Experimental investigation on a complex roof incorporating phase change material

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Contents:

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Abstract

This article deals with a new configuration using a phase change material (PCM) in a complex roof on a dedicated test cell. For the first time and in real conditions, an experimental device using phase change material was set up for a tropical and humid climate such as that in Reunion Island. Results showed that in the configurations tested and for a non-ventilated air layer, the measured temperatures were on either side of the PCM's melting point. It means that the PCM is able to store thermal energy in the daytime and release it at night. Furthermore, this study has made it possible to determine the thermal resistance of the roof via a mean method meeting international standards (ISO 9869) using dynamic data. The test was implemented in a multi-zone building software in order to automatically determine the thermal indicator.

Keywords: Thermal resistance; Mean method; Phase change materials; Experimental study.

Nomenclature

Variables

R	Thermal resistance
T	Temperature

Subscripts

i	Interior
si	Interior surface temperature
se	Exterior surface temperature

Greek symbols

φ	Heat flux

Abbreviations

ISOLAB	A building simulation software, which integrates the hygro-thermal and aeraulic phenomena
PCM	Phase Change Material
RTAA DOM	Thermal, Acoustic and Ventilation standards regulations in French overseas department

1. Introduction

To combat global warming, it is necessary to reduce both energy consumption and the emission of greenhouse gases. According to reference [1], energy-hungry appliances in buildings increasingly contribute to global warming. To reduce energy consumption, a possible solution may be found in the passive design of buildings. This entails using a complete set of chosen materials in building construction as well as specific technical solutions [2] to reach high energy efficiency, therefore rendering energy-hungry appliances useless. To achieve this aim, insulation products are used to improve the building's behaviour. Indeed, insulation of the building envelope makes it possible to retain heat during winter and decrease heat loads during summer. Furthermore, thermal insulation can save energy and improve the comfort of the building because heat flow is reduced.

Additional thermal insulation can be used to help improve the energy efficiency of a building. With this objective in mind, phase change materials (PCMs) have been studied and developed for certain applications [3]. These materials have higher thermal energy storage densities than other heat storage materials. During a phase change process at constant temperature, PCMs are able to store and release latent heat. Latent heat storage involves storing energy during melting and energy release during freezing. Organic and inorganic PCMs are often used and solid-liquid phases are chosen. Paraffin is the PCM most frequently used for latent heat thermal energy storage. It has useful thermal properties such absence of super cooling, chemical stability and low vapour pressure [4,5].

In this paper, the PCM chosen consists of 60% microencapsulated paraffin within a copolymer and laminated with protective aluminium foil [6]. In addition to the phase change process, the surface of the PCM acts as a reflective insulation. The action of reflective insulation is usually closely linked to the radiative properties of the surface. The reflective surface reduces

the radiant heat transfer across an enclosed air space, for example between the metal and the plasterboard in a specific roof configuration. According to reference [7], the air layer is used to induce heat transfer by infrared radiation. The combination of homogenous and inhomogeneous materials with the air layer can be qualified as a complex wall. A complex wall can be defined as an assembly of materials separated by one or several air layers [7]. Nevertheless, such an assembly complicates the determination of thermal performance owing to the multiple configurations of the air layer: opened or closed, naturally ventilated or ventilated by force. Generally, studies on the thermal performance of a roof system do not take into account the air layer [8]. It is important to characterize the thermal effects of a complex roof incorporating PCM for the chosen configuration. Therefore, for the specific conditions of Reunion Island (characterized by a tropical and humid climate with strong solar radiation), experimental and numerical approaches were conducted. A methodology was set up to determine both the thermal behaviour and thermal performance of a complex roof with PCM. In this article, the experimental study is presented. To begin with, it is important to highlight that the methodology presented can be used for all climates, not only tropical and humid.

2. Research statement and methodology

2.1. Introduction

Located in the Indian Ocean, Reunion Island is a French overseas department characterized by a tropical and humid climate. Microclimates make it an ideal location for experimental investigation. During the summer, temperatures are generally above 30°C, with wind speed oscillating between 0 and 1.5 $m.s^{-1}$, and the mean relative humidity is usually above 80%. It should be made clear that sometimes Reunion Island is subject to powerful and destructive cyclones [2].

In Reunion Island, depending on the building materials used, buildings have different thermal performance. Mainly wood and concrete have been used in construction. Recently, a new type of residential building has appeared using concrete and traditional construction materials. The roof consists of a corrugated sheet and a false ceiling. The false ceiling is generally plywood or plasterboard. However, thermal insulation used in the roofing are not effective. Usually, the roofs are inclined at 20°. The problem with these types of roof is the large heat gain due to the roof coverings. The roof is the part with highest energy losses (20% to 30%) [9]. Furthermore, radiative effects must not be disregarded.

Thermal regulations have been implemented in Reunion Island since 2009 with PERENE [10] and since 1st May 2010 with RTAA DOM to avoid construction of buildings with different thermal performance. Current regulations make insulation and other technical solutions compulsory to minimise the energy consumption of buildings. This major step in building design reduces the need for air conditioning or heating systems and the harmful effects they have on the environment.

2.2. Research statement

PCM incorporated in a typical roof in Reunion Island will result in complex physical phenomena. PCM is inserted into an enclosed air space between the corrugated iron and plasterboard. Once installed, an air layer is present between the corrugated iron, the surface of the PCM and the metal. All heat transfers are fully combined and coupled. In this way, heat transfer by conduction, convection and radiation has to be taken into account on the PCM surface. Between the plasterboard and the PCM, only heat transferred by conduction is considered.

The ventilation of the air layer is an important parameter. The thermal performance of the roof varies depending on whether the air layer is naturally ventilated or force-ventilated [2].

Insertion of the PCM into the roof posed two problems for the chosen assembly:

- Will the temperature of the PCM enable phase change?
- What is the thermal performance of a complex roof with PCM?

A methodology was established and presented in order to solve these problems.

2.3. Methodology

The methodology is based on both numerical and experimental studies. From a numerical viewpoint, a building simulation code called ISOLAB was developed by Miranville during his thesis and recently a mathematical model dedicated to phase change materials presented in [11,12] was implemented based on the heat apparent capacity method. From an experimental point of view, a specific experimental platform was set up. For more details, refer to [9].

This article focuses on the determination of thermal performance of a complex roof with PCM and the results of an experimental protocol for a full-scale outdoor PCM test-cell in Reunion Island. Usually, the equivalent thermal resistance is determined in steady-state conditions whereas the focus of this paper is the determination of equivalent thermal resistance in dynamic conditions. To obtain more precise information for the determination of equivalent thermal resistance in these conditions, an international standard mean method [13] has been used, and is explained in the following paragraph.

2.3.1. The mean method

To evaluate the thermal resistance from dynamic field measurements, the mean method is used. This method is applied to dynamic data series and can be summarized by the following equation (1):

$$R = \frac{\sum_{i=1}^{n}\left(T_{se,i} - T_{si,i}\right)}{\sum_{i=1}^{n}\varphi_i} \quad (1)$$

With: $\begin{cases} R\ thermal\ resistance\ of\ the\ wal \\ T_{si,i}\ interior\ surface\ temperatur \\ T_{se,i}\ exterior\ surface\ temperatu \\ \varphi\ heat\ flux\ through\ the\ wall \end{cases}$

This method requires many conditions to validate the results and respect conservation of energy over the entire study period. To validate the results, two criteria must be respected during the calculation in order to determine the thermal resistance in steady-state conditions [2]:

1. The percentage difference (ε_1) between resistance calculated from the entire data series and resistance calculated from the database minus one day must be less than 5%.
2. The percentage difference (ε_2) between resistance calculated from the first $\frac{2}{3}$ of the data series and resistance calculated from the last $\frac{2}{3}$ of the database must be less than 5%.

Miranville implemented the mean method in the building simulation ISOLAB during his post-doctoral degree (authorisation to supervise PhD students). The method used was a specific model able to determine the thermal performance of building materials. This module is very easy to use. It requires either a series of simulation results or measurements from experimental data. The following figure illustrates the procedure:

Figure 1: Calculation of thermal resistance in ISOLAB

In this case, the complex roof consists of both homogenous and inhomogeneous material with an air layer with different modes of heat transfer. The presence of an air layer can have an impact on the thermal performance depending on convection intensity. The air layer can be ventilated or not and will modify heat transfer. These different conditions are taken into

account by the module and ensures conservation of energy during the study period. Furthermore, the ε_1 and ε_2 indicators are verified as illustrated in Figure 1.

For the final calculation on a whole database or a part of it, the following parameters are taken into account:

- Positive heat flux conduction
- Day-time selection
- Night-time selection
- User-time selection

According to reference [2], these criteria allow for a pre-treatment of the database and increase the possibilities of exploitation of the data series. This approach constitutes an alternative option when the validity of the final results is not obtained.

In this part, a brief description of the mean method was presented. See [14] for more details.

3. Experimental environment

3.1. The experimental platform

The experimental platform was set up in the South of Reunion at the University Institute of Technology of Saint-Pierre (Reunion Island) at a low altitude (55 m). The total area of this platform was approximately 600m^2. Réunion has a tropical climate with strong solar radiation and humidity. These climatic conditions offer ideal conditions for an experimental study. This location was chosen by many researchers from the PIMENT laboratory to observe the phenomena relative to building physics [9].

Figure 2: Experimental devices

On the experimentation site, two experimental buildings were installed (see Figure 2), a small-scale device (named ISOTEST) [7,15] and a normal-scale (or unit scale) building (named LGI) [7,9] (see Figure 3). The ISOTEST building corresponds to the LGI building on a smaller scale. The different test cells are oriented north in order to receive symmetrical solar radiation. The test cells do not shade each other, and thermal interactions between the cells are negligible.

Figure 3: LGI and ISOTEST test cells

Two meteorological stations are installed near the experimental buildings, in order to collect meteorological data. These allows the data obtained by each one to be compared [9].

3.2. LGI test cell design

In order to observe building physics phenomena, an LGI test cell was used in real weather conditions. With dimensions of 3m (height) × 3m (weight) × 3m (length), it is representative of a typical room in a building encountered in Reunion Island. The modular structure of the roof allowed several configurations to be studied. The roof was inclined at 20° to the horizontal and was equipped with PCM. The suspended ceiling is made of plasterboard and PCM. The components of the LGI test cell are given in Table 1 and Figure 4.

Table 1: Arrangement of the LGI test cell [12]

Figure 4: Exploded view of the LGI test cell roof

With the aim of obtaining extreme condition input from the roof, a dark colour was chosen for the corrugated covering. In order to have different experimental conditions, a mechanical ventilation and split-system air conditioner were set up. For the experimental sequence, the blind windows and the windowpanes in the door were masked as shown in Figure 5. The geometric details without PCM were provided by [7]. The LGI test cell was chosen because it represents a typical lightweight construction with a low thermal inertia.

Figure 5: Experimental conditions

3.3. LGI test cell instrumentation

Sixty sensors were used in the study. These were located both in the enclosure and on the roof of the LGI test cell. The enclosure walls were equipped with thermal sensors on their surfaces. To highlight the effect of air stratification, the interior volume was measured at three different heights from the floor. The ground is the part of the building where the boundary conditions are very difficult to measure and to overcome this problem, thermocouples were placed in the concrete floor. Experimental measures are used as boundary conditions without taking into account the ground model. This way, it possible to avoid errors in the code validation step. The thermocouples were checked before use and were placed in three different positions:

- On the inside surface of walls for surface temperature measurements
- Inserted in an aluminium cylinder for air temperature measurements
- Put inside a black globe for radiant temperature measurements

All surfaces of the complex roof were also instrumented. Heat fluxmeters were installed on the roof surfaces, PCM and plasterboard to determinate the heat flux through the complex roof with PCM. In the air layer, radiant and air temperatures were also measured as described above.

To ensure the accuracy of the measured data, protocol dictates that each thermocouple be calibrated on site and that factory sensors be checked. Margin of error from the thermocouples is about $\pm$ 0.5°C. According to the manufacturer's data, the error margin of the heat fluxmeters is approximately 5%. The temperature error margin from the entire data acquisition system is estimated to be $\pm$ 1°C.

A data logger was installed in the LGI test cell to automatically collect the data from the sensors every 15 minutes. All data were saved on a computer.

3.4. Description of PCM test

In this paper, the PCM tested is the commercial product from Dupont™ called Energain®. It is a flexible sheet 5 mm thick, made of 60% microencapsulated paraffin wax within a copolymer laminated on both sides by an aluminium sheet. The dimensions of the Dupont™Energain® are 5.26 mm in thickness, 1000 mm in width and 1198 mm in length. The composite PCM heat capacity was measured using a differential scanning calorimeter. The heating and the cooling rate is 0.05 $K.min^{-1}$. The freezing and heating curves are given in [6]. The latent heat of melting and freezing are 71 $kJ.kg^{-1}$ and 72.4 $kJ.kg^{-1}$ respectively, and the phase change temperatures are 23.4°C and 17.7°C respectively. According to reference [6], the difference between the melting temperature and the freezing temperature characterizes the hysteresis of the material, i.e the fact that the mixture is not a eutectic. In their work, the hysteresis effect is highlighted but in this case it is ignored. From the values given by Dupont™Energain®, the densities are 750 $kg.m^{-3}$ in liquid phase and 850 $kg.m^{-3}$ in solid phase. Thermal conductivities were measured using the guarded hot-plat test method [16]. The value varies between 0.18 $Wm^{-1}K^{-1}$ (liquid phase) to 0.22 $Wm^{-1}K^{-1}$ (solid phase). These parameters are dealt with in detail in [6,17].

3.5. Climatic data and experimental sequences

The tests were carried out between August and October 2012. After studying the data from different meteorological stations on the site, this period was chosen to ensure phase change and regeneration of the PCM. During the experimental sequences, the most important physical variables were measured every day. Variables measured included, solar radiation (global, direct and diffuse, on a horizontal plane), ambient air, exterior relative humidity, wind speed and

direction. The data is measured every minute, and every 15 minutes an average value is calculated and saved.

The data from 20th September to 24th September 2012 are given in Figure 6.

Figure 6: The climatic conditions during the experimental period [12]

4. Results

4.1. Introduction

The experimental platform is located at low altitude and near the coast, and is subject to variable weather all year round. The difference between summer and winter for experimental location usually depends on wind conditions. Winter was chosen for the experimental sequence presented here because this season offered ideal conditions for this study. In Figure 6, during the daytime, exterior air temperature varied between 16°C and 27°C, global solar radiation reached 1000 $W.m^2$ and was unchanged through the study period. The exterior relative humidity rate oscillated between 60% and 80%, the mean of wind speed was generally 4 $m.s^{-1}$ except on one day when it reached 6 $m.s^{-1}$ (corresponding to trade winds) (Figure 6(b)). Trade winds occur in winter in Reunion Island. On days where trade winds are observed, the exterior air temperature is relatively low.

In order to obtain accurate measurements from the complex roof components, sensors were placed at three levels (top, middle and bottom) and fully instrumented as shown in Figure 7. To ensure good experimental data, the middle values of the complex roof were used.

Figure 7: Instrumentation of the complex roof

4.2. Experimental results

To begin with, the curves obtained during the experimental period are in agreement with the physical phenomena observed because from the roof cover to the inside surface of the

plasterboard, the temperature decreased. The corrugated iron is the surface where the solar radiation is highest and will have a tendency to heat more than other walls of the complex roof. In Figure 8, the temperature of a corrugated iron reached 50°C. However, according to reference [2], the temperatures of the corrugated iron are often superior to the value obtained.

Figure 8: Surface temperature of each roof component

The maximum temperature difference between the inside plasterboard surface and the outside PCM surface can reach 5°C (see Figure 9). These results are very interesting because without using other thermal insulation and with a low PCM thickness, the inside surface temperature of the plasterboard is reduced. However, it is necessary to check that the PCM temperature is on either side of the melting temperature in order to regenerate it. That's why a heat fluxmeter was installed on each surface as shown in Figure 10.

Figure 9: Difference between exterior surface PCM temperature and inside plasterboard surface temperature

Figure 10: Heat fluxmeter on PCM exterior

This step is required to ensure that the physical phenomena can be observed. According to Figure 11, phase change occurred. The phase change shows that PCM installed is working at full efficiency and justifies the chosen assembly. Although the air layer is not ventilated, PCM regenerates during the night. This last point is important because performance may be enhanced by ventilating the upper air layer and ensuring phase change every day without using additional appliances. A study on the ventilation rate of the upper air layer is required. Thermal insulation can be installed on the exterior PCM surface to enhance thermal comfort and give a higher energetic performance of the LGI test cell.

Figure 11: Phase change on 21th September 2012 (day)

During the daytime, the heat flux measured in outside PCM surface is higher than the inside plasterboard surface. At night, the phenomena are reversed. A plausible explanation may be that during the day the energy is stored and during the night the energy is released by the

PCM. The temperature curves are consistent with heat flux curves and show that PCM is able to reduce heat transfer from the outside to inside of the test cell. PCM is effective for the given configuration.

ISOLAB has already been validated by the IEA BESTEST protocol (International Energy Agency for Building Energy Simulation Test) for the LGI test cell without PCM. To highlight its impact on the inside air temperature of the test cell, a simulation without PCM was run in order to compare results from experimental data. These results are illustrated in Figure 12. Without PCM, the inside air temperature is higher than the test cell equipped with PCM. During the daytime, a peak difference of temperature of 2.4°C is observed. Temperature rise is also delayed as shown by the curves [12].

Figure 12: Comparison of test cell air temperature with and without PCM [12]

4.3. Determination of the R-value

Experimental data and the mean method were used to determine the R-value of the complex roof. The upper air layer is obstructed and no ventilation takes place. In this case, the curve between the two roof boundaries is shown in Figure 13. Evolution of temperatures in the roof covering and inside plasterboard is similar with an average value of 2.15°C, a minimum value of 7.87°C, and a maximum value of 26.10°C. The heat flux through the roof is also periodic, with an average value of 0.69 $W.m^{-1}$, the minimum and maximum values being -1.69 $W.m^{-1}$ and 5.53 $W.m^{-1}$ respectively.

Figure 13: Heat flux through the roof and temperature difference between corrugated iron exterior and plasterboard interior.

The R-value was calculated by applying the calculation module implemented in ISOLAB code and leads to the following values:

$$\begin{cases} R = 0.60\ m^2.K.W^{-1} \\ \varepsilon_1 = 0.80\% \\ \varepsilon_2 = 5.61\% \end{cases}$$

Under steady-state conditions a hypothesis is obtained, the R-value being calculated using the sum of thermal resistance of each wall and taking into account the exchanges of convection and radiation, and applying the Reunion Island thermal rules on the air layer. This gives a value of R=0.61 $m^2.K.W^{-1}$. The value is of the same order as the one determined by the calculation module. It is noticed that the R-value is very small and that the result was expected. This result can be explained by the thickness of the upper air layer and thermal insulators that have not been added to the complex roof. In addition, the air layer was not ventilated and hence heat exchanges by convection are smaller. It should also be noted that the R-value is similar to that obtained by a radiant barrier used on the same test cell. However, the thermal resistance value is significant and shows that PCM alone can not be considered as a thermal insulator but as supplementary insulation. This is consistent with the literature.

5. Conclusion

This article deals with the first experimental study carried out in Reunion Island on a complex roof with PCM in real conditions. The significance of this article results both from the choice to install PCM and the determination of thermal performance via the R-value in dynamic conditions.

It was necessary to test PCM without using a thermal insulator in order to determine its performance. A PCM was set up in these conditions to highlight the phase change process and to use the reflective properties of its surfaces. The PCM phase change occurred and is guaranteed for the given configuration. It is very interesting because PCM can regenerate without the help of appliances. This is a positive point in terms of both energy consumption and environmental impact because no fossil fuel is used to generate energy, to power appliances

to facilitate phase change. Thus, its inclusion in the complex roof reduces heat transfer, in most cases by infrared radiation.

This configuration clearly showed the phase change phenomena. Comparison with the roof without PCM made it possible to highlight the exact phenomena. On either side of the melting temperature, it is observed that energy is stored during daytime and released during at night, implying a delayed energetic demand. By adding PCM, the temperature of test cell was reduced by approximately 2°C. Following these observations, the R-value was calculated in order to evaluate PCM performance.

The mean method was used to asses thermal performance of the LGI test cell equipped with PCM. The principle of conservation of energy was respected and was applied to the ISOLAB code. Experimental measurements in realistic conditions were used. The results give a low R-value corresponding to the experimental conditions. Furthermore, the mean method is able to determinate the thermal performance of any building envelopes with PCM, and this value can be improved by adding a layer of thermal insulation. The value obtained is equivalent to the thermal performance of the radiant barrier value determined for the same LGI test cell. However, other scenarios must be take into account such as a naturally ventilated or mechanically ventilated air layer in order to determinate the R-values for these conditions. Many experimental studies need to be done.

These particular components of the complex roof were chosen to obtain numerical values. The numerical code developed is able to take into account the thermal behaviour of building envelopes, including PCM, and was incorporated into the ISOLAB code. The results of the numerical simulation and validation of the thermal model will be presented in a future publication.

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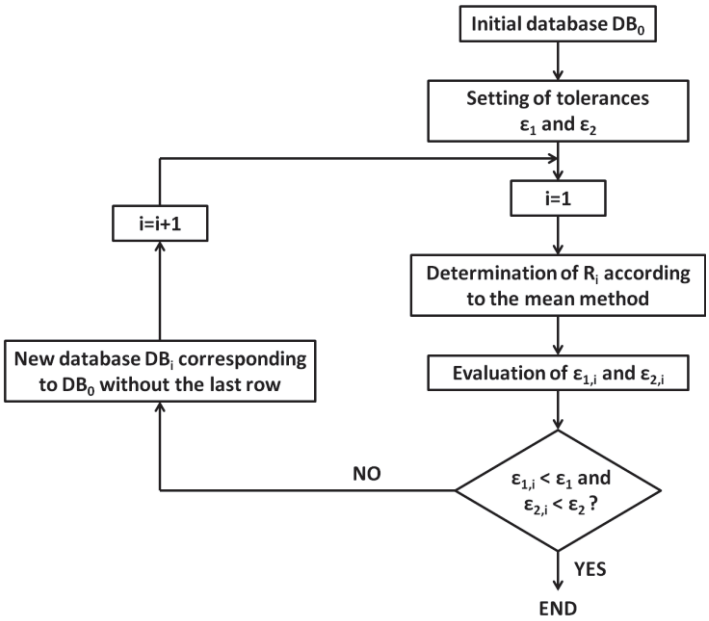


Figure 1: Calculation of thermal resistance in ISOLAB

Figure 2: Experimental devices

Figure 3: LGI and ISOTEST test cells

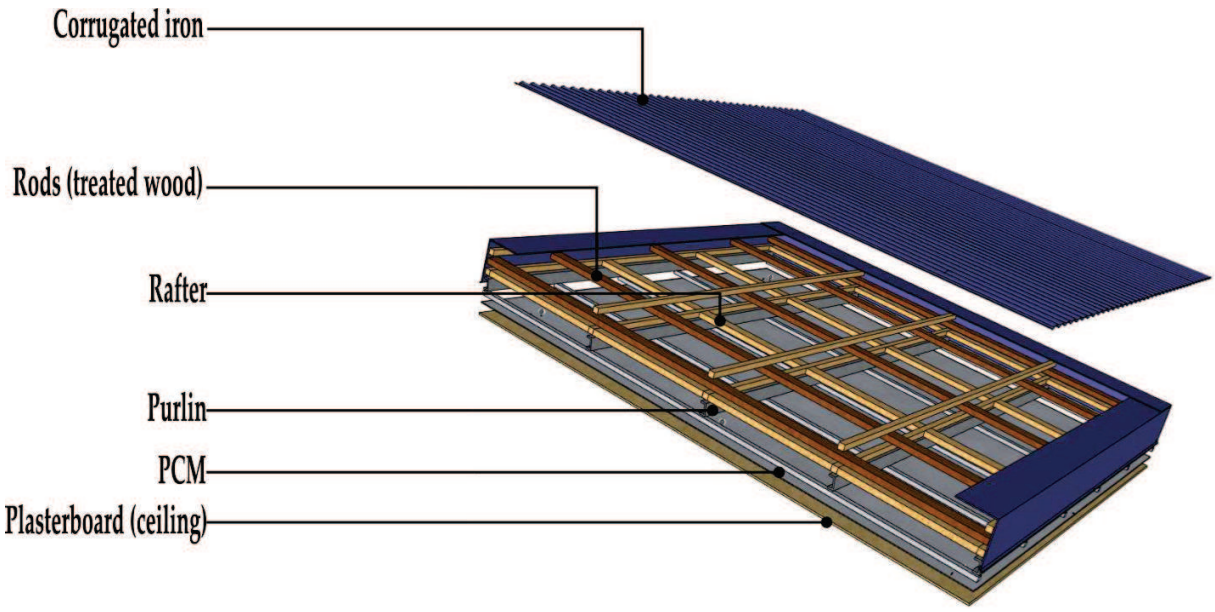
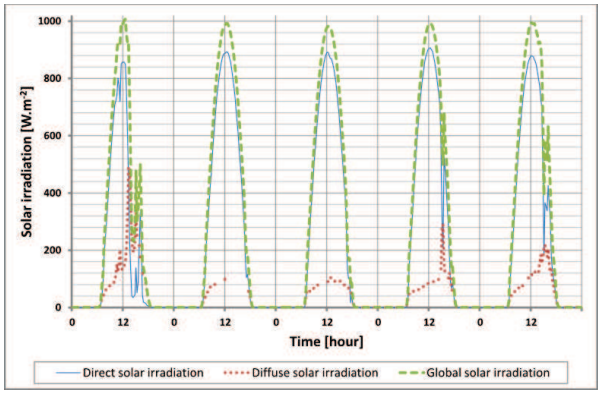


Figure 4: Exploded view of the LGI test cell roof

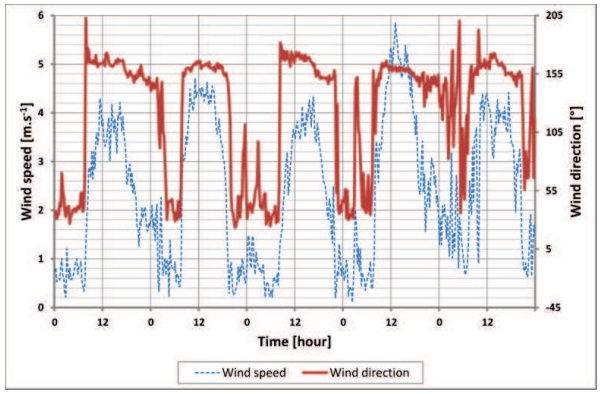
(a) Blind windows

(b) The window panes in the door

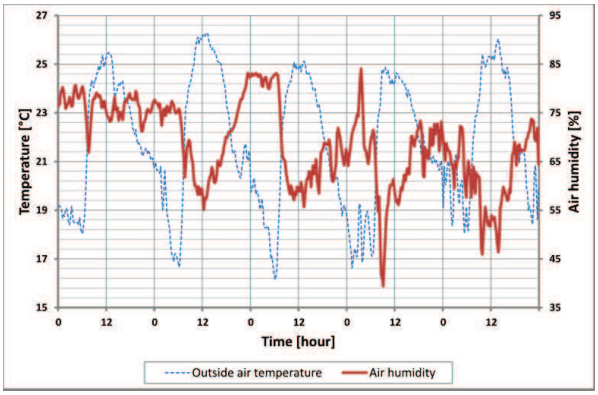
Figure 5: Experimental conditions



(a) Solar irradiation



(b) Wind speed and wind direction



(c) Outside air temperature and air humidity

Figure 6: The climatic conditions during the experimental period [12]

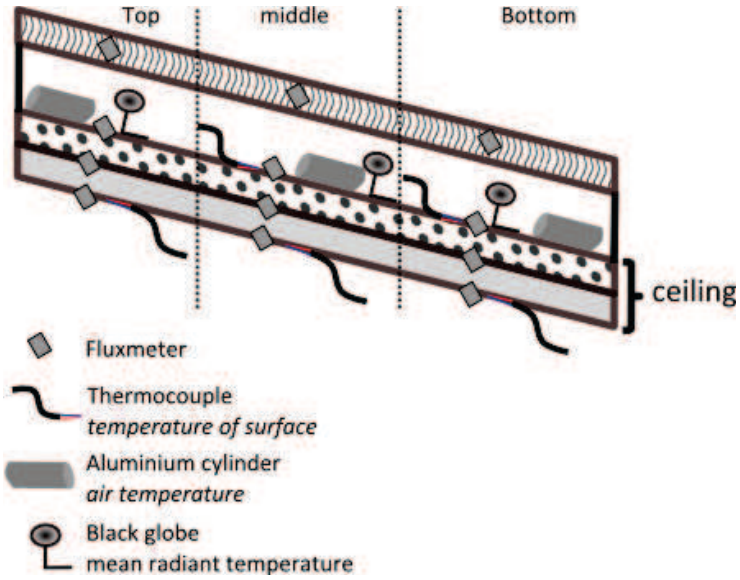
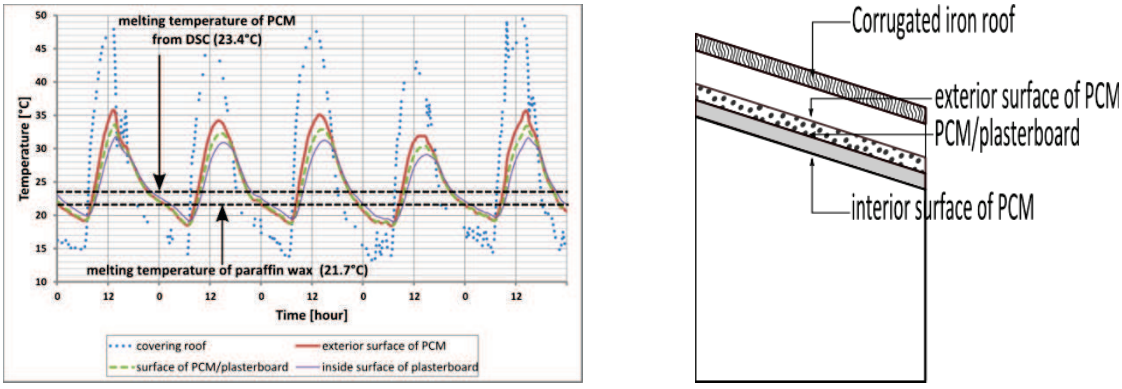


Figure 7: Instrumentation of the complex roof



(a) Temperature (b) Localization

Figure 8: Surface temperature of each roof component

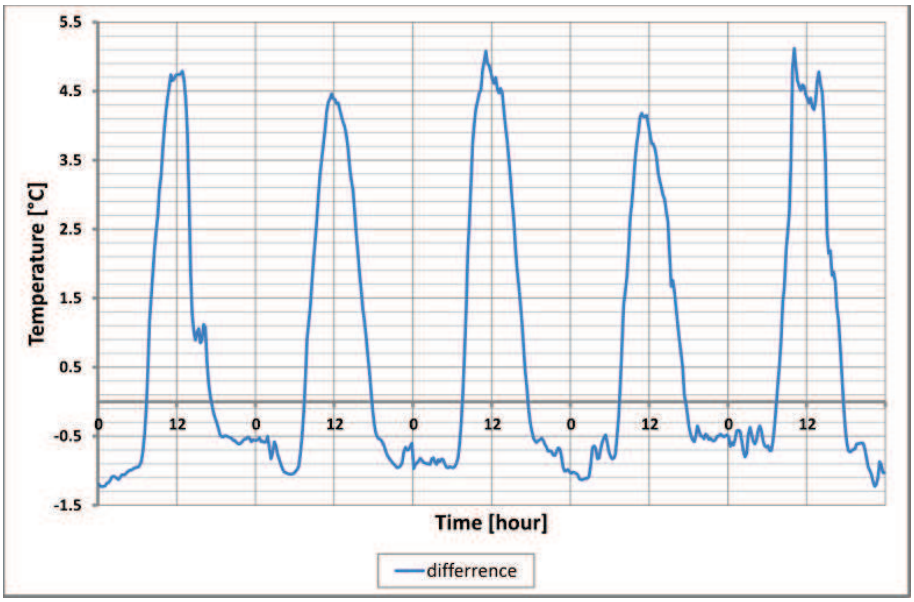


Figure 9: Difference between exterior surface PCM temperature and inside plasterboard surface temperature

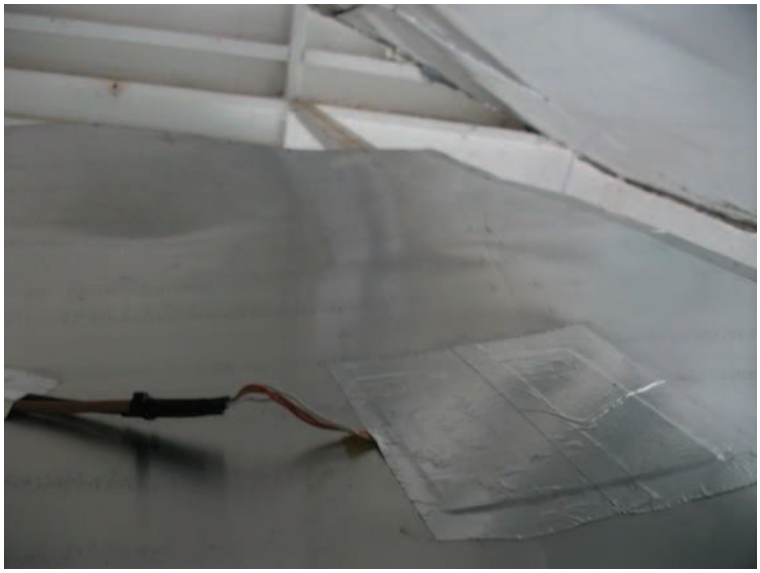


Figure 10: Heat fluxmeter on PCM exterior

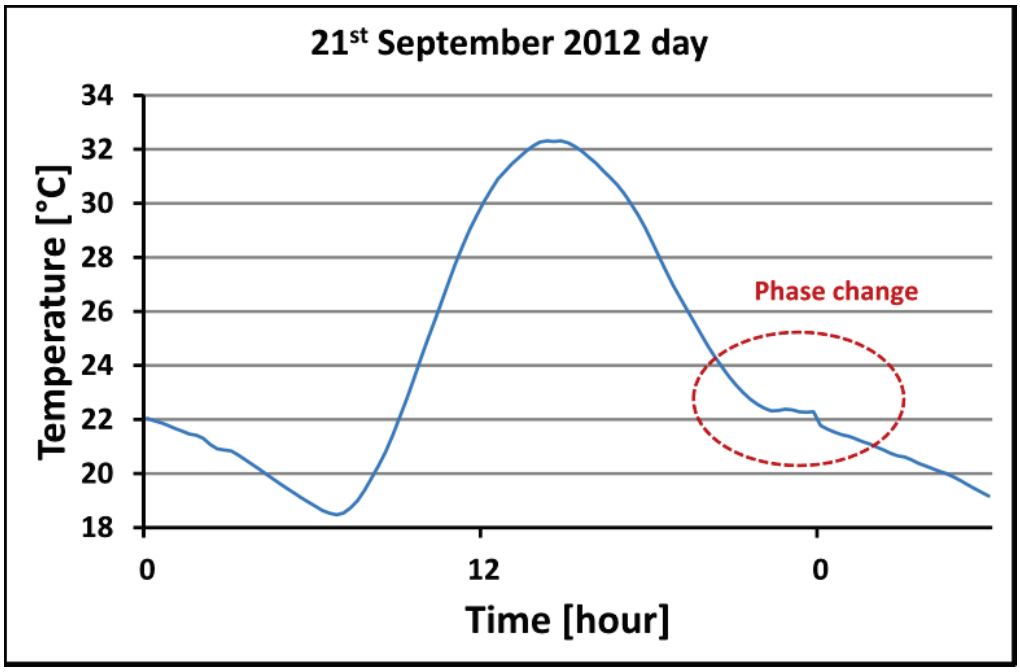


Figure 11: Phase change on 21th September 2012 (day)

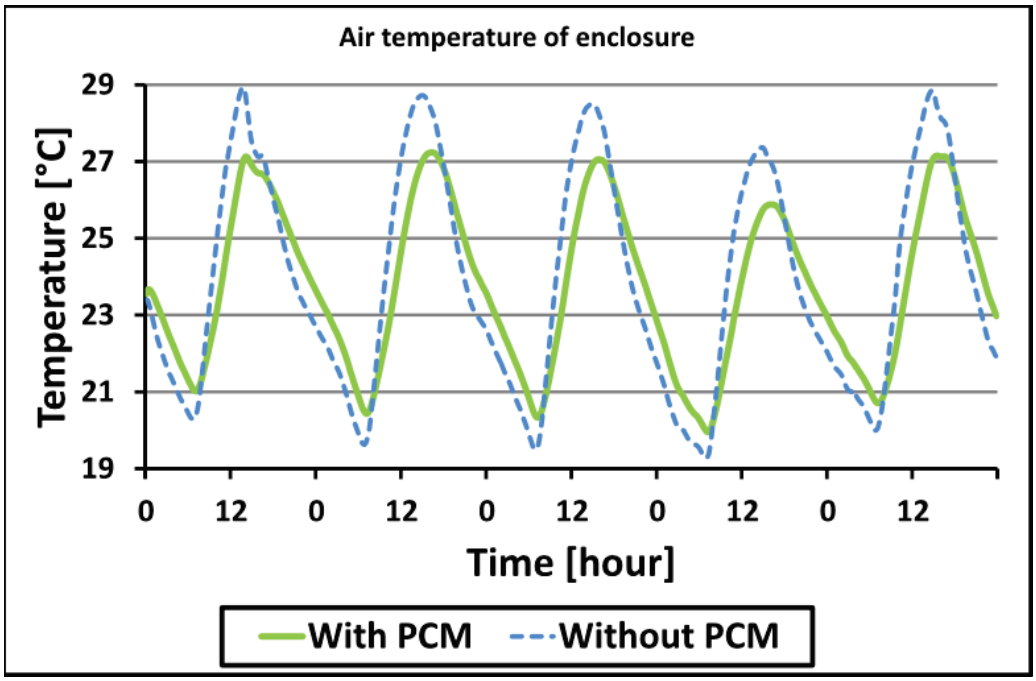
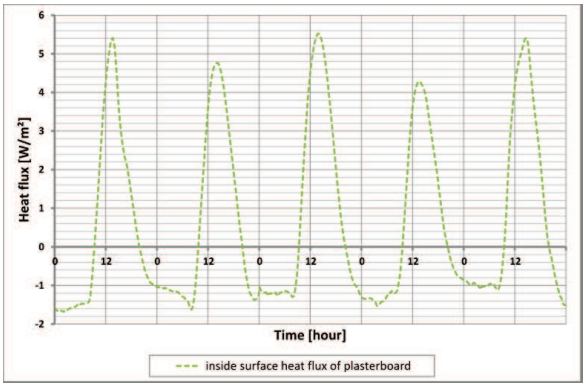
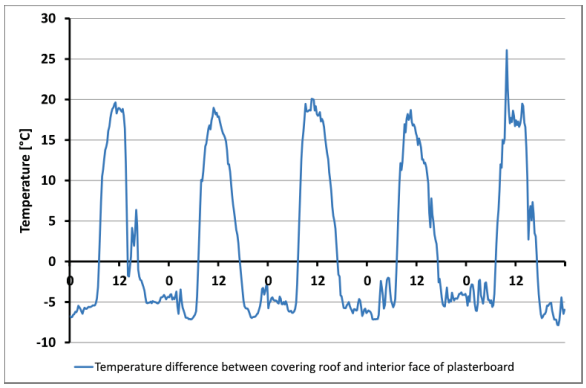


Figure 12: Comparison of test cell air temperature with and without PCM [12]



(a) Heat flux



(b) Temperature difference between the two boundaries of the roof

Figure 13: Heat flux through the roof and temperature difference between corrugated iron exterior and plasterboard interior.

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List of tables

Element	***Composition***	***Remark(s)***
Opaque vertical walls	Sandwich board 80mm thick cement-fiber / polyurethane / cement-fiber	
Window	Aluminium frame, 8 mm clear glass	Blind-type 0.8x0.8m
Glass door	Aluminium frame, 8mm clear glass	Glass in upper and lower parts, 0.7x2.2m
Roofing complex	Corrugated galvanised steel 1 mm/air layer of 280 mm thick/PCM 5.26 mm thick/ Plasterboard 12.5 mm	PCM is laminated to aluminium protective foils. Roof inclined at 20°
Floor	Concrete slabs 80mm thick on 60 mm thick polystyrene	

Table 1: Arrangement of the LGI test cell [12]

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- *Highlights*

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Highlights

- First experimental investigation conducted in Reunion Island for a tropical and humid climate
- Experimental method to evaluate R-values of Phase Change Materials in a dynamic state
- The method used field measurements from an experimental test cell
- R-values are proposed for winter over a period of five days
- The mean method is used to determine thermal performance of Phase Change Materials