for high temperature generation, suffer from poor material stability and high operating cost [8].

Table 1 : State of the art for various thermal storage technologies for buildings showing the current positioning of PCM in respect to the other solutions. (*) As described below, HPs can work at lower temperature with PCM what increases the CoP.

Thermal Storage Method	price	price per storage capacity	storage density	thermal loss to storage ratio	increased CoP for HP	integrable in a home	material stability	maturity	(dis-) charge control	reactivity for fast heating	thermal conductivity of storage material	cooling potential	optimal for holiday building	seasonal capacity
Water (1 m^3)	low	medium-high	medium	high	no	yes	very high	mature	yes	high	medium	no	yes	no
Water (30 m^3)	high	medium	medium	medium	no	yes	very high	mature but rare	yes	high	medium	could be	large	yes
Building thermal Inertia	low	medium	---	medium	--	yes	high	mature	no	low	medium	yes	no	no
Thermochemical	very high	open	very high	inexistant	--	yes	low	basic research	yes	high	--	yes	--	yes
PCM	medium	medium	high	low	yes (*)	yes	high	early maturity	yes	high	low	yes	yes	yes

PCMs have been studied since the 1970's [1, 2] and benefit from an early maturity, high storage density and low loss. Its ability to store large amounts of heat at low temperature means that the use of air-water heat pumps can be limited to the hottest hours of the day, with small inlet-outlet temperature differences, resulting in a high CoP. It should be noted that PCM thermal storage can be optimally combined with solar power, as these periods of HP use often correspond to peaks in solar energy production.

PCM cannot transport heat in a circuit like water, has low thermal conductivity and can be corrosive. We can partially eliminate these drawbacks by placing non-corrosive PCM in metal Heat eXchangers (HX) that efficiently (dis)charge and transfer heat. The objective of the presented work was to build such a system in a room of an existing building and measure its thermal performances.

3. Thermal storage concept and operating modes

The largest market for energy optimized building being the renovation, our solution is proposed to replace existing radiators and at the same time provide the not existing air renewal.

The operational principle is shown in Figure 1. Preinstalled solar thermal or PhotoVoltaic (PV) panels with a HP heats the PCM of an air/PCM/water HX. As PCM cells are located between the air and water circuits of the HX, they are efficiently charged and discharged.

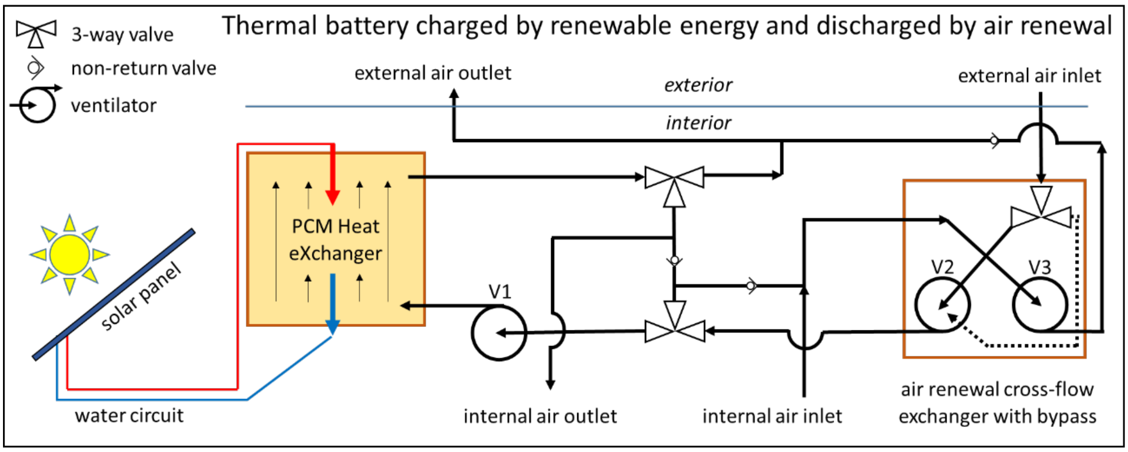


Figure 1: Schematic view of the thermal battery dedicated to a building room. The PCM Heat eXchanger (in orange) is connected to the air renewal system on the right through flow channels, fans and valves displayed in black. The water circuit, which can be the existing central heating circuit of a renovated home, charges the PCM and the ventilated air discharges it.

The displayed valves allow the system to work at charge, storage, discharge and free cooling modes with or without air renewal as presented in Figure 2. Replacing all radiators by thermal batteries and using the existing central heating circuit not only has economic advantages: it also provides substantial thermal storage and allows independent control of the temperature and air renewal of each room. This can be achieved by selecting the appropriate mode of Figure 2. PCM charge and discharge power can be set according to the thermal requirements of each room and the outside temperature; the air exchange rate can be determined according to the number of people in the rooms, possibly using CO_2 detectors. In this way, air renewal could be deactivated in unoccupied rooms.

The difficulty to achieve high heating/cooling power with PCM due to the small temperature differences is compensated by heating directly the external air as displayed in mode 2b. It is naturally related to heat loss coming from the cold outdoor air but the increased heating power does not create higher losses than conventional air renewal systems.

Another interesting aspect represents the free cooling. In summer, as soon as the external temperature is colder, the room free cooling mode (3b) can be activated with an air exchange without heat recovery by using the bypass illustrated with the dashed line. If the night temperature is low enough, the PCM can be solidified by ventilating it: this the PCM free cooling mode (3a).

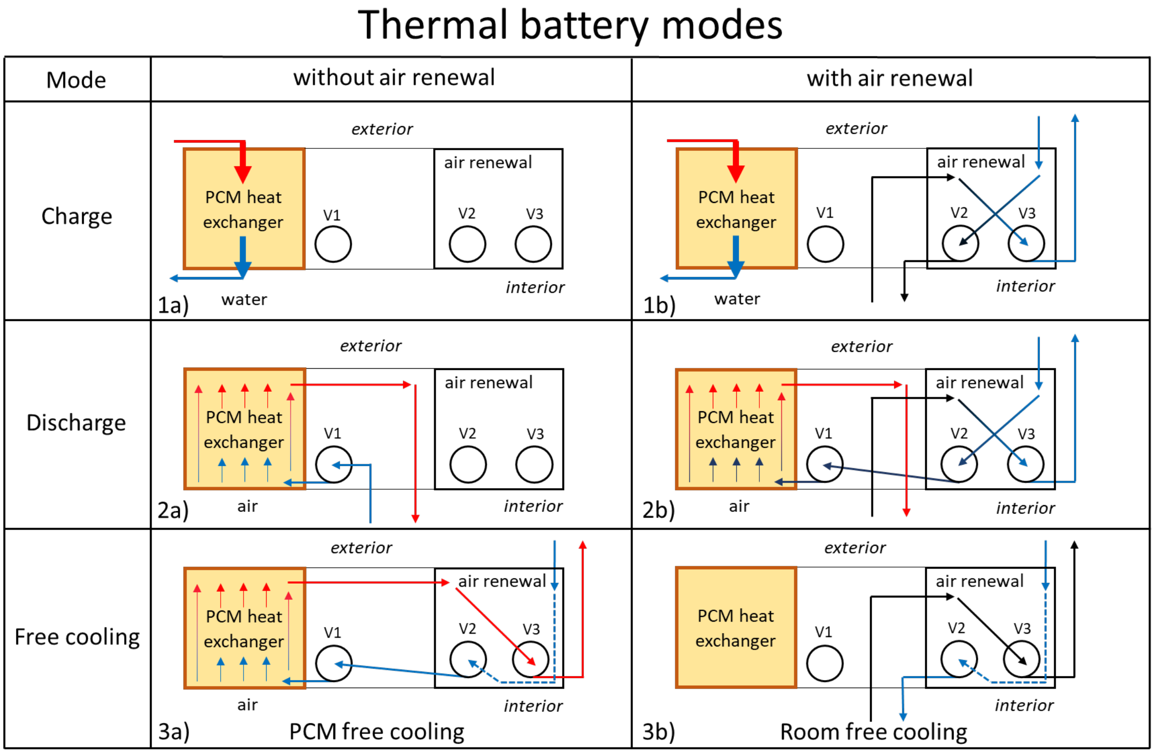


Figure 2. Operating modes of the thermal storage system a) without or b) with air renewal. Both heat and cold can be 1) charged or 2) discharged depending on winter or summer seasonal needs. Cool outdoor air on summer nights can be used to charge cold: 3a) PCM free cooling, or to cool the room directly 3b). Note that the storage mode without water and air circulation is not shown in the picture. For simplicity reasons, the flows are drawn without valves and flow channels.

4. Experimental setup

A prototype of the system described in Figure 1 was mounted in a 25m^3 room of a test house to measure its thermal properties in a real environment. A laboratory water heater/cooler (used to simulate solar thermal panels or HPs) charged the air-PCM-water HX. The PCM HX and the air renewal system of Figure 1 were placed below a window of the room.

The HX measuring 0.8 x 0.5 x 0.25m contains 18 kg of PCM with a fusion temperature of 25°C. It is a modified plate HX with a succession of water, PCM and air zones located between the plates [5]. The PCM cells of about 60 x 23 x 0.35 cm take 38% of the HX volume with the air and water circuits containing 20 and 10 liters respectively. Fourteen thermocouples were integrated to measure the air, water and PCM temperatures at the in-, outlet and within the HX. Water and air flow sensors were placed in both circuits to measure the air and water dis/charge powers and the storage capacity of the prototype.

5. Results

The hot and cold loads were performed with a water flow of 0.17 l/s. The water circuit was able to heat the PCM from 20°C to 40°C in less than one hour with a load power of 2kW. An air heat discharge shown in Figure 3 and corresponding to the mode 2b (Figure 2) has been tested with an incoming air flow of 19°C and ~ 70m^3/h. The discharge lasted about 6 hours starting with PCM at 40°C. The large temperature difference caused a high power of 600W at the beginning which stabilized at 240W after 2 hours. Integrating the power during the discharge process from 40°C to 21°C gave a total thermal energy storage of 1.5kWh.

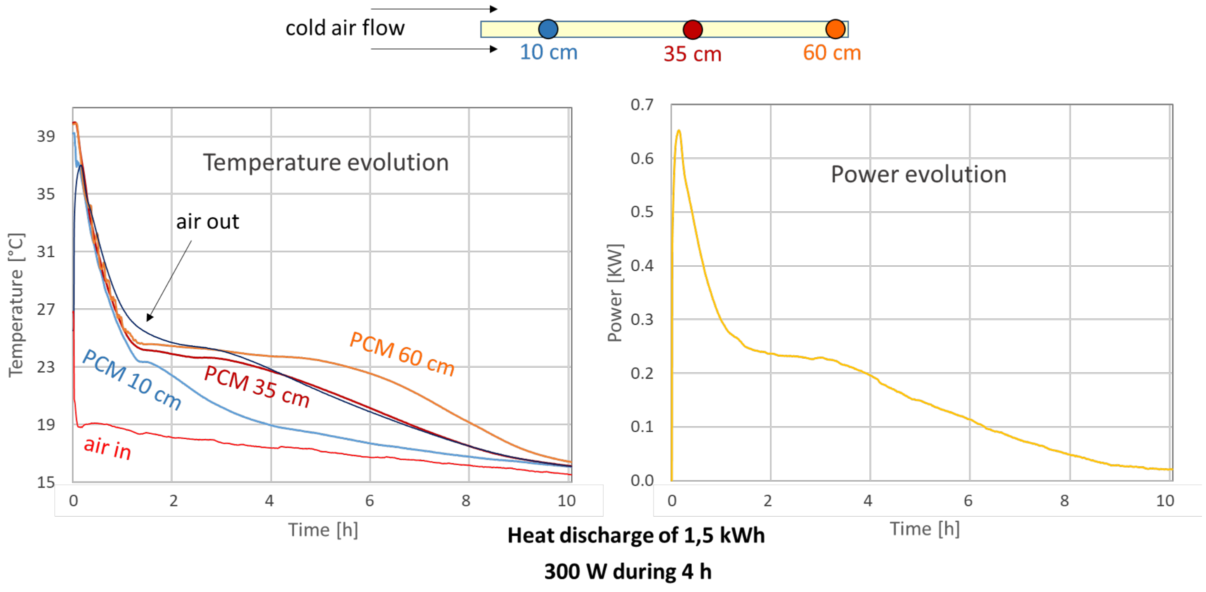
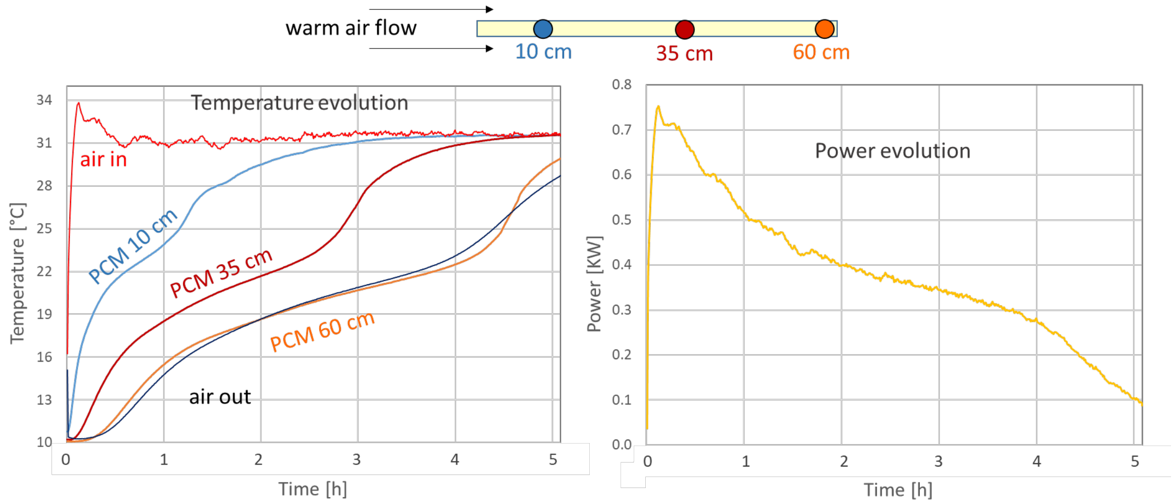


Figure 3 : Heat discharge with a ~70 m^3/h air flow. The three PCM temperature sensors situated along the air flow illustrate the discharge behavior within the HX. The air inlet and outlet temperature sensors show the strong decrease during the first hour and stabilization at 240W afterwards. The average power during 4 hours is 300W.

A cold discharge illustrated in Figure 4 has also been measured. An air flow of 40°C was directed towards the heat exchanger with PCM layers initially at 10°C. The HX was discharged in 4.5 hours with an average discharge power of 440W, a peak power at 750W after 15min and a cold storage capacity of 1.8kWh. The PCM temperature curves at positions of 10, 35 and 60 cm along the air flow show inflection points corresponding to the discharge time at 1h15, 2h50 and 4h30. Based on the temperature curves, we can estimate the latent heat load level corresponding to the percentage of liquid PCM at 85%, 45% and 0% for the three different times.

A pressure drop of 200Pa was measured between the entrance and exit of the PCM-HX. Basic calculation for flows between 70 and 100 m^3/h gives flow powers of about 6 W what is less than the power consumption of the ventilator of 13 W.



Cold discharge of 1,8 kWh

440 W during 4 h

Figure 4 : Cold discharge: it displays a larger storage capacity: 1.8 kWh, due to the solid sensible heat larger than the liquid one. Interestingly, the output air temperature is very close to the PCM temperature at 60 cm.

The last figure treats the PCM free cooling. It corresponds to a charge of cold by using an air-flow below the fusion temperature. It presents similar features as the heat discharge: a power lower than charges with water due to the lower air specific heat and a large storage capacity due to the large PCM solid state specific heat. Once again, the PCM temperature profile shows a cold front progressing through the storage material along the HX plates towards the air outlet. An airflow between 17°C and 14°C completely solidified the PCM initially at 30°C in less than 7 hours. This demonstrates that a PCM HX can be fully charged on cold summer nights to cool a room on the next day.

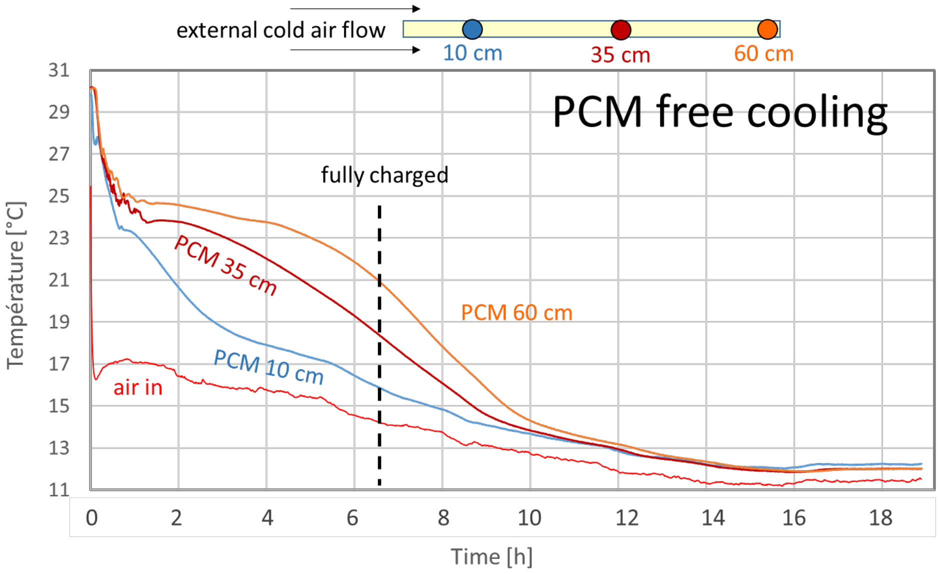


Figure 5 : PCM temperature behavior during a free cooling charge. Due to the low air specific heat compared to water, the charge needs 7 hours to fully solidify the PCM.

Conclusion

The charge and discharge processes have been tested on a new thermal battery made of an air-PCM-water plate HX and connected to air renewal and water circuits. The water circuit can solidify and melt the 18 kg of PCM in less than an hour. Heat and cold air discharges of 70m^3/h were respectively performed in 6h and 4h30 with powers of 300W and 440W. The solution is ideal for renovation as these powerful thermal batteries can replace the radiators and use the existing central heating.

The large power can be explained by to factors:
1) the use of outdoor air for the discharge resulting in a greater air-PCM temperature difference.
2) the narrow PCM cells assuring an efficient heat transfer towards the metal plates of the HX despite their low thermal conductivity of 0.16W/(m.K).
The strength of the proposed system lies in its simplicity and versatility which stems from the presence of both water and air circuits interacting directly with the PCM. It performs thermal storage for heating and cooling, air renewal with heat recovery or without by using a bypass channel, and can store by free cooling the cold of the summer night to refresh the room on the following day. To the best of our knowledge, a single system enabling all these modes has not been yet realized. The published systems investigated use either PCMs integrated in air channels [7] or in water circuits [9] with specific applications such as free cooling and air conditioning for the first approach and thermal storage for water heating for the second one.

As the prototype was based on a commercial off-the-shelf water-water HX, it is not optimised to contain the largest volume of PCM. Optimized batteries with a length of 1.6m and storing 4.5 kWh with 50 kg PCM are being built now. By replacing 11 radiators of a typical single-family home with those thermal batteries, one can achieve 50kWh of thermal energy storage. This capacity can be charged with daily solar overproduction to heat such buildings at night and on cloudy days, and thus reasonably reduce their use of grid energy or fossil fuels.

Acknowledgments

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