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Phase Change Materials for building envelopes in Reunion Island, France

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Abstract.

This study is being conducted to evaluate the effects of Phase Change Materials (PCM) on thermal comfort in buildings in Reunion Island. Experimental and numerical approaches are used to determine the criteria for the integration of bio-based PCM. A full-scale platform is divided into two rooms, where a layer of PCM is applied to one surface of the test room. Results show that the application of PCM delays the temperature rises and its maximum is reduced by up to 4 degrees. Finally, the experimental results are compared to those of a Dynamic Thermal Simulation (DTS) program to evaluate the ability of such programs to predict the thermal behavior of the building with and without PCM.

1. Introduction

The 2019 Pluriannual Energy Program (PPE) stated that at least 50% of the electricity consumption in the residential sector of Reunion Island (France) is related to air conditioning [1]. New policies for sustainable development are encouraging the enhancement of buildings' envelope to improve thermal comfort and the management of energy consumption [2]. Half of the 900,000 inhabitants live on the coast, where a cooling strategy is required, and a quarter is installed in the mid-altitude area, where heating is a more appropriate strategy. In the context of a severe building materials crisis, Reunion Island will have to identify and develop local resources in the future, this is the purpose of the MCP-iBAT¹ project.

One of the diverse available technologies is Phase Change Material (PCM). It can store a large amount of energy during a phase change through its latent heat. Many authors have researched this topic, starting with A. Abhat in 1983 [3], who extensively reported the properties and potential of PCMs. Besides, scientists have mainly investigated PCMs experimentally by assessing the efficiency through parameters such as the melting temperature, the latent heat, the integration method or the positioning in the buildings [4, 5, 6, 7, 8].

Such studies have led to some recurrent conclusions. First, the melting temperature should be near the average ambient temperature [9]. Second, the latent heat should be the utmost, providing the PCM goes through a complete thermal cycle. Moreover, the location of PCM depends on the application, e.g., near the external surface of the wall to reduce solar heat gain or near the internal surface to regulate indoor temperature [8]. In addition, direct incorporation

¹ "Matériaux à Changement de Phase : une innovation pour le Bâti Tropical"

and micro-encapsulation have been widely approved since the former is the cheapest method and the latter prevents leakage and has a higher latent heat. Lately, some researchers have focused their interest on shape-stabilized PCM, which consists of melting and mixing the PCM with the support material at a high temperature followed by tempering [10], which could have the benefits of the two previous methods.

The current study, which aims at determining selection criteria for suitable PCMs in a tropical climate, is both experimental and numerical. The main steps are first, developing tools to collect and analyze local data, secondly, modeling the experimental benches with the measured properties of the selected PCM, and finally, validating the simulation code.

2. Materials and methods

2.1. Weather context

Due to its very uneven topology, Reunion Island presents multiple microclimates that are grouped into three main categories according to Köppen-Geiger's classification: *Aw*, tropical savanna climate (coastline); *Cfb*, oceanic climate for high altitudes; and *Cfa*, humid subtropical climate, for mid-altitude areas. The present article focuses on the test platform located at Saint-Pierre, representative of the coastline area. Figure 1 highlights a significant variation of

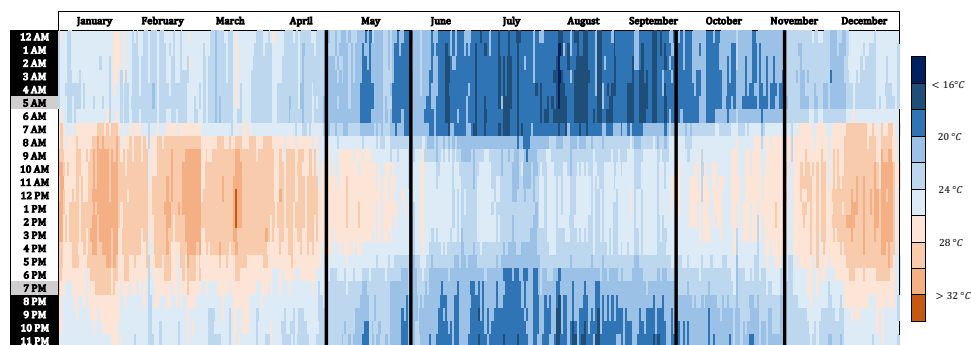


Figure 1: Mean annual evolution of the outdoor air temperature in 2018-2019, for the city of Saint-Pierre, Reunion Island

the air temperature, pointing out the two main seasons of Reunion Island. The southern summer extends from November to April, when the air temperatures fluctuate from 24°C to over 32°C. By contrast, the southern winter (June to October) is marked by a maximum temperature of 24°C and minimums below 15°C. Two inter-season periods, from April to June and from September to November, are marked by temperatures between 18 and 28°C. Overall, the mean annual temperature of Saint-Pierre is 22.3°C.

2.2. Experimental set-up

2.2.1. Test-platform The experiments are conducted using a full-scale platform parted into cell A, the reference room, and cell B, the test room, whose dimensions are presented in Figure 2(b). It also shows the composition of the panels that is a layer of polyurethane stacked between two layers of steel. Besides, the coating applied to the surface of the North wall in cell B covers an area of 6.86 m² with a thickness of 5 mm. Data collection (still operating) started in June 2020. Type T thermocouples are used to measure the exterior and interior temperatures of the North wall surfaces. An HFP01SC heat flux meter, manufactured by Hukseflux, is also installed on the North wall. These sensors are connected to the CR3000 datalogger, sampled at 0.1 Hz and averaged every minute. In addition, the indoor air temperature and relative humidity are measured with a Testo 175 H1. The layout of the devices is presented in Figure 2(a).

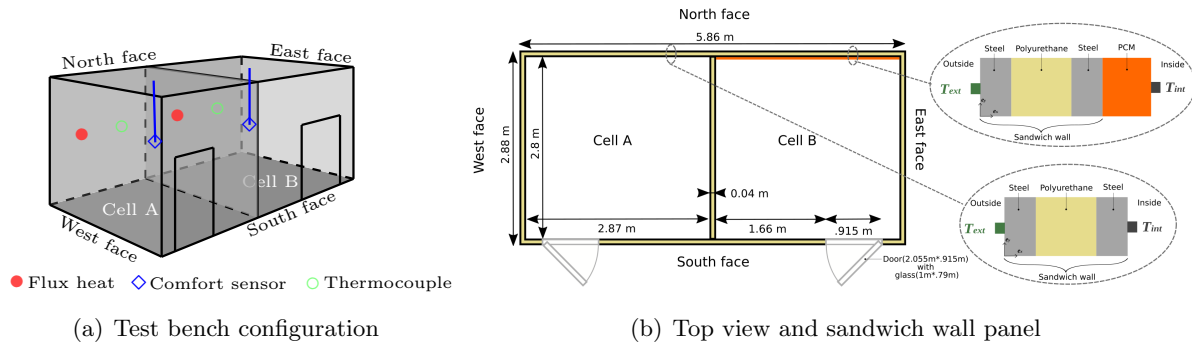


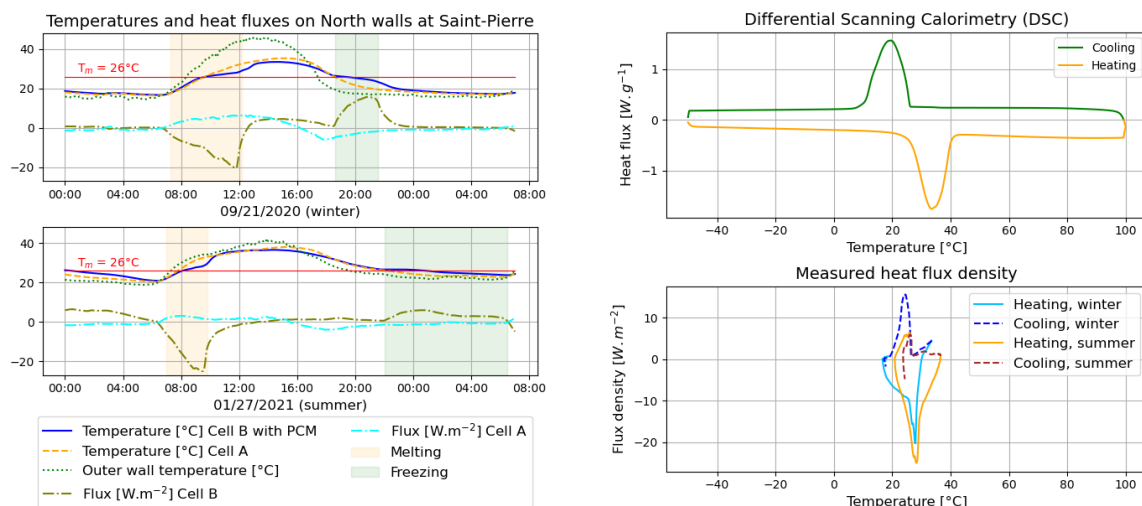
Figure 2: Illustration of the test bench

2.2.2. PCM properties The selected PCM for this study is the Thermo Comfort PCM from Winco technologies, an interior coating composed of micro-encapsulated wax. It was chosen for its melting temperature of 23°C , close to the mean annual temperature in Saint-Pierre, and for its high latent heat of 184 kJ.kg^{-1} . We performed a Differential Scanning Calorimetry (DSC) on the PCM samples, with a heating rate of $5^{\circ}\text{C.min}^{-1}$. It gave actually a melting temperature of $T_m = 26^{\circ}\text{C}$ and values of latent heat L_f ranging between 165 and 173 kJ.kg^{-1} . An analysis of the sample through Fourier-Transform Infrared (FTIR) spectroscopy showed that the PCM is mainly composed of a mixture of paraffin. In addition, the cellulose fibers and PVA found in the sample are presumed to form the support material for the coating.

3. Results and discussion

3.1. Experimental results and discussion

The behavior of the PCM is presented in Figure 3(a) for clear sky days in winter (09/21/2020) and summer (01/27/2021).



(a) Temperatures and heat fluxes on North walls, at Saint-Pierre during winter and summer.

(b) DSC and flux density

Figure 3: Experimental results

3.1.1. The effect of PCM on temperatures In winter, the temperature amplitude in cell A is approximate $\Delta 16^{\circ}\text{C}$ for the North wall's inner surface, meanwhile, in cell B, the recorded amplitude is $\Delta 14^{\circ}\text{C}$. In summer, the values are $\Delta 13^{\circ}\text{C}$ and $\Delta 12^{\circ}\text{C}$, for cell A and cell B respectively. Although the temperature variations with and without PCM are close, it can be noticed that during fusion, PCM reduces the wall surface temperature by 4°C in winter and summer. On the contrary, during freezing, the temperature with PCM increases up to 4°C in winter and up to 2°C in summer.

3.1.2. Phase change characterization From the DSC, the melting temperature is $T_m=26^{\circ}\text{C}$, assumed to be the same as the freezing temperature. Thus, it is expected that phase change occurs when the PCM temperature reaches T_m . However, the heat flux measured in cell B for both seasons shows that energy storage starts before the wall temperature reaches 26°C . Indeed, the negative values of heat flux covered by the orange area, on Figure 3(a), illustrates the endothermic process of melting, i.e. the material absorbs heat. Similarly, the end of the transition is graphically deduced from the highest slope of the heat flux derivative. The positive values of heat flux in the green area correspond to an exothermic process, leading to a release of energy during freezing.

3.1.3. Energy storage analysis Based on the transition zones defined previously, the energy density is obtained with the area under the heat flux curve. Therefore, on 09/21/2020 (winter) the energy density stored during fusion is 207.2 kJ.m^{-2} and phase change has a duration of 4 hours 55 minutes. During solidification, the released energy density is 131.6 kJ.m^{-2} with a duration of 3 hours. On 01/27/2021 (summer), the flux shows a narrower concavity where the stored energy density is 181.2 kJ.m^{-2} for 2 hours 50 min. The end of liquid to solid transition is estimated when the heat flux becomes endothermic, which corresponds to the beginning of melting. The released energy density over this period is 112.3 kJ.m^{-2} , for 8 hours 30 min.

A qualitative comparison between the measured heat flux density in Figure 3(b) shows that the heating part of measured heat flux density is shifted to the left and the maximum temperature never reaches 40°C when PCM should be integrally melted. Hence, we postulate that PCMs have partially melted during the solid-to-liquid transition. This can be caused by the thickness of the coating (5 mm), whereas the supplier suggested applying a thickness of 3 mm. In addition, the inner wall temperature cannot reach 40°C because of the isolating power of the polyurethane and the limited solar energy intake. Furthermore, it was observed in Figure 3(a) that PCM starts to store energy before the inner surface temperature reaches 26°C . We assume that the weaker bonds of the micro-encapsulated PCMs' molecules are more responsive to temperature variations.

Conversely, the cooling peak starts at 26°C for both studied days, which conforms to the freezing temperature of the DSC. Nevertheless, the area under the cooling curve is much smaller in summer than in winter. This can be correlated to the fact that fewer PCM particles solidify due to the partial fusion of the material. Hence, the cumulative effect of the cycles makes the coating inefficient in summer.

We concluded that the knowledge of the temperature range during phase transition is substantial. An optimization of this parameter would enable better exploitation of PCMs' properties.

3.2. Numerical validation

Numerical simulations have been carried out to provide a better understanding of PCM behavior. The software used in this study is EnergyPlusTM [11], a Dynamic Thermal Simulation (DTS) program. It predicts the building's thermal behavior when subject to external environmental factors. The selected parameters in this study are the construction's

characteristics (dimensions and materials) and the environment's description (meteorological data and building surroundings). The experimental data and EnergyPlus simulation results are compared on Figure 4, with and without PCM. In addition, the absolute relative error between numerical results and measures is calculated, where the measured data is the reference.

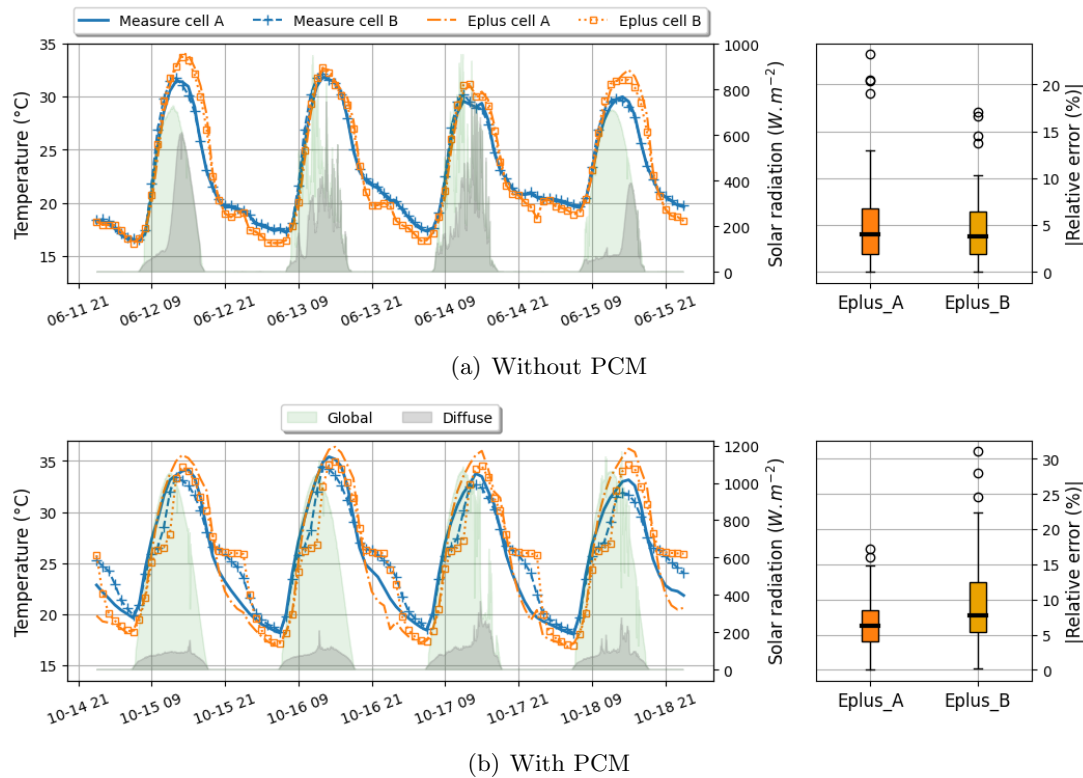


Figure 4: Simulation results and experimental measure

3.2.1. Results and discussion The studied period without PCM is from 06/12/2020 to 06/15/2020. As shown in Figure 4(a), the temperatures of cell A and cell B are close. The box plots of relative errors present good accuracy of the model with medians under 5%. The figure also depicts an overestimation of the simulated temperatures, generally after the sun reaches its zenith and more particularly for clear skies (06/12/2020 and 06/15/2020). Conversely, during the night, the temperatures are underestimated. An analysis of all wall temperatures shows that the overheating is mainly due to heat transfers through the roof. These essentially come from radiative effects: solar irradiance during the day (overheating) and radiative exchanges with the celestial vault (overcooling) during the night, which may explain the isolated points on the box plots. Considering the global and diffuse irradiances, we assume that these discrepancies are generated by insufficient knowledge of the roof's external radiative properties and by misleading solar diffuse measurements due to an incorrect adjustment of the shadow ring. A spectrometric study will be carried out to determine these parameters more precisely.

The simulation with the addition of PCM on the North wall in cell B is realized for the period of 10/15/2020 to 10/18/2020. Similar to the previous considerations, the amplitude of the simulated temperatures, displayed in Figure 4(b), is still greater than the amplitude of the measures. However, a better measurement of the diffuse irradiance reduced the outliers of cell A's relative errors.

In cell B, the PCM model has the same tendency as the measures, with a phase change occurring around 26°C. The relative errors are significant, caused by the irradiance as noticed previously, but also by the model used in EnergyPlus. Phase change seems to be modeled as a constant temperature process, conforming to theory. It is visible during freezing, where temperature stalls at 26°C and then drops sharply when the transition looks complete, whereas the measures show a smoother decrease in the temperatures. Hence, we presume that the experimental PCM is not accurately described in the EnergyPlus model. Accordingly, further chemical and thermophysical analyses will be performed to characterize the material.

4. Conclusion and perspectives

The work presented in this paper aims to evaluate the effects of Phase Change Materials (PCM) on thermal comfort in buildings on Reunion Island. Results show that the PCM was not optimally used due to its partial fusion. Indeed, the DSC showed that the melting starts at 26°C and is complete when it reaches 40°C while the manufacturer announced only a melting temperature of 23°C. The ranges of fusion and solidification have to be clearly described to optimize the PCM efficiency and its impact on the building's thermal performance. As the user must be at the center of the concerns, the temperatures of thermal neutrality (in winter comfort and summer comfort) should be considered in the future as phase change temperature. Finally, simulation results have shown a good prediction of a building's thermal behavior with and without PCM, but some modeling improvements have to be investigated in future work.

5. Acknowledgments

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