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PCM thermal energy storage in buildings: experimental study and applications

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Abstract

The study aims at analyzing the performance of Phase Change Materials (PCMs) in residential housing for different climates. This paper presents the results of an experiment performed in the Concordia University Solar Simulator and Environmental Chamber research facility (SSEC, Montreal, Canada). PCM boards were embedded on the back wall of a test hut placed in the climatic chamber. Several experiments were performed to explore the potential for verification of the proposed analysis and to produce enough data to perform model calibrations. Results show a strong increase in the apparent thermal inertia of the room allowing for a reduction in daily temperature fluctuations in the test hut. Simulations were carried out by means of a calibrated EnergyPlus model to broaden the analysis in both a cold Canadian climate and in a Mediterranean temperate climate. Other configurations for the setup environment were studied to simulate the issues of very hot summers in Mediterranean climate. The different configurations ended up with mixed results for the two locations analyzed: the maximization of the solar gains and its storage in a high density multiple layer PCM wall is the better configuration for the cold climate analyzed, while its performance is non optimal for hot climates where the “emulation” of high thermal mass walls by PCM in lightweight structures requires a different positioning of the PCM panels.

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Keywords: Phase-change materials, Building simulation, EnergyPlus, Model calibration

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1. Introduction

As energy accessibility and demand often do not match, thermal energy storage plays a crucial role to take advantage of solar radiation in buildings. Building integrated thermal energy storage systems [1, 2] cover a wide range of materials and techniques, and solutions depending on technology applications and aims. They however all have in common this underlining concept: being able to store excess energy for later use in order to reduce the time mismatch between energy availability and demand. Latent heat storage via phase-change material (PCM) is particularly attractive due to its ability to provide high energy storage density. Several studies have demonstrated that the use of PCMs in well-insulated buildings can reduce heating and cooling energy in residential buildings by as much as 25% and obtain similar reductions in the peak power required for air conditioning [3-5]. Such applications are of interest since they would have lower space requirements than most sensible systems and may be used in contexts where the application of standard solutions would be difficult, such us in renovation of historical buildings. On the other hand however, it is required to design with care since although the storage capability of PCMs is higher than common construction materials, daily charge-discharge cycles must be carefully planned.

Different PCMs are commercially available varying in type (salts, paraffins, fatty acids), encapsulation technology (micro and macro encapsulation), and melting temperatures (18-40°C). PCMs represent a potential solution for reducing peak loads and heating, ventilation, and air conditioning (HVAC) energy consumption in buildings. The use of latent energy storage systems may be one of the solutions to the energy mismatches in Net-Zero Energy Buildings [6, 7] when renewable energy production and building energy demand are out of phase. A building integrated and distributed thermal storage could shift part of the load of residential air conditioners at peak to off-peak time periods. As a result, capital investment in peak power generation equipment could be reduced for power utilities and then the savings could be passed on to customers. Areas where power utilities are offering time of day rates, building integrated thermal storage would enable customers to take advantage of lower utility rates during off peak hours.

The study aims at analyzing the performance of Phase Change Materials (PCMs) in residential housing for different climates. Several experiments were performed to explore the potential for verification of the proposed analysis and to produce enough data to perform model calibrations. Deviations from monitored results are analyzed and reported as error analysis. Simulations were carried out by means of a calibrated EnergyPlus model to broaden the analysis in both a cold Canadian climate and in a Mediterranean temperate climate investigating different configurations of geometrical, architecture and thermo-physical features of the test room.

Nomenclature

i	node being modelled
i_{+1}	adjacent node to interior of construction
i_{-1}	adjacent node to exterior of construction
j_{+1}	new time step
j	previous time step
Δt	calculation time step
Δx	finite difference layer thickness (always less than construction layer thickness)
C_p	specific heat of material
k_w	thermal conductivity for interface between i node and i+1 node
k_e	thermal conductivity for interface between i node and i-1 node
ρ	density of material

2. Experimental setup and modeling

The study describes the results of an experiment performed in the Solar Simulator and Environmental Chamber (SSEC) research facility located at Concordia University Montreal, Canada).

PCM layers were placed on the interior surface of the wall room facing a large window of the test room and are tested under different indoor and simulated outdoor conditions. The main objective of this study is to investigate the potential for use of such materials on the interior walls of existing buildings and indirectly as a mean to save energy and reduce room temperature fluctuations for improved thermal comfort. The PCM panels used are DuPont Energain [8], each measures 1.2 x 1.0 m with a 5.2 mm thickness. Five layers are used to cover around 80% of the back wall surface area. The main specifications given by the manufacturer are listed in Table 1. An electrical 1 kW duct heater attached to a 6" (duct air booting) fan is used as a heating source and is controlled by a PID controller with time proportional outputs.

Table 1. Properties of the Energain modules

Latent heat of fusion	70,000 J/kg (18-24°C)
Specific heat capacity (average)	2,500 J/(kg°C)
Density	855.5 kg/m^3
Dimensions	1,000 mm x 1,198 mm x 5.2 mm
Thickness	5.26 mm

The test room is a raised parallelepiped with interior dimensions (See Fig.1) of 2.80 m width x 1.30 m depth x 2.44 m height. A large window on the front is square (2.2 m) with a U-value of 1.1 W/m^2·K at the center. The test room is located inside the large climatic chamber with dimensions of 8.9 m x 7.3 m x 4.7 m. The tests were performed at either constant heating or constant temperature inside the hut with steady-state or sinusoidal temperatures in the environmental chamber.

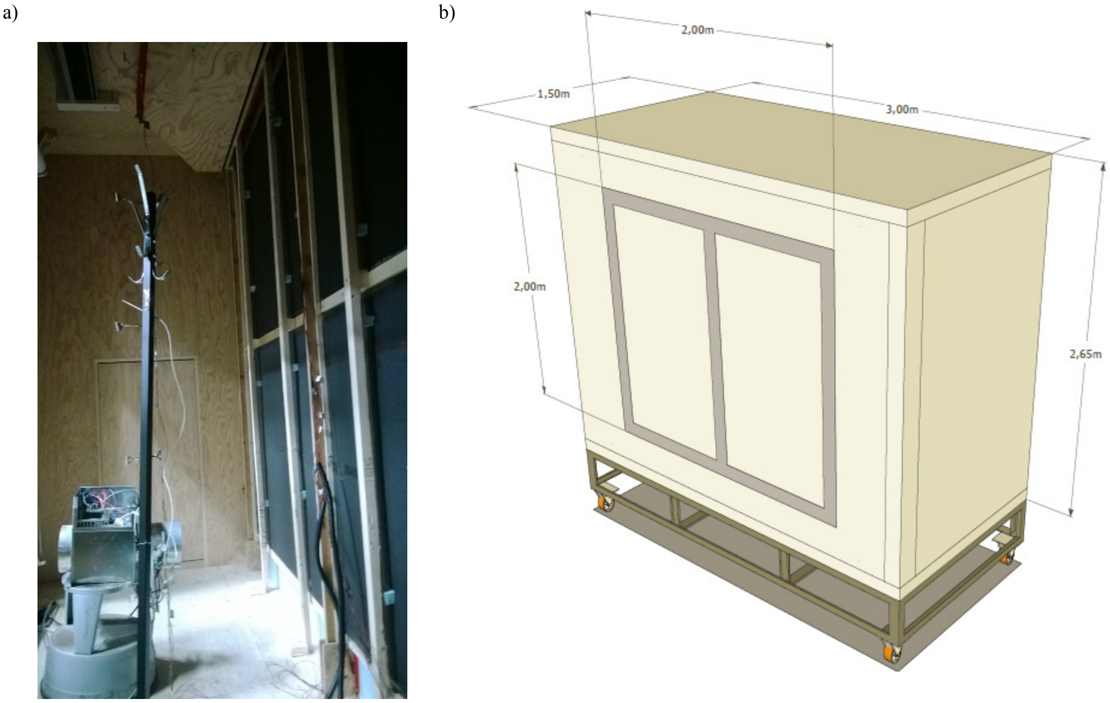


Fig. 1. (a) Indoor picture of the PCM wall (right, painted black) , (b) schematics of the test hut

Solar radiation is also emulated by means of a solar simulator equipped with six special metal halide lamps as source of radiation. Such lamps produce a dense multiline spectrum that is comparable to a continuous spectrum. In combination with glass filters, the lamp system provides a spectral distribution very close to natural sunlight, which fulfils the specifications of the relevant standards EN12975:2006 and ISO 9806-1:1994.

A "constant heating" test was first performed for model calibration purposes to determine the room thermal conductance and time constant. It lasted 60 hours; the environmental chamber was set to a constant 16°C while the indoor environment of the test room was heated at 350 W by the duct heater. The heating phase lasted 21 hours and was followed by the temperature decay phase with the heater and its fan turned off during the remaining test period. Temperatures from the thermocouples were read every 15 seconds and 3-min averages were stored every three minutes.

In order to perform further studies, a model was created in EnergyPlus by using a customized weather file to model the environmental chamber conditions. The simulation used the finite difference conduction model and TARP convection calculations. PCMs were modeled through the enthalpy and conductivity curves described in [9]. A 3rd order backward difference solution for the room air heat balance was adopted.

EnergyPlus allows for modeling of PCM through the following Eq.1. The algorithm uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase change energy accurately. The implicit formulation for an internal node is shown in Eq.1.

$$C_p \rho \Delta x \frac{T_t^{j+1} - T_i^{j}}{\Delta t} = \frac{1}{2}\left[k_w \frac{\left(T_{t+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_e \frac{\left(T_{t-1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_w \frac{\left(T_{t+1}^{j} - T_i^{j}\right)}{\Delta x} + k_e \frac{\left(T_{t-1}^{j} - T_i^{j}\right)}{\Delta x} \right] \tag{1}$$

Then, this equation is accompanied by a second equation that relates conductivity and temperature. In the following, the potential for energy savings and comfort improvement with different PCM configurations for actual houses in both the Canadian and in the Mediterranean context is assessed.

3. Results

3.1 Experimental results and model calibration

Figure 2 shows a part of the results from one test. Layers 1, 2 and 3 each refer to a different PCM layer at different depths, from the outside to the inside of the room. The phase change melting is also clearly recognizable between 17 and 23 °C in the PCM panels. It also heavily influences the air temperature whose slope drastically changes while the PCM completely melts after around 17-18 hours. It is interesting to note as well that the heater is switched off, the PCM temperature of the most inner layer (Layer 1) continues to grow due to higher temperatures in the adjacent layers.

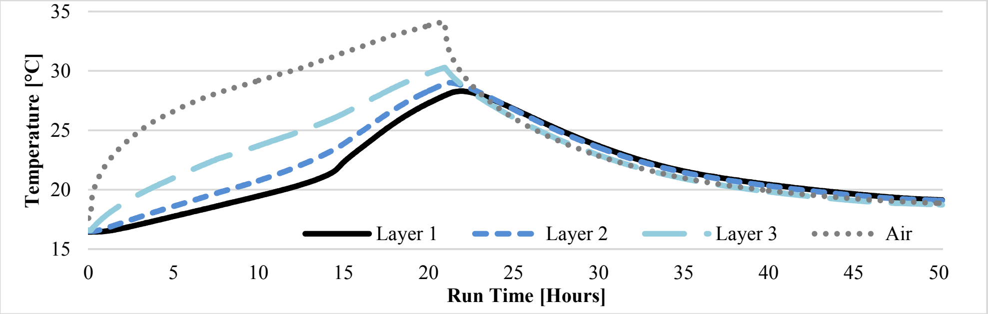


Fig. 2 – Results for the test performed: PCM inter-layer temperature and air temperature

Calibration has been performed comparing all the measured average temperatures for every layer with simulation results. Some examples are reported in Figure 3.

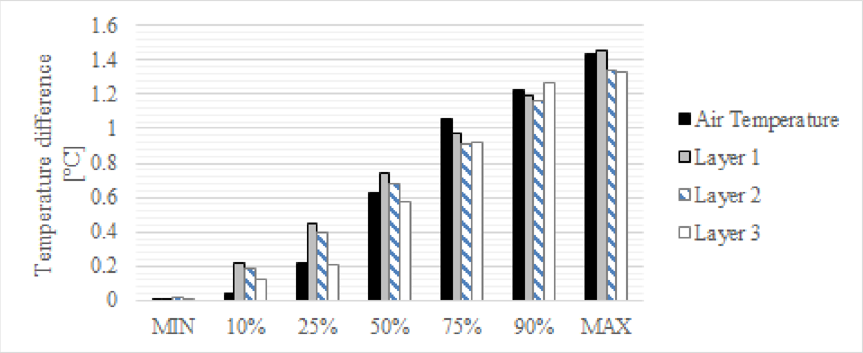


Fig.3 Error analysis in the EnergyPlus modeling

The simulation time step was adjusted to match the timeframe of the temperature readings: it was therefore possible to directly compare temperature readings and simulated results. Absolute error for each timestep was then calculated and arranged in ascending order ranging from the minimum to the maximum absolute error: i.e. 25% means that 25% of the absolute errors for Layer 1 reported in the simulation is below the value readable on the y axis (around 0.45°C).

3.2 Configurations definition

In order to explore the energy performance of PCM applications in the indoor environment, a wide parametric analysis has been developed, some results of which are reported in the following. Two main configurations were explored in the paper, focusing respectively on optimizing the heating phase and the cooling phase:

1) A PCM wall, composed of five layers of DuPont Energain panels, is located on the wall opposite to the large south oriented glazed opening (60% window to wall ratio - WWR). The main concept behind this solution is to allow for a direct solar radiation on the latent energy storage in order to maximize solar heat gains and store them for later use during winter. No other walls PCM. This is the system actually built and tested in the SSEC;
2) In addition to the PCM placement in Solution 1 above, two layers of PCM panels are added to the interior surfaces of all the other vertical walls and to the ceiling. The aim of this solution is to create in a lightweight structure a dampening effect similar to the one caused by massive walls. Since the focus is no more on the maximization of solar gains through the south window, the window area is reduced to roughly half the original size and a shading horizontal system is added to the original configuration. The WWR is between 30 and 35 %.

These two systems were first studied and simulated without any ventilation aside from external infiltration and then implementing natural night ventilation strategies: modeled through the “Zone: Wind and stack object” in EnergyPlus, such scenarios use empirical formulations to correlate wind angle and speed, fenestration areas and opening factors to calculate the air change rate. The control system chosen has some boundary values outside which ventilation is not provide: indoor temperature should be higher than 20°C and outdoor temperature should not be lower than 16°C. The scenarios studied in simulations are listed in Table 2.

Table 2. Scenarios in EnergyPlus simulations

Scenario	Description
S0	Base case, real configuration of the test hut, the PCM layers are removed;
S1	PCM placement described Solution 1;
S1Vent	Solution 1 implementing a natural ventilation scenario;
S2	PCM placement of Solution 2;
S2Vent	Solution 2, plus a natural ventilation scenario.

All these solutions have been tested in two different climates: a typical cold climate with short and fresh summers (Montreal, Canada) and a Mediterranean location (Palermo, Italy) with mildly cold winters and hot summers. However, due to high temperatures during the day in southern Italy during summer, the PCM used was diversified for all the Palermo simulations: although the same curve was used, it was moved 4 degrees towards higher temperatures, thus moving the enthalpy peak towards 26°C. Although this is not an existing and documented PCM product, it has features and characteristics close to others PCMs described in literature[10].

3.3 Parametric study

The main results of the study are presented in Figures 4-7. All figures describe monthly contribution to ideal thermal loads for all the six scenarios in Table 2, calculated with the standard 20-26°C setpoints respectively. Figures 4 and 5 describe respectively heating and cooling ideal loads for Montreal, Canada. Figure 6-7 report heating and cooling loads for Palermo, Italy.

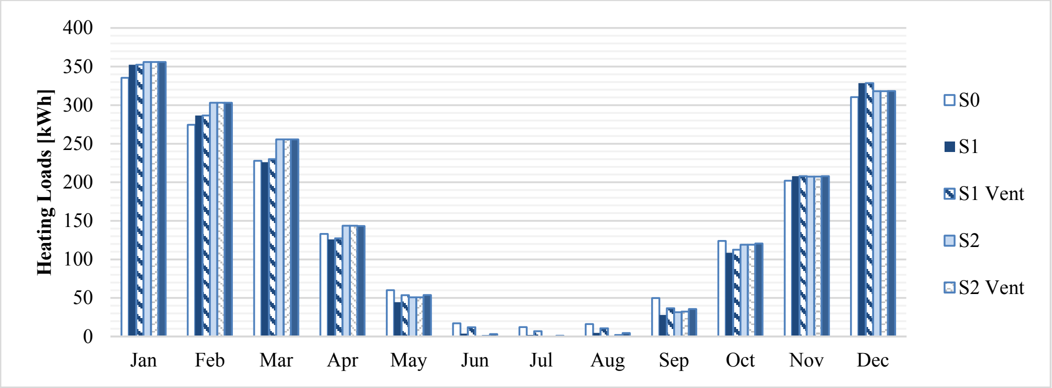


Fig. 4 – Heating loads in Montreal

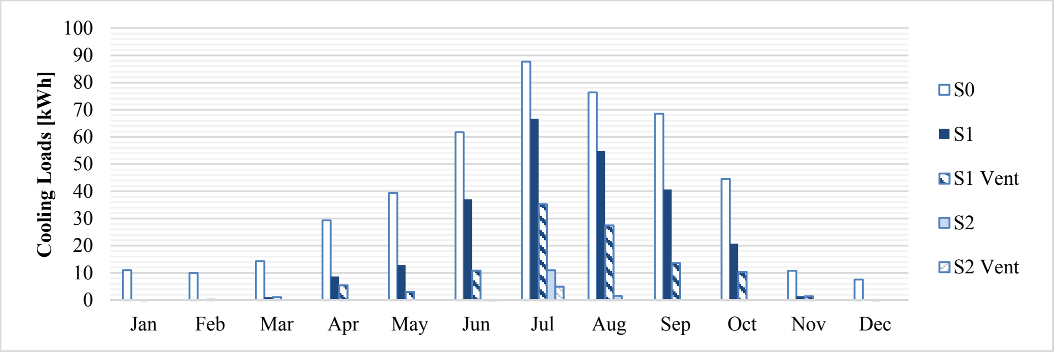


Fig. 5 – Cooling loads in Montreal

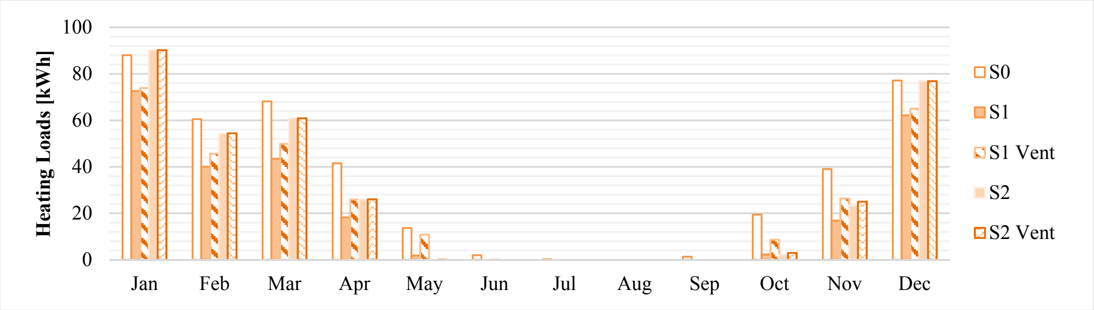


Fig. 6 – Heating loads in Palermo

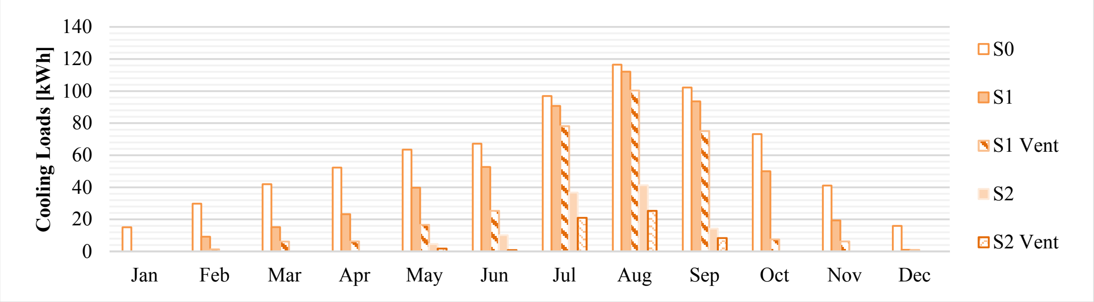


Fig. 7 – Cooling loads in Palermo

From Fig. 4, it is clear that the very cold, low insolation winter months in Montreal would limit the potential of scenario S1. However, from the end of February on, the situation would improve. Ventilation scenarios do not have a strong impact on the heating loads, as expected from the control choices adopted. Only scenario S1 achieves a 2.5% heating energy saving level compared to the base scenario S0 with no PCM and has consistently better performance from April to October gaining a +23% energy savings in that time frame, due to larger solar insolation. Winter months show an opposite trend. Fig. 8 clarifies this concept by showing temperatures of the external layer of the PCM wall and of the back wall of the test hut without PCM for a typical week during January in Montreal.

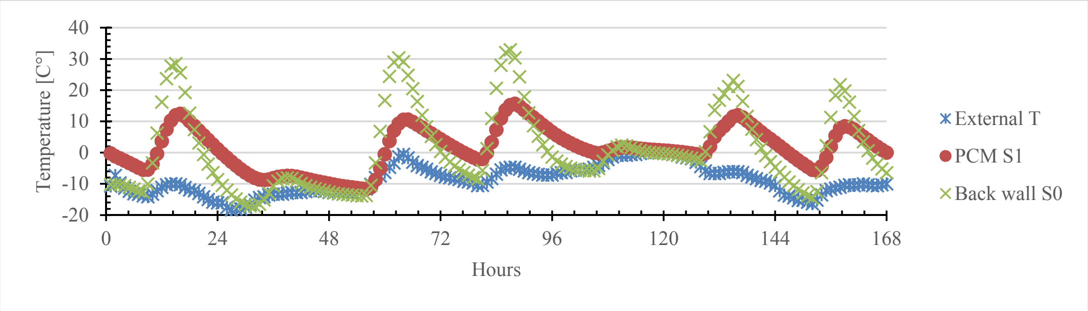
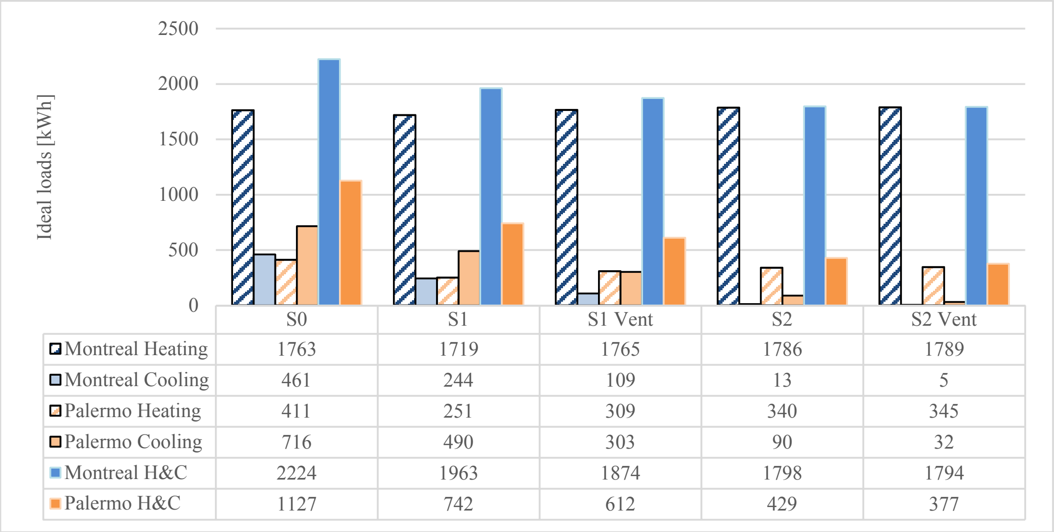


Fig. 8 - Simulation results for a week in Montreal during January

Although achieving 20°C reductions in peak temperature inside the room during sunny hours, the heat transferred to the PCM is not able to reach melting temperatures in the most external layer. The scenarios S2 and S2 Vent based on Solution 2 have worse performance compared to Solution 1 scenarios. These are mainly due to the lower irradiated PCM volume from the south window and due to the lower glazed area. Scenarios S1 and S2 in Fig.5 reduce the cooling energy use by around 47 and 76 %, respectively, for Montreal. Ventilation further reduced the cooling energy.

Different results are obtained for the Mediterranean climate. The lowest heating energy is achieved by scenario S1 with a 38% reduction compared to the baseline scenario. The best performing solution for cooling in Mediterranean areas is S2 with an 87% cooling reduction during the simulated year compared to scenario S0.



	S0	S1	S1 Vent	S2	S2 Vent
▨ Montreal Heating	1763	1719	1765	1786	1789
■ Montreal Cooling	461	244	109	13	5
▨ Palermo Heating	411	251	309	340	345
■ Palermo Cooling	716	490	303	90	32
■ Montreal H&C	2224	1963	1874	1798	1794
■ Palermo H&C	1127	742	612	429	377

Fig. 9 – Yearly total heating and cooling loads for Montreal and Palermo

Fig. 9 shows the main results of the study, with the yearly total energy required for heating and cooling. Heating loads for Montreal are nearly constant on a yearly level, on all the proposed scenarios. Overall energy savings would range around 20% on a yearly base compared to the S0 scenario.

In Palermo, the limited heating needs are only moderately reduced by the use of the PCM solutions; cooling loads – accounting for around 63% of the total energy needs for scenario S0 – would be reduced by nearly 95%. Overall energy savings are estimated being around 65% on a yearly base.

3.4 Discussion of the results

The analysis of the performance of the technical solutions proposed based on the calibrated EnergyPlus show that performance of PCM applications differs with the PCM placement, natural night ventilation, and sites analyzed.

The first solution proposed is the creation of a PCM wall directly facing a large window south oriented. The main concept behind this solution is to allow for a direct solar irradiation on the latent energy storage in order to maximize solar heat gains and storage during winter. This configuration proved moderately effective to reduce overall heating energy needs for the Canadian context when solar availability was high. Although overall yearly heating loads are nearly constant, the trend is different during the year: during January, February and December, the solution performs poorly compared to the baseline one. Instead, during shoulder months, Solution 1 would yield significant energy savings compared to the base scenario. The PCM enthalpy peak distribution – partly below 20°C- would cause energy systems to also partially activate the latent storage to meet the desired setpoint. This means that energy systems should also partially activate the latent storage to meet the desired setpoint. Using lower heating temperature setpoints might be an option even though it may lead to thermal comfort issues and it would need to be carefully analysed in future studies. Solution 1 in Montreal gives mixed results: however the technical solution proposed is proved interesting to work for applications in both the residential and non-residential sector in cold climates. A week in Montreal during early April is shown. Reduction in overall energy consumption and in peak power required is around 10%.

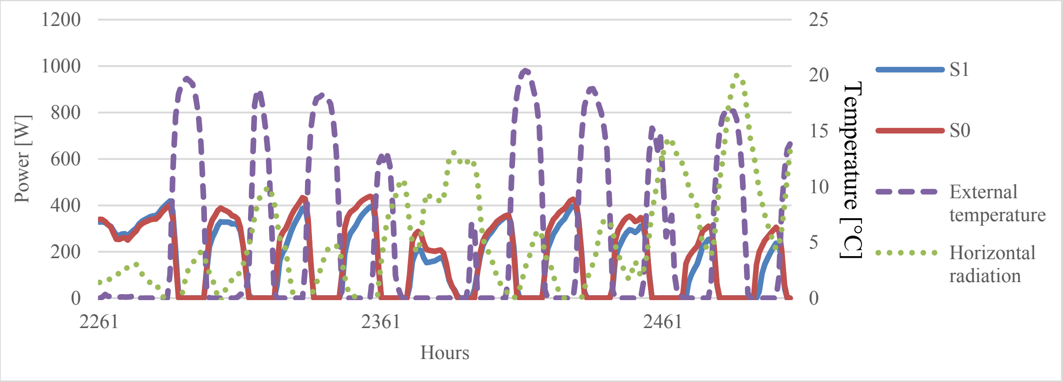


Fig. 10– Power required for heating in Montreal for solution 0 and 1 – Early April

The situation is different for the Mediterranean where cooling is the main source of energy consumption. Solution 1 gives mixed results, in particular for the heating season, but Solution 2 with more PCM covering areas would allow for consistent energy savings especially in summer. Fig. 11 shows the behavior of the building under extreme conditions: the hottest days of the year during summer. The thermal inertial behavior of the building is particularly clear since for the first 34 hours of simulation the PCM temperature on the back wall is inside its melting range. The highest external peak of around 38°C is highly shaved up to 30°C and it is delayed until the following night, after nearly 10 hours. Night ventilation (hours 53-54) is not able to fully discharge the PCM under these extreme conditions and in the following hours, a much more clear temperature swing is observed. For the Mediterranean climate, a careful handling of solar gains and the use of PCM on all the walls allows to obtain good results.

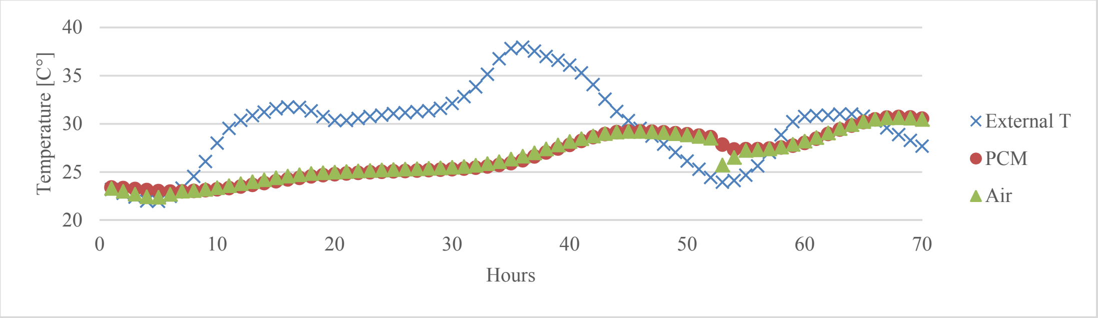


Fig. 11 – Free floating temperatures for July in Palermo, highest outdoor values for the whole year

4. Conclusions

An experiment using PCM integrated in the back wall of a small test-hut simulating a solarium/sunspace under controlled conditions in an environmental chamber with a solar simulator is presented in this paper. In order to perform parametric and sensitivity analyses, a model in EnergyPlus was created and calibrated with measured data. Relying on the model, a set of scenarios were developed and simulated to assess the potential of different technical solutions to improve the energy performance of the test environment for a cold and temperate climates.

The reduction of the energy consumption and performance potential of some simple system geometries was investigated.

In Montreal the use of PCM proved not very effective during the coldest months due to a limited solar availability. However, from the end of February the solution proves effective (around 20 % energy consumption reduction in this time frame), even reaching a positive net saving during the whole year. This proves that using off-peak and lower cost energy to heat the storage predictively is effective. Another improvement may lie in the control of the solution, for example, by employing model predictive control techniques. Active PCM techniques using mechanical ventilation to pass room air through gaps between PCM layers, currently under study at Concordia University, may also be a viable way to maximize heat transfer between the room and the PCM.

The second solution proved viable in the Mediterranean climate only when improving the passive design of the building and using a different PCM enthalpy curve fitted to the target climate. If the original PCM was to be used, it would simply be fully melted for the whole month of July and August. By proposing a design more suited to the climate and adding more PCM panels to walls, cooling loads would be nearly eliminated in Palermo. The results look promising. The use of PCMs yields a good thermal inertia buffering the outdoor conditions through a very thin wall. The importance of the optimal choice of the PCM is particularly relevant in Mediterranean conditions. A trade-off between performance at peak conditions and over a year needs to be achieved, in addition with optimal control strategies.

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