Building energy autonomy increase through thermal storage: numerical and experimental analysis of PCM storage systems for hot water and air temperature control

Jacques Robadey, Dominique Voide, Simon Rime

Energy Institute, University of Applied Sciences of Western Switzerland, Pérolles 80, 1700 Fribourg, Switzerland, +41 79 211 89 72, jacques.robadey@hefr.ch

Abstract. Thermal storage is one solution to efficiently use the renewable energy. In this paper we analyze the impact of thermal storage on the building heating and domestic hot water autonomy in the case of local renewable energy production. To be relevant, various building types have been investigated. We proposed earlier a PCM storage solution [1] that solved the efficient heat extraction challenge for building heating [2] [3]. In this paper, we present the first results of a PCM storage system for domestic hot water with measurements of discharge heating power in line with computational fluid dynamics simulations. A comparison of both heat storage systems is however not possible because of their different structures. In order to compare the efficiencies of the PCM discharge for hot water production and air temperature control, we have designed a new PCM heat exchanger that can be used in both cases. Its structure consists of several PCM layers sandwiched between loading and discharge layers. By circulating air or water in the discharge circuit, the heat exchanger can be used for heating air or water, respectively. For both use cases, a three-dimensional analysis of the phase change and calculations of the charge/discharge powers were performed for the fusion and solidification processes. We obtained heating discharge powers ≥ 2.6 kW/m^3 for 8 hours for air and ≥ 65 kW/m^3 for 13 minutes for water with a respective total storage capacity of 28 kWh/m^3 and 37 kWh/m^3. The heat extraction of air and water flows and their time dependence are discussed according to the percentage of liquid PCM and the temperature profile of the discharge flow inside the heat exchanger.

Keywords: Phase Change Materials, Building energy autonomy, thermal energy storage, domestic hot water, air temperature control, microencapsulated PCM, PCM discharge power, computational fluid dynamics

1 Building energy autonomy simulations

Three types of middle size buildings with different insulation properties and representative of the Swiss real estate have been compared: 1) buildings built before 1970, buildings with 2) medium and 3) high energy efficiency (that follow the Swiss “minergie” standard). Their respective thermal needs for hot water and building heating was 150, 80 and 45 KWh/m^2. All considered buildings were equipped with 300 m^2 photovoltaic (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 the average solar thermal energy production and the monthly heating energy needs for each building type (figure 1a). This figure displays the total thermal energy needs during the day from 6:00 to 18:00 and during the day+night. With energy storage solar power, can be used at night-time and thermal energy autonomy is achieved when the daily PV production is sufficient. This is visible in figure 1a when the total required energy (continuous lines for each building type) is below the PV driven heat pump thermal energy production (in yellow). The most energy efficient buildings become totally autonomous, while buildings with medium energy efficiency remain dependent on the grid energy in December and January. The less efficient buildings built until 1970 show an energy autonomy from March to October.

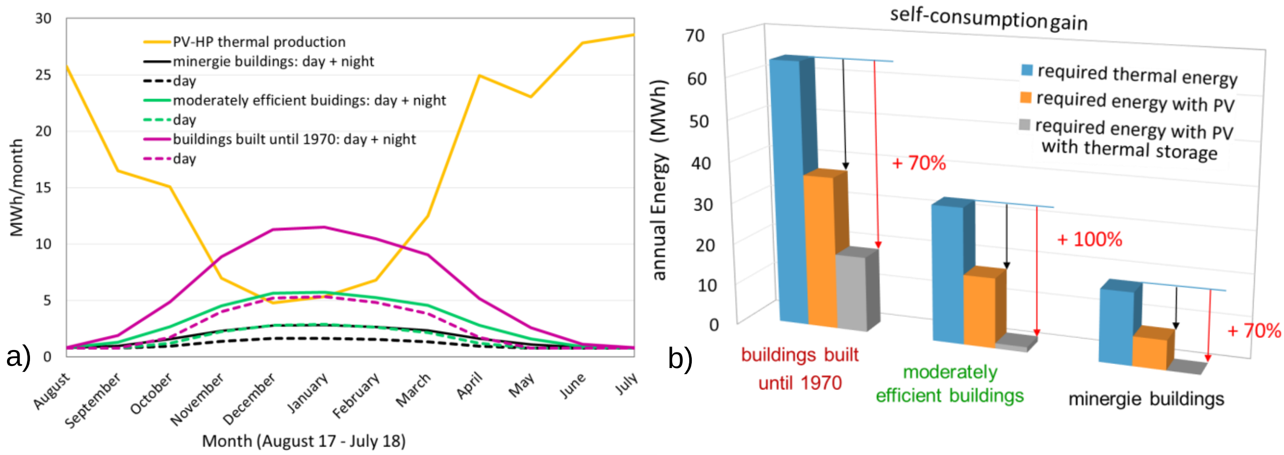

Figure 1: a) Monthly PV driven thermal energy production and thermal needs for differently insulated buildings. b) For all buildings equipped with PV panels, thermal storage increases the self-consumption of the thermal needs by at least 70% as shown by the red and black arrows.

A summary of the energy autonomy with and without heat storage is given in figure 1b. For each building type, the thermal energy needs (from the grid) and the self-consumption with and without PV panels and 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 become autonomous all year long, their absolute energy autonomy gain remains lower.

2 PCM storage system for air temperature control

We propose a new system based on PCM layer(s) placed between two circuits: one for loading and the other for discharging, which makes on-demand activation of the charge and discharge processes possible. Such a system was developed with a 4m^3 test bench displayed in Figure 2, which was repeatedly loaded and unloaded to study its thermal properties [1] [4]. The developed test bench used an internal wall as a storage element. Microencapsulated PCM (Micronal) was used and integrated in plasterboards in the center of the insulated wall. The PCM boards could be heated by a water circuit and thermally discharged by ventilating the interior of the wall.

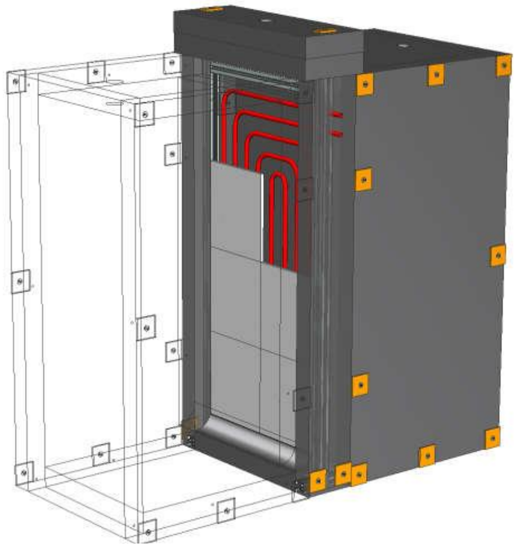

Figure 2: Illustration of the 4 m³ test bench. The loading water circuit is represented in red, and the PCM plates in light gray.

Figure 3 shows a daily cycle with the loading, storage and discharge phases. PCM was heated up to 30°C during the afternoon. Its temperature slowly decreased during the overnight storage phase due to an outdoor temperature of approximately 12°C before stabilizing at its melting temperature of 23°C. The discharge activated early in the morning by ventilating the interior of the PCM wall allowed an increase of the testbed air temperature from 15°C to 20°C in less than 40 min [1].

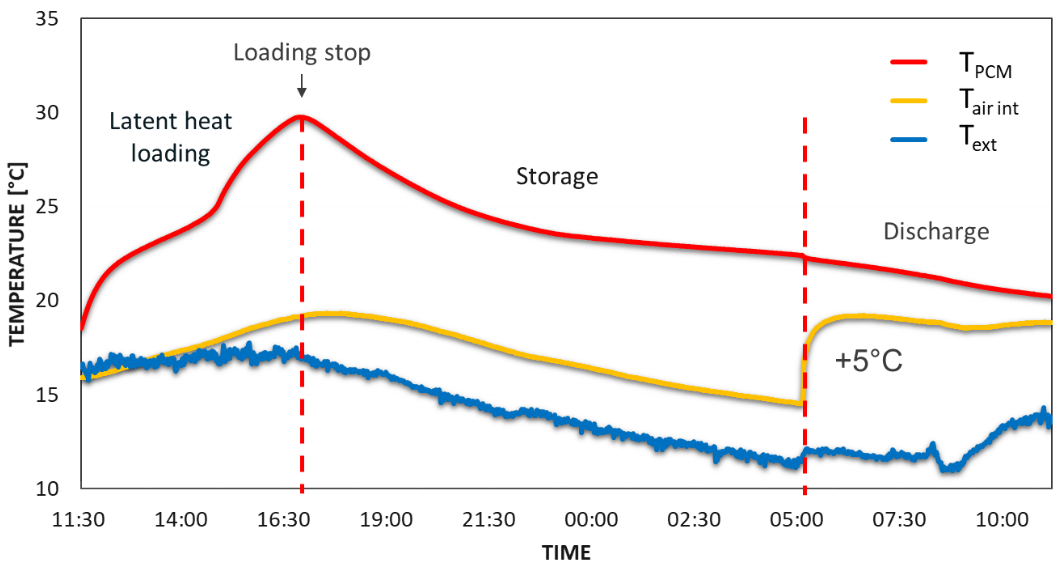

Figure 3: PCM loading, storage and discharge phases for a 24h cycle and temperature behaviour of PCM, interior and exterior air.

3 PCM Storage System for domestic hot water

As hot water is a major energy consumer for all types of buildings, we simulated, planed and realized a thermal storage prototype for domestic hot water. The 226x266x1900 mm device contains 50 liters of Rubitherm RT44HC PCM with fusion temperature: T_{fusion} of ~43°C. A cross-section of the device during the discharge phase is shown in Figure 4a based on the results of Computational Fluid Dynamics (CFD) simulations. The metallic structure and the discharge (or charge) water circuit are displayed in white. The liquid PCM (red) gradually changes its color according to its solidification. The image shows a homogeneous solidification process taking place at a specific distance from the cooling surfaces. Simulations have shown that the discharge (charge) power strongly depends on the size of those surfaces.

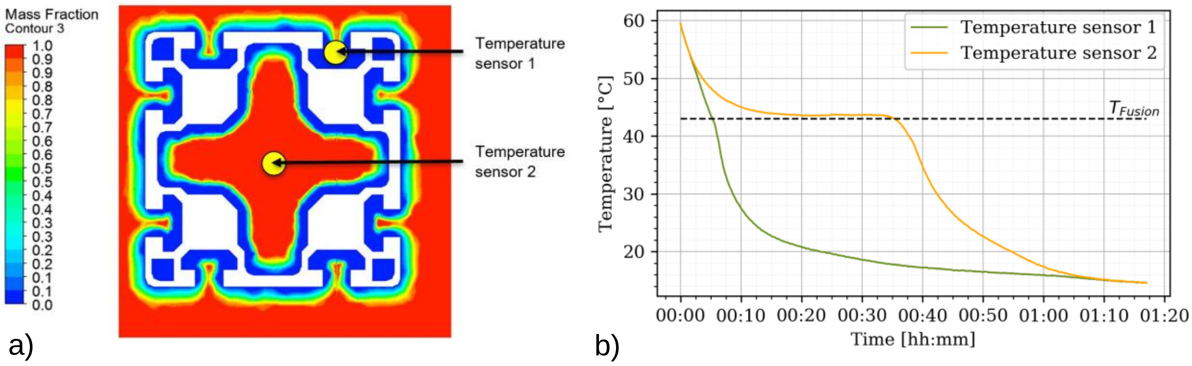

Figure 4: a) Distribution of PCM solid (blue) and liquid (red) phases after 10 minutes of discharge.
b) PCM temperature during discharge for the two temperature sensors displayed in figure 4a.

Preliminary measurements have been realized during the discharge process with a water flow of 28 l/m and an initial PCM temperature of 60°C. The temperature of the two yellow points displayed in figure 4a are shown as a function of the discharge time in figure 4b. At short distances (< 1cm) from the metallic surface, the solidification process takes place after 5 minutes of cold-water flow ($T < T_{fusion}$). The temperature curve of the PCM central part (temperature sensor 2) shows a solidification process only appearing after 10 minutes but lasting for about 25 minutes. The simulations indicate that the PCM solidification can provide large heating power > 10 kW but only for 5 min and after 20 min the power drops to 5 kW. This may be due to the structure with part of PCM located too far from the metallic surfaces. The integration of the heating power gave a PCM storage capacity of about 4 kWh.

4 PCM structure that can be used for air temperature control and domestic hot water

For building applications phase change materials must be encapsulated to prevent leakage and increase heat transfer rate. Two solutions are available for this purpose: microencapsulation where tiny PCM particles are embedded in a protective coating and macroencapsulation with PCM containers usually larger than 1 cm [5]. The choice of encapsulation depends on PCM use. For an integration in the working fluid of the heating circuit, microencapsulated PCM slurry could be used. High heat transfer coefficients have been reported [6], but large PCM slurry thermal storage tanks are required. In the case of passive thermal storage, integration of microencapsulated PCM in concrete, plaster wallboard, ceiling and floor is ideal [5] [7]. The lower PCM content is compensated by the large size of the storage elements. However, if the PCM must be integrated in a smaller volume such as small size heat exchangers, a macroencapsulation within the exchanger is advantageous.

We propose therefore a new PCM heat exchanger structure with macroencapsulated PCM that can be either used for air temperature control or for hot water production. The advantage of using the same structure for different purposes is to be able to perform simulations on the same basis to then define the adaptations to be made for each use case.

A horizontal cut of the structure is illustrated in Figure 5. As for the previous structure of Figure 2, it consists of vertical layers with a loading fluid circuit surrounded on both sides by PCM layers and discharge fluid layers. In the new design, this layering is repeated five times. This compensates the reduction of the device size. Another main difference consists of the aluminum structure separating the different layers, which not only allows the macroencapsulation of PCM, but also increases the heat extraction surface between PCM and both loading and discharge layers.

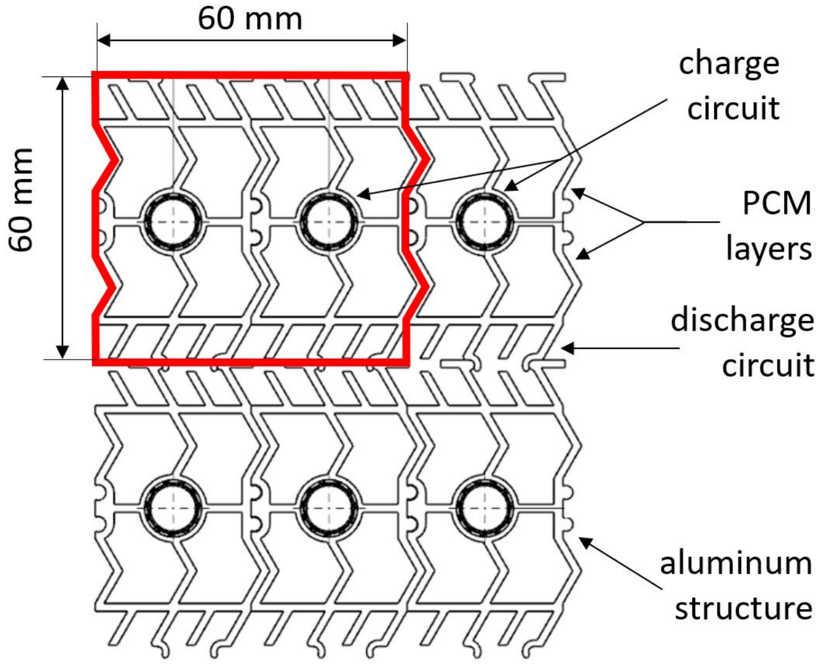

Figure 5: Horizontal cut of the new PCM heat exchanger. The water charge circuit is surrounded by PCM. In the discharge circuit an air or water flow is used for air temperature control and hot water generation, respectively. The red line delimits the cell used for the simulations.

The discharge circuit and the PCM type of the new structure determine if it can be used for hot water production or for air temperature control. In the case of hot water, the discharge circuit is a water circuit and the PCM has a melting temperature of 43°C. For air temperature control, PCM with a melting temperature of 23°C is used with an air discharge circuit. The resulting devices are a water-PCM-water heat exchanger for hot water production and an air-PCM-water heat exchanger for air temperature control.

While the thermal storage device for hot water is dedicated to an entire building, the storage devices for air temperature control are dedicated to one room or less. The size of the PCM heat exchangers must therefore be adapted but the basic structure displayed in Figure 5 will remain the same.

5 Simulations of PCM charge and discharge for hot water and air temperature control

We performed charge and discharge simulations of the PCM heat exchanger for the two use cases of air temperature control and hot water production using the ANSYS CFD modelling tool for a cell illustrated in Figure 5. To our knowledge, this type of analysis has not yet been carried out.

5.1 Charge process

The charge was performed by a 3 l/min water flow of 35°C for air temperature control and of 50°C for domestic hot water, flowing through a heat exchanger of a height of 0.5m. The PCMs were PureTemp 23 and Rubitherm RT44HC with fusion temperatures of 23°C and 43°C and heat storage capacities of 201 kJ/kg and 250 kJ/kg, respectively. The increase of the PCM liquid phase during the charge process is illustrated in Figure 6.

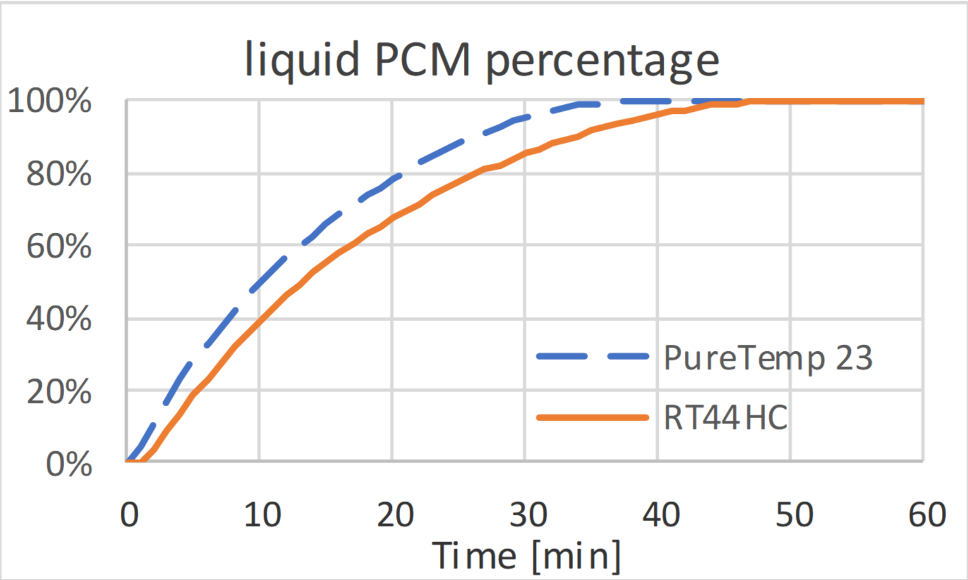

Figure 6: Percentage of the liquid phase during loading for the PCMs used for air temperature control (dashed line) and hot water (continuous line).

The slower fusion of the RT44HC PCM shown in Figure 6 is due to its larger heat storage capacity, the larger temperature increase between its starting temperature and the fusion temperature, as well as the lower difference between the PCM fusion temperature and the loading circuit temperature (7°C instead of 12°C for the PureTemp23 PCM). Despite this difference in loading speed, the behavior of both PCMs was similar.

Figures 7 shows the evolution of the fusion process during a charge of 40 min.

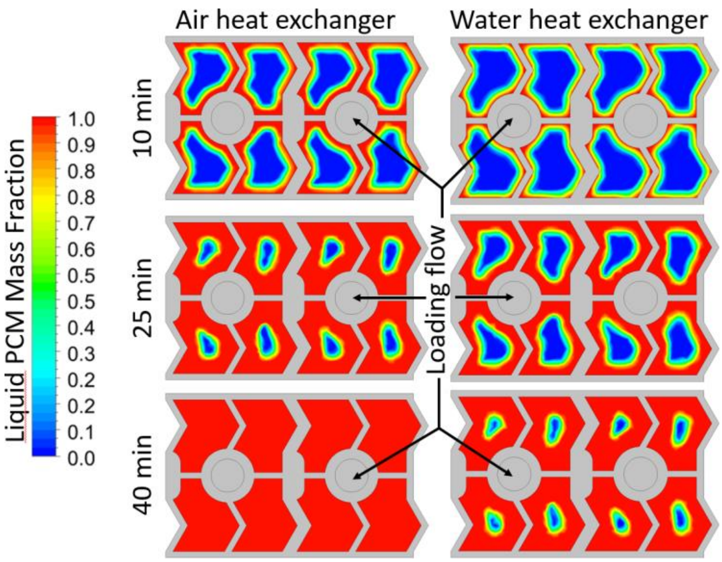

Figure 7: Proportion of liquid PCM after 10, 25 and 40 min of charge just before the exchanger exit. The starting temperature is 22°C and 30°C for PCM melting temperature of 23°C and 43°C for the air and water heat exchanger, respectively. Note that only charge and PCM layers are shown.

5.2 Discharge process

The discharge was carried out by air and water circulating at 0.75 l/min through a 0.5m and 2m high heat exchanger cell (Figure 5), respectively. In the first case the chosen incoming air temperature is 11°C as it is considered to be the fresh air from the air renewal system. For the hot water case the chosen water temperature was also 11°C. Note that the PCM temperature at the start of the discharge was at the melting temperatures of 23°C and 43°C, respectively.

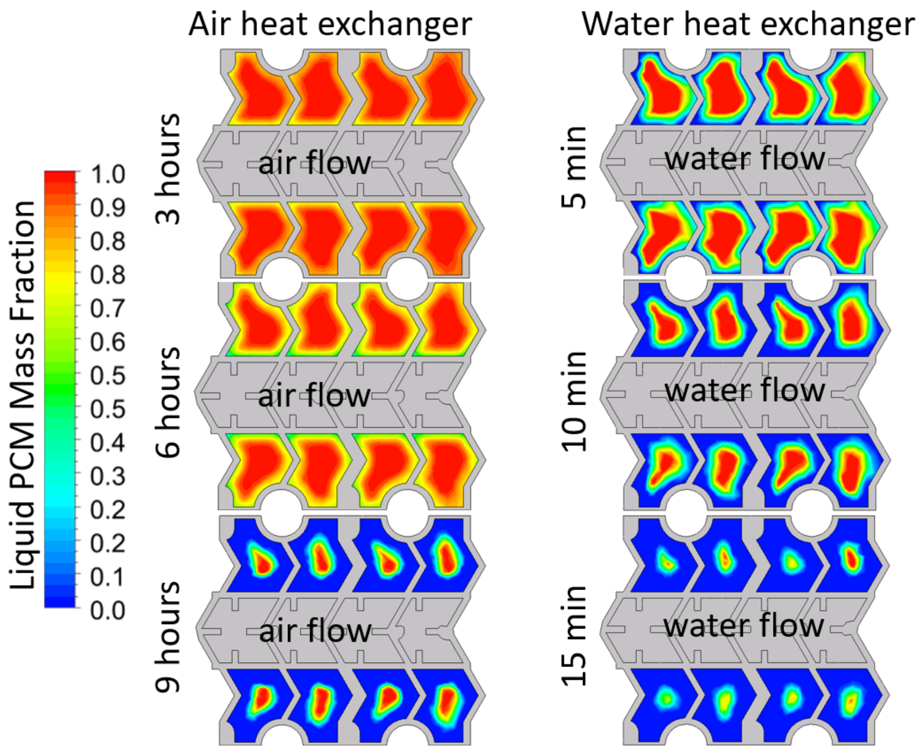

Figure 8: Evolution of the liquid PCM proportion after discharges of 3, 6 and 9 hours for air heating and of 5, 10 and 15 min for water heating. Discharge and PCM layers are shown.

Figure 8 shows the gradual reduction of the PCM liquid phase caused by the flow of fresh air or water through the grey area just before the heat exchanger exit. One can observe a discharge about 40 times faster for heating water than for air heating. This is mainly due to the large difference between the volumetric heat capacity of air and water.

Figures 9a and 9b describe the heating power of one cell as a function of time for both air and water heating. As a heat exchanger of 1.5m x 0.3m x 0.5m is made of 125 cells, the simulation indicates that an air heating power larger than 600W can be maintained for 8 hours. By considering the dimensions of the exchanger, it corresponds to heating power densities of 2.6kW/m^3 with a storage capacity of 28kWh/m^3.

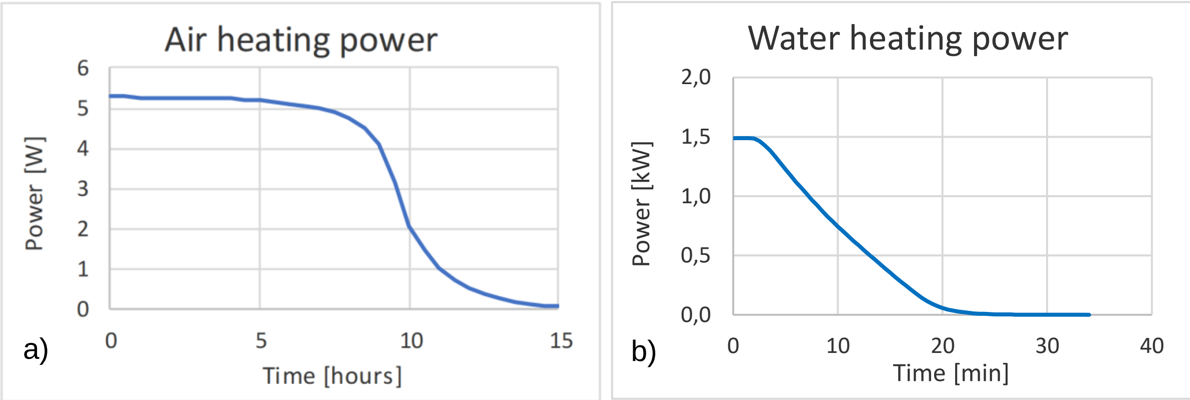

Figure 9: Discharge power of one cell of a) the air-PCM-water heat exchanger and b) the water-PCM-water heat exchanger b)

The water heating power is much larger due to a better heat transfer and a heat exchanger height of 2m. By using 50 cells with a dimension of 0.6m x 0.3m x 2m (L, W, H), a heating power ≥ 23.5 kW could be achieved for about 13 min. This corresponds to 65kW/m^3 with storage capacity of 37kWh/m^3.

The constant reduction of the power only observed for the water discharge can be explained by the different fluid temperature profile in the heat exchanger. At the start of the discharge, the air flow reaches its maximal temperature (which is close to the PCM fusion temperature) before leaving the heat exchanger. The point where the maximal temperature is reached moves toward the exit of the exchanger during the discharge. As displayed in Figure 10a, after one hour of discharge, the air flow temperature reaches its maximum after approximatively 35 cm and remains stable thereafter. After 5 hours the maximal temperature is reached at the exit of the exchanger and the power, displayed in Figure 9a, begins to drop. In the case of the water heat exchanger illustrated in Figure 10b, the flow reaches its maximal temperature before the exit of the exchanger only during the first 3 minutes. As displayed in Figure 9b, the power remains constant during that time and decreases continuously afterwards.

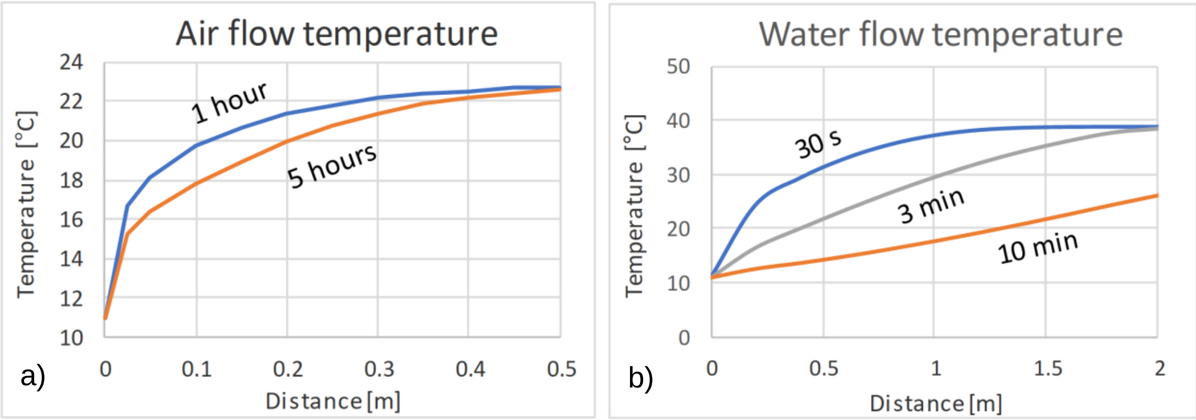

Figure 10 a) Air flow temperature profile after one and five hours of discharge.
b) Water flow temperature profile after different discharge times.

6 Results discussion

The proposed structure can be either used for air or for water heating but the efficiency of the water discharge rapidly decreases even for a heat exchanger height of 2 meters. As the power is larger than 20kW and the total thermal storage is 13kWh, it however satisfies the hot water demand of a single-family home. The simulated discharge power of the proposed structure is in line with the measurements of a water-PCM heat exchanger of similar dimension.

The simulated PCM air heat exchanger showed a discharge power of 600W for dimensions of 1.5m x 0.3m x 0.5m that lasts for 8 hours with a storage capacity of 6.3kWh. The low power can be explained by the non-optimized structure for air flows. A larger exchange surface between PCM and air layers is necessary, which can be achieved by adding new air channels in the PCM layers. A higher PCM fusion temperature and a slightly larger heat exchanger would also increase its power. By doubling the power of such heat exchangers and integrating them into the rooms of a well-insulated building ($U \leq 0.2 W/m^2K$), the discharge heating power would be sufficient for temperatures down to -5°C with a storage capacity allowing a thermal energy autonomy of 1.5 day [4]. Experimental works should be realised in the near future to check the validity of the simulations and further optimize the storage device.

Note that if sufficient heating powers could be obtained with PCMs with a melting temperature of 23°C, they could also be used for cooling. As we proposed to use air renewal to ventilate the PCM heat exchanger, such a system could perform heating, cooling, heat and cold storage as well as air renewal. This opens up new perspectives in the field of heating, ventilation and air-conditioning for new and renovated buildings.

Conclusions

Thermal storage is a key solution to increase the energy autonomy of buildings equipped with solar panels. We propose therefore different PCM structures to store heat for hot water and air temperature control. A PCM integration in building walls or in heat exchangers of 0.35 m^3 placed in the radiator locations can allow by its discharge sufficient heating for well-insulated buildings. To this end, the proposed structure must however be further optimized by the addition of new air channels. Water PCM heat exchangers of the same volume can also be sufficient for individual houses. The efficiency predicted by the simulations must still be verified by in situ experiments and costs calculations must be made comparing the PCM devices with large water tanks.

The relatively low temperature required to load the air PCM heat exchanger makes the use of heat pumps advantageous. Interestingly, the PCM heat exchanger for domestic hot water has the advantage of heating cold water directly before consumption. This could prevent the occurrence of salmonella without necessitating high temperature water heating. The use of PCM heat exchangers is therefore promising for both air temperature control and hot water production. However, the same structure cannot be used optimally for both applications and requires adaptations for each of them.

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