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Numerical and experimental study of a PCM-Air heat exchanger

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Abstract

Thermal storage can be an important element of an efficient building, as it addresses the issues of intermittent energy production and peak electricity demand. In particular, France faces significant peak load during the late afternoon hours in the winter period. A PCM-Air heat exchanger is proposed as a solution, studied both experimentally and numerically.

The heat exchanger is composed of a set of plates containing paraffin as the heat storage material and conceived in a way to be easily integrated in a ventilation system. Despite efforts to acquire a fast discharging unit, the proposed system does not always satisfy initial requirements regarding load shifting and thermal comfort. In parallel, a numerical model is developed, using the heat balance approach and the apparent heat capacity method. A study is carried out in order to obtain adequate PCM specific heat capacity values and the model is validated using experimental data. Finally, the model is coupled with a building simulation program and an experimentally tested control strategy is reproduced, presenting good agreement.

The model is aimed to be used in order to perform an optimization study of the heat exchanger, altering its dimensions and PCM properties, for minimum discharge time and maximum energy storage.

Key words: thermal storage, PCM, numerical, experimental

1. Introduction

Over the last years, the increasing concern for environmental and energy issues has led to new agreements and legislation at a national, European and worldwide level. In particular, the Paris COP 21 of the UN Framework on Climate Change and the European's Union Horizon 2020 program aim at a significant reduction of greenhouse gas emission and a notable increase of renewable resources energy production. The building sector has been identified as a key factor to this transition as it represents over a third of all final energy consumption and a third of global greenhouse gas emissions [1].

Energy storage offers multiple solutions to the intermittence of renewable sources energy production and the daily or seasonal variations of electricity demand in buildings [2]. Concerning the latter, an important peak power demand is observed in France during the late afternoon winter period, highly linked to electrical space heating [3]. In response, an experimental PCM-Air heat exchanger was developed, along with a numerical model.

2. PCM-Air heat exchanger prototype

The heat storage medium used for the prototype is the Microtek 37D paraffin; it was macro encapsulated in 16 aluminum containers that are then placed parallel one to another, as shown in figure 1 [4]. Fins are used to increase the heat exchange between the air and the containers. Temperature sensors were installed on the surface as well as the interior of the containers in order to provide the downstream temperature evolution. Furthermore, temperature and relative humidity measurements are performed on the inlet and outlet section of the unit.

The prototype was designed considering an integration into a HVAC system, for example in a ventilation plenum, a false ceiling or the ceiling over a corridor, this leading to a modest size of (1,05x0,80x0,25)m and 31.8 kg of paraffin. The operation principle lies on storing heat during the off-peak period, in order to render it back to the building during the two hours load peak period (18:00-20:00), while the electrical heating is turned off.

A characterization study was performed, varying the inlet airflow rate during full thermal charging and discharging cycles and providing reliable experimental data of the system's operation. The needed charging/discharging time was superior to the peak period, this observation pointing to the need for an optimization study for the heat exchanger.

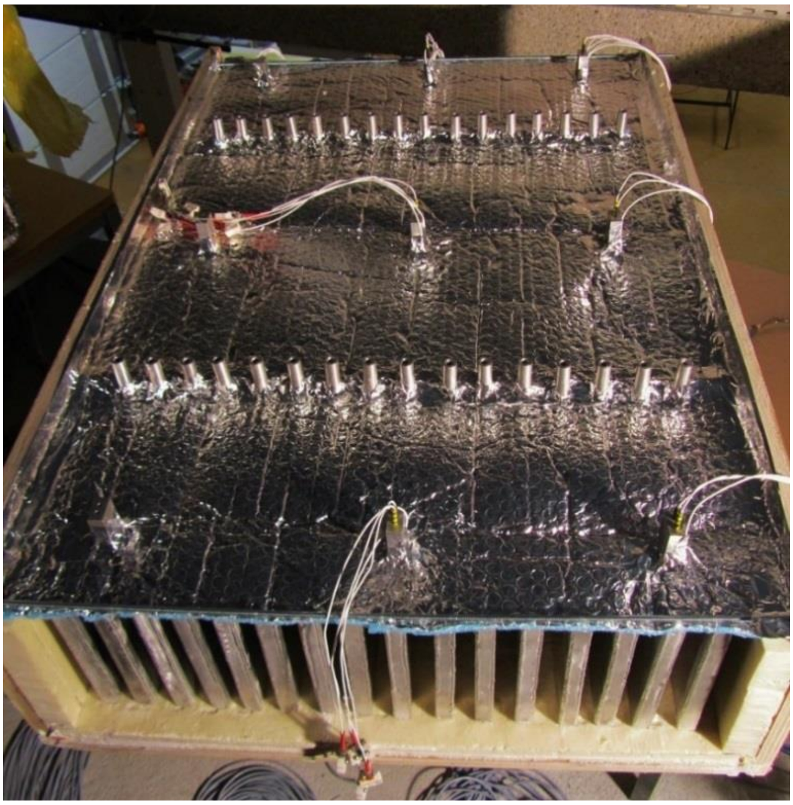

Fig. 1 PCM-Air heat exchanger prototype

3. Numerical model

Parallel to the experimental study, a numerical model was developed, based on the heat balance approach and the apparent heat capacity method [5]. It considers three heat transferring media: air, (aluminum) surface and PCM (figure 2); each of them is discretized in n equal nodes lengthwise. One node is considered crosswise for the air and surface layer and m nodes are considered for the PCM layer. Inlet air temperature and airflow rate are the model's inputs and the temperature evolution is calculated at each node.

The objective of the numerical study is double: perform an optimization study of the heat exchanger and develop control strategies once coupled to a building model.

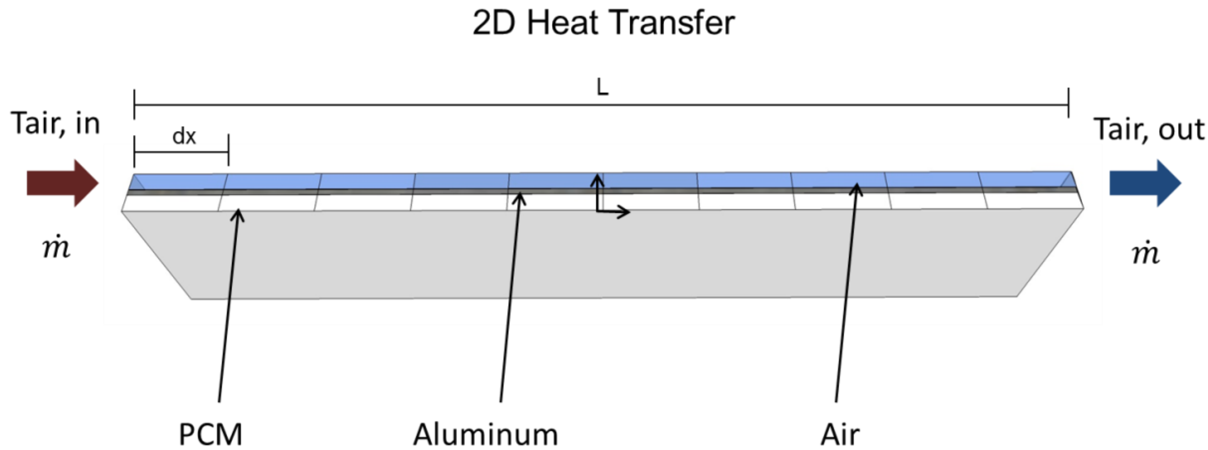

Fig. 2 Schematic representation of the considered layers for temperature evolution calculation

The apparent heat capacity method consists in the representation of the paraffin's phase change by an apparent increase of the PCM's heat capacity (C_p) values for the corresponding temperature range. Numerical and experimental data were compared showing coherent results but with noticeable differences. The impact of several properties was investigated, including surface and PCM conductivity, density and specific heat capacity values. The importance of the PCM specific heat capacity values was observed, leading to a thorough study of this parameter.

4. Adequate heat capacity curves

The PCM heat capacity values of the PCM were obtained using the Differential Scanning Calorimetry (DSC) [6] method by Materials and Mechanics of Components laboratory of the Electricity of France, partner of the project. DSC is a measuring technique where a sample material (in this case paraffin) is compared to a reference material (with known properties) while undergoing a heating or cooling process. For the Microtek 37D paraffin, measurements were made on a 0.22623 g sample, for three different heating/cooling rates of 0.15, 0.5 and 1 °C/min. Results are illustrated in figure 3.

During the heating process, the phase change occurs between 30°C and 42 °C, shifting towards higher temperatures as the heating rate increases. During the cooling process, the phase change occurs between 25 and 35°C, shifting towards lower temperatures as the cooling rate increases. Moreover, two peaks are observed during the cooling process, linked to the intrinsic properties of the paraffin.

Several simulations were carried out using the available heat capacity curves and results were compared with the experimental data from the characterization study. In all cases the model provided underestimated values of the temperature evolution. Furthermore, no distinct start and end of the phase change was observed for both the melting and the solidification process.

These observations demonstrated the need of the creation of adequate heat capacity values. The followed approach included several steps, each time modifying the heat capacity values and observing the impact while comparing to experimental data.

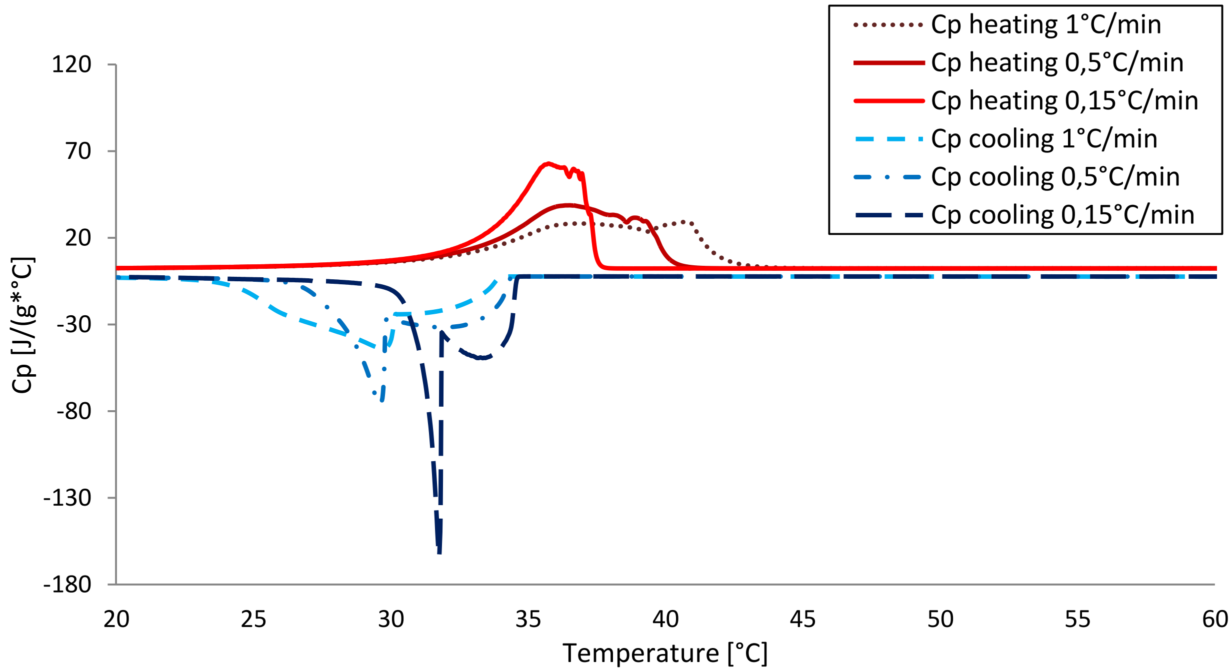

Fig. 3 DSC obtained heat capacity curves for the Microtek 37D, 3 different heating/cooling rates

In particular, the first step consisted in creating a specific heat curve having the form of an isosceles triangle and testing it for both the cooling and heating process. The values were also lowered comparing to the DSC results in order to address the previously underestimated results. Indeed, the use of this adequate curve led to better results.

However, the two peaks observation during the experimental discharge phase was still not represented in the numerical results. As a result, a second curve was created for the discharging phase, with two distinct peaks for the heat capacity values. This led to satisfying results but an offset was still observed for the PCM temperature values along the plate (inlet, middle and outlet parts). Detailed analysis of the experimental data resulted in two observations: heating/cooling rates of the PCM also depend on the stage of stocking/destocking process as well as the part of the plate that we are considering (inlet, middle, and outlet). This led to the separation of the considered PCM section into three parts (inlet, middle and outlet) and the use of different heat capacity values for each part. In the end three curves were used for the heating process and another three for the cooling one, according to the lengthwise position of the considered node. The final form of the adequate heat capacity values is represented in figure 4.

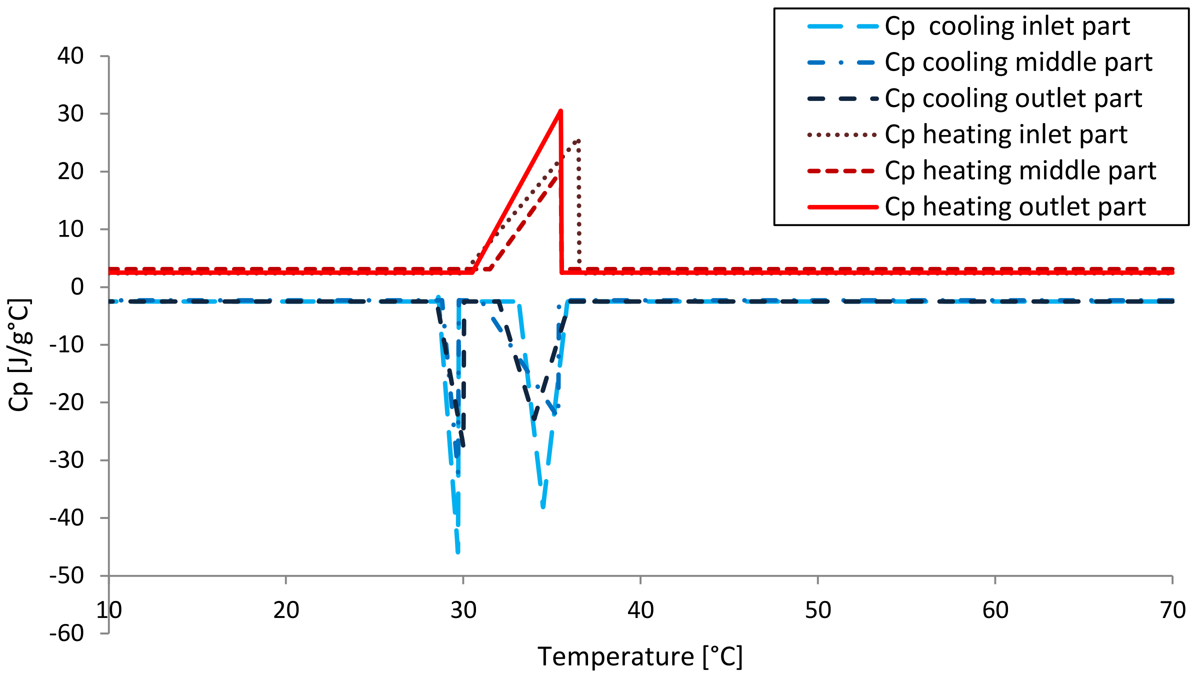

Fig 4 Calibrated cp values created for the numerical model

The calibration of the model (adequate heat capacity curves) led to results presenting good agreement with experimental ones. This was confirmed through a vast comparison of numerical and experimental data, for three different airflow rates (100, 300 and 500 m^3/h) and for different locations of the heat exchanger (PCM and surface, inlet, middle and outlet part).

Figure 5 illustrates part of the obtained numerical and experimental results for the PCM temperature evolution at the middle part of the heat exchanger for the three aforementioned airflow rates.

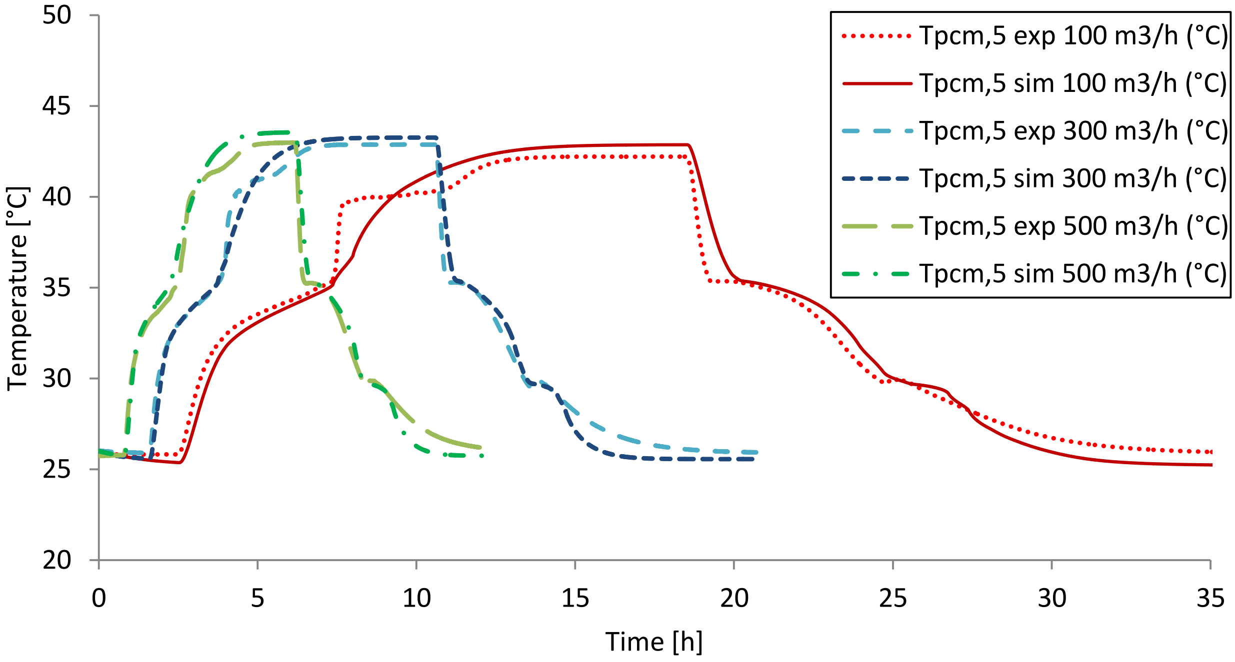

Fig 5 Numerical and experimental results for PCM temperature at node 5, for 100, 300 and 500 m^3/h

More specifically, the non-linearity of the temperature evolution during the phase change is reproduced, including the two peaks that occur during the solidification stage.

5. Coupling with building model and testing of a preliminary control strategy

The heat exchanger was coupled with an experimental test cell (Hybcell) [7] and a test was performed during a consecutive four day period, with similar climatic winter conditions. The aim of the developed strategy was to maintain a comfortable thermal environment inside the test cell throughout the testing period. During the peak power hours (18:00-20:00) the electrical heating was turned off and the heat absorbed by the exchanger was released into the cell. For the first three days load shifting was performed during the peak period, whereas the last day was taken as a reference (no heating at all).

Similarly, the numerical model was coupled to an existing building model, the HYBCELL 1.2 [7] and the four days testing was reproduced. The heat exchanger model uses, the experimental inlet air temperature and the airflow rate as input; this time these values vary according to the implemented control strategy during the experimental test. The outlet heat exchanger model air temperature and the airflow rate are then employed as ventilation inputs for the building model.

Figure 6 illustrates numerical and experimental results for the four days test. The heat exchanger model manages to reproduce the experimentally observed behavior even for varying inlet air temperature and airflow rate. Likewise, the building model represents with precision the evolution of the indoor air temperature during the three days of peak load shifting and the fourth reference day.

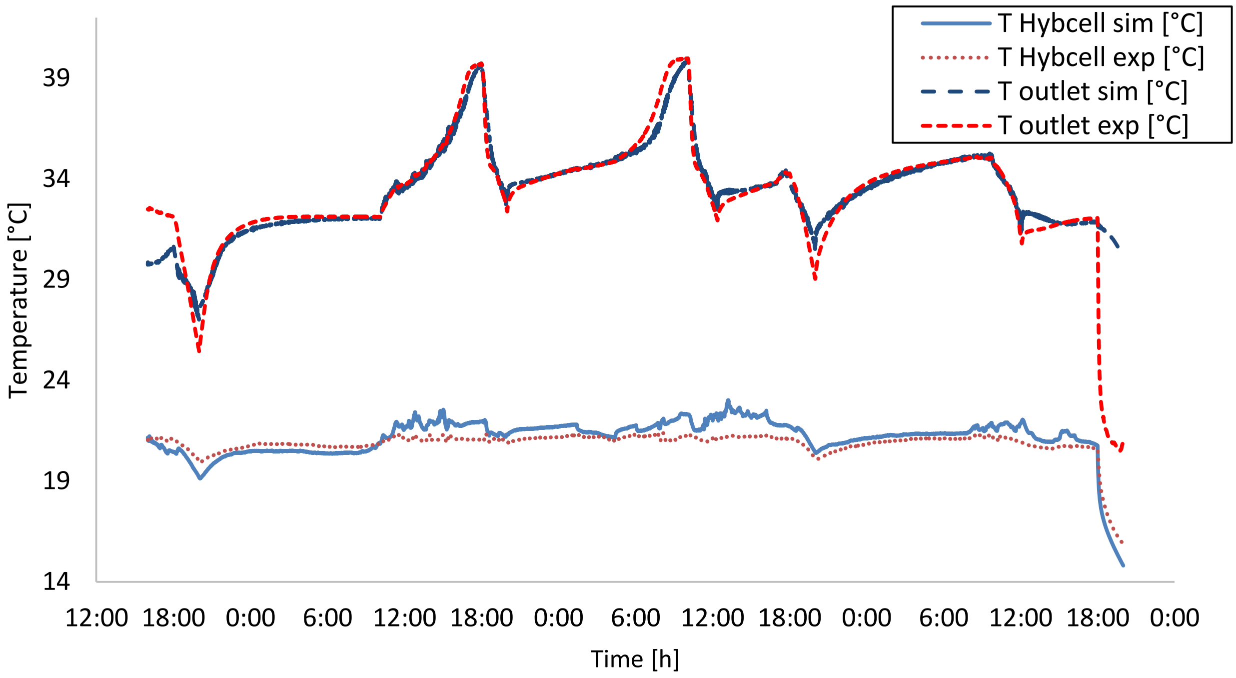

Fig. 6 Numerical and experimental results for the heat exchanger unit and the Hybcell room coupling during a 4 days test

6. Conclusions

A study was performed in order to confront the peak power issue of the French electricity network, strongly influenced by electrical space heating. As a solution, an active latent heat storage experimental prototype is proposed using Microtek 37D paraffin. A numerical model was also developed, based on the formulation of heat balance equations and the apparent heat capacity method. It considers three heat transferring mediums, air, aluminum surface and PCM, and is able to reproduce the downstream temperature evolution for each of them. A significant part of the study focused on the specific heat capacity values through the phase change and the creation of adequate curves, based on DSC results.

The model was then be used for an optimization study of the heat exchanger and the development of control strategies when coupled to a building [4].

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