Experimental and Numerical Investigation of Thermal Energy Storage in Natural Stone Treated with PCMs

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Abstract

Improving energy efficiency in buildings is a matter of concern nowadays, since it can essentially contribute to reducing both CO_2 emissions and global energy demand. Towards this direction, the use of Phase Change Materials (PCM) is promoted, as an energy storage solution in the building sector. The application of PCMs in building elements such as wall layers made of concrete, gypsum or plasterboard panels helps in stabilizing abrupt variations of room temperatures within the human comfort zone throughout the day, leading to the reduction of energy demand in buildings. In this work, the potential of PCM treated natural stone to be used as construction material with the ability to store thermal energy, is investigated. At first, and in order to experimentally demonstrate the effectiveness of this concept, a number of "model" pilot stations made of concrete and "Bateig azul", a Spanish natural stone (with and without PCM) for the façade, have been built and placed outdoors. Temperature measurements were obtained in the interior of the pilot houses for several day – night cycles. Secondly, two simulation models have been developed and are presented, based on MATLAB – Simulink and on the heat transfer analysis computational tool TRNSYS. Their performance is evaluated with respect to the aforementioned measurements. It is shown that a good agreement between computational results and experimental data can be achieved and discussion is mainly focused on (a) the PCM influence, when added to the natural stone façade and (b) the possibility of exploiting the advantages of both implemented models as a future task, by developing an efficient coupled solver combining the TRNSYS platform for the simulation of complex building structures and the MATLAB – Simulink for the prediction of thermal behaviour at a component level. This part of the study is classified under the framework of developing dedicated computational models with the

ability to accurately predict composite wall materials - components thermal behaviour and thus support potential energy saving studies in buildings.

Keywords: phase change materials (PCM), MATLAB - Simulink, TRNSYS

1. Introduction

It is well known that the building sector is responsible for more than 40% of the total EU energy consumption. Thus, it represents today the highest potential in terms of energy savings. Many European studies carried out have assessed the impact of energy saving in the building sector. It has been proven that, by saving 20% of energy consumption, it would be possible to secure 50% of the necessary reductions of CO2 emissions and to save up to 60 billion Euros every year on the energy bill (Green Paper on energy efficiency, 2005)

Specifically, buildings smaller than 1000 m^2 represent 90% of the potential energy, CO_2 and cost savings in the residential sector (EURIMA). Extension of the Directive on the Energy Performance of Buildings to these residential buildings would enable to:

- Save up to 270 billion EURO a year in energy costs at current energy prices,
- Reduce energy use by the equivalent of 3.3 million barrels of oil a day (compared to 6 today),
- Reduce CO_2 emissions of 460 Million tonnes a year by 2032.

Improving energy efficiency in the building sector can drastically contribute to reducing CO2 emissions and EU energy dependence. Significant efforts are currently made to promote the introduction of new technologies around improved materials (such as insulation, glazing, energy storage through phase change materials) that can find direct application in “energy efficient buildings” such as dwellings, offices, hospitals, schools, factories, airports, rail stations, public buildings, for new and retrofitted buildings and retrofitting Cultural Heritage.

Towards this direction, a demo house in Amphilochia, Greece is being built within the frame of the EU-NMP funded projects I-SSB and MESSIB, where innovative elements will be integrated with conventional technologies, RES, and building architecture. Multi-source energy storage systems such as phase change materials for improved active components and ground storage will be installed, monitored and evaluated in the building. The present study can be classified under the framework of developing new dedicated simulation tools for the integrated simulation of a building. These tools will support the construction process of the building and will aid in optimizing its operational parameters. They must consist of discrete reliable computational models, with the ability of accurately predicting the individual phenomena, associated with the technologies that will be integrated in the design of the building. The objective is to achieve maximum performance of the systems and the successful introduction of energy efficient technologies in building under an integral approach.

2. Phase change materials and energy saving

In building applications, PCMs can be used to control internal temperatures. PCMs have a characteristic melting point. When temperatures become warmer, the PCM is liquefied by absorbing and storing heat, leading to the cooling of the house. Conversely, when the temperature decreases and becomes cooler than the PCM's characteristic melting point, the material solidifies and the previously absorbed heat (latent heat) is subsequently released, leading to the warming of the house. By incorporating PCM in the building envelope, they can absorb heat due to the higher exterior temperatures during the day, and dissipate the heat to the interior at night when it is cooler. This absorption and release of heat takes place at a constant temperature, which is ideal to smooth temperature fluctuations. Several building materials exhibit a low heat capacity. Introduction of phase change materials into the building materials will considerably increase the thermal mass of the building.

Properties of PCM that are desirable for residential use include:

- A melting temperature above 25°C,
- low cost material,
- not toxic, corrosive, or hydroscopic, and
- Commercially available in sufficient quantities for producers to incorporate into ordinary building materials.

The addition of PCM in construction materials such as concrete, gypsum or plasterboard panels is promoted, as an energy storage solution to reduce energy demands in buildings. In this work, computational models are built in order to simulate a system for thermal energy storage with walls of natural stone treated with PCM. The computational results are validated against experimental results. The viability of natural stone as a system for thermal energy storage is considered of great importance due to their aesthetic value and their versatile applications in facades, walls, floors, etc.

The use of Phase Change Materials (PCMs) for energy storage purposes in buildings has been proposed since the first applications in the 1940s. However, in the last two decades it has become an object of increasing interest. Several review papers can be found in the literature, providing a thorough analysis on the main characteristics of PCMs and presenting the latest developments in their application for buildings heating and cooling. Zalba *et al.* (2003) have reviewed the history of energy of thermal energy storage with solid – liquid phase change, depicting the materials that have been used as PCMs, focusing on their applications and elaborating on the numerical solution of heat transfer phenomena, occurring in energy storage systems associated with phase change. Farid *et al.*, (2004) have also presented a review of PCM implementation, focusing on their encapsulation, summarizing their applications in buildings and reporting on all the recent technological innovations, that are associated with PCMs. Tyagi and Buddhi (2005), have examined the thermal performance of various PCM systems to evaluate their potential for use in buildings heating and cooling. Other references demonstrating the use of PCMs to improve thermal properties of construction materials, such as concrete or gypsum, can also be found in the literature. Hawes (1990) has studied the thermal performance of PCMs in different types of concrete blocks. Thermal storage in concrete containing PCMs was increased more than 200%. Salyer *et al.*, (1995) have developed different methods of PCM incorporation to building blocks: by imbibing the PCM into porous materials, PCM absorption into silica or incorporation of PCMs to polymeric carriers.

Natural stones are commonly used for external façades and internal (floors, walls etc) building applications. The use of PCMs for the treatment of natural stone in order to improve its thermal properties is proposed for several reasons:

- Energy savings in heating/cooling systems;
- Enhancement of thermal comfort inside the building (reduction of temperature differences between day and night and different rooms inside the building);
- Storage of the heat from outdoors; Avoid excessive heat from outdoors.
- Protection of the natural stone in extreme climatic variations

3. Experimental work

3.1 The pilot stations

In order to demonstrate the effectiveness of PCM treated natural stones, a number of pilot stations made out of concrete and The Spanish marble “Bateig azul”(with and without PCM) for the façade have been built and placed outdoors, in Alicante - Spain (Figure 1). The pilot house model has been selected as a simplified, standard case, fitting for the demonstration of the PCM influence in natural stones.

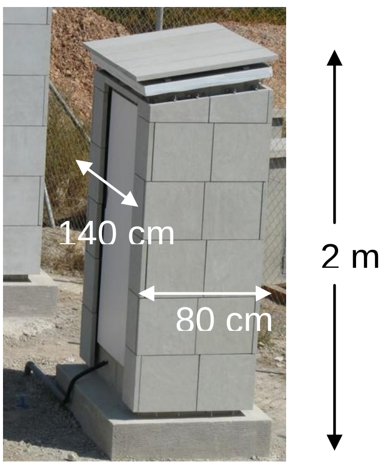

Figure 1: Pilot station made of concrete and Bateig Azul as natural stone for the façade.

Temperature sensors have been placed inside and outside the pilot stations, measuring both ambient and interior temperature for several day-night cycle every 10min. In this work, the period of measurements used for computational simulation is from the 2nd to the 3rd of September 2008.

The measurements show a reduction of temperature variations during the monitored time period, when natural stone is treated with PCM. Hence, an improvement in human comfort and a reduction of energy consumption can be anticipated. (Romero-Sánchez, *et al* 2009).

3.2 Materials

Bateig azul has been selected in order to study the thermal storage properties of natural stone materials after PCM treatment. This material is extracted in Novelda-Alicante-Spain. It is blue and consists of calcite and quartz, with medium porosity size.

The Micronal DS 5000X (provided by BASF) has been selected as the phase change material. It is a water-based solution with following characteristics: viscosity equal to 30-100 mPa·s, solid content of 1-43% and melting temperature ca. 26ºC.

Bateig azul has been immersed in this solution in order to be impregnated with the PCM. The measured thermal conductivity and volumetric thermal capacity of Bateig azul and Bateig azul with PCM are shown in Table 1.

Table 1: Thermal properties of Bateig azul and Bateig azul with PCM.

	Thermal conductivity (W/m·K)	*Volumetric thermal capacity (kJ/m3·K)*
Bateig azul	*1.87*	*2191.7*
Bateig azul -PCM	*1.99*	*2308.7*

The pilot stations have been made of concrete, while Bateig azul (with and without PCM) has been used as façade. The west side of the pilot station is a door. The properties of the materials for the door and the wall layers are shown in table 2.

Table 2: Thermal properties of wall layers and door

	Thermal conductivity (kJ/h·m·K)	*Density (kg/m3)*	*Thermal capacity (kJ/kg·K)*	*Thickness (cm)*
Concrete (wall)	*7.56*	*2400*	*0.8*	*7*
Polyspan Insulation (door)	*0.14*	*10*	*1.40*	*1*
Metal Sheet (door)	*720*	*2700*	*0.86*	*0.2*
PVC Coating (door)	*0.83*	*1500*	*1*	*1*

4. Computational models

4.1 Building a model in matlab – simulink

A simple model has been developed in MATLAB – Simulink for the simulation of the pilot houses. At this stage of the study, a simple case of natural stone without PCM has been considered for the façade. Heat balances taking into account conduction and convection effects are formed for two wall layers (concrete – natural stone), three door sheets (Polyspan – Metal – PVC), the air gap and the pilot stations internal space. Hence, the resulting model contains 7 ordinary differential equations calculating temperature distributions over time and can be written as:

$$\begin{cases} \dot{x}(t) = A * x(t) + B * u(t) \\ y(t) = C * x(t) \end{cases}$$

The u(t) vector is related to the model input, which in this particular case is the measured ambient temperature. The output y(t) vector corresponds to the pilot houses internal room.

The geometry characteristics and thermal properties of the simulated case, as well as the resulting system of energy balances are incorporated in a specific m – file which has subsequently been linked to the Simulink model (Figure 2).

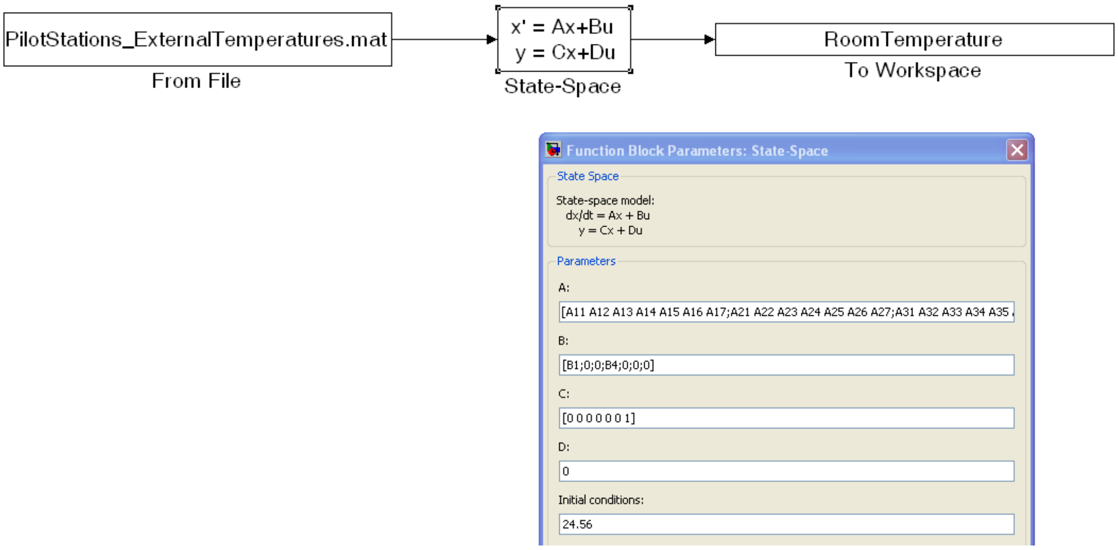

Figure 2: Model scheme by Simulink

4.2 Building a model in TRNSYS

The second model is built using TRNSYS software (TRNSYS). TRNSYS is a complete and extensible simulation program for the transient simulation of systems, including one-zone or multi-zone buildings. The systems are considered to be a set of components linked together to provide the results. Each component is called “Type” and Type 56 is the component which defines a building with different thermal zones. This Type solves a set of differential equations to compute the energy balance of each thermal zone (Ahmad *et al.*, 2005)

Among the components available in TRNSYS, walls of different materials can be chosen. A new wall component (Type 204) was added to TRNSYS to simulate the PCM wall. It was created by a team at Helsinki University, in which the heat equation is solved in 3D for PCM in various phases: solid, liquid or two-phase (Jokisalo *et al.*, 2000).

The pilot stations are modelled as one-zone building, using the properties of the materials given in TRNSYS library. The properties of the Bateig Azul containing PCM are used for Type 204. The pilot stations are located outdoors and are subjected to the local climatic variations. The weather file for Valencia - Spain is used. The file has been altered, in order to include the measured temperatures of 2^{nd} and 3^{rd} of September. The simulation is for three months, but only the results of those specific dates are evaluated. Ground temperature is considered constant.

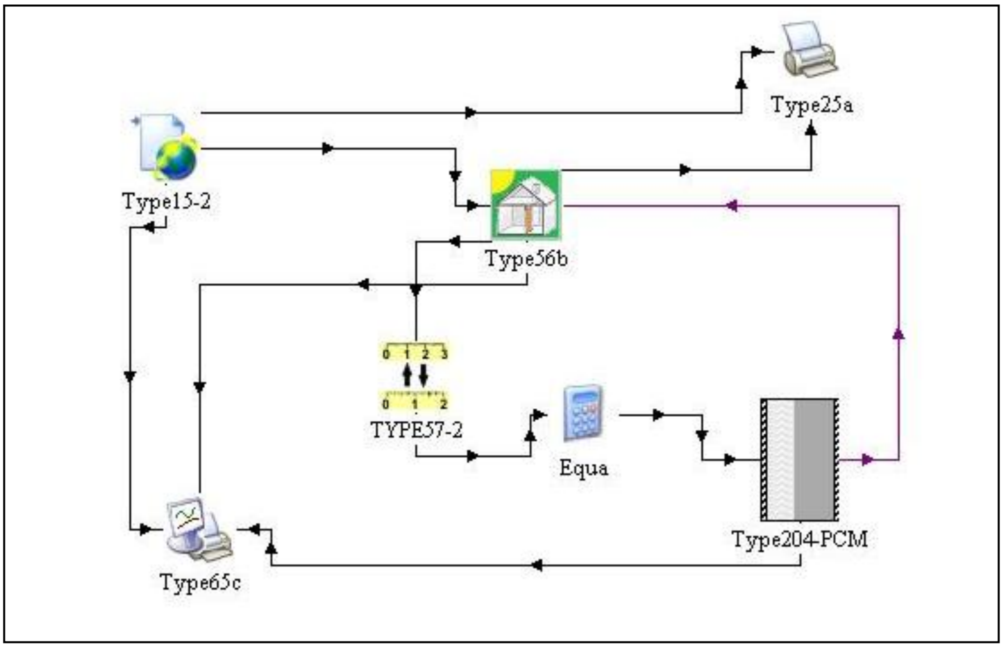

Figure 3: Diagram of the PCM wall simulation showing the links between the components in TRNSYS

Two simulation cases are considered: one pilot station without PCM and one with PCM. The results are then combined and compared to the experimental data. Type 204 is used to simulate the PCM case and takes into account the specific heat capacity (kJ/kg) and the density of the PCM, its melting point and the density and thermal capacity of the other material in the wall layer.

5. Results and discussion

The developed MATLAB – Simulink model has been incorporated for the simulation of the pilot houses thermal behavior during a two – day cycle, between the 2^{nd} and 3^{rd} of September. A simple case without PCM has been considered. Computational results show that the pilot house internal temperatures follow reasonably well the excremental data (Figure 4). However, it should be noted that the temperature distribution tends to be slightly over predicted by the implemented model. Further improvements are expected with the implementation of the ground temperature effect in the model. Additionally, ongoing and future work will focus on the extension of the existing model to take into account possible PCM effects in structural components.

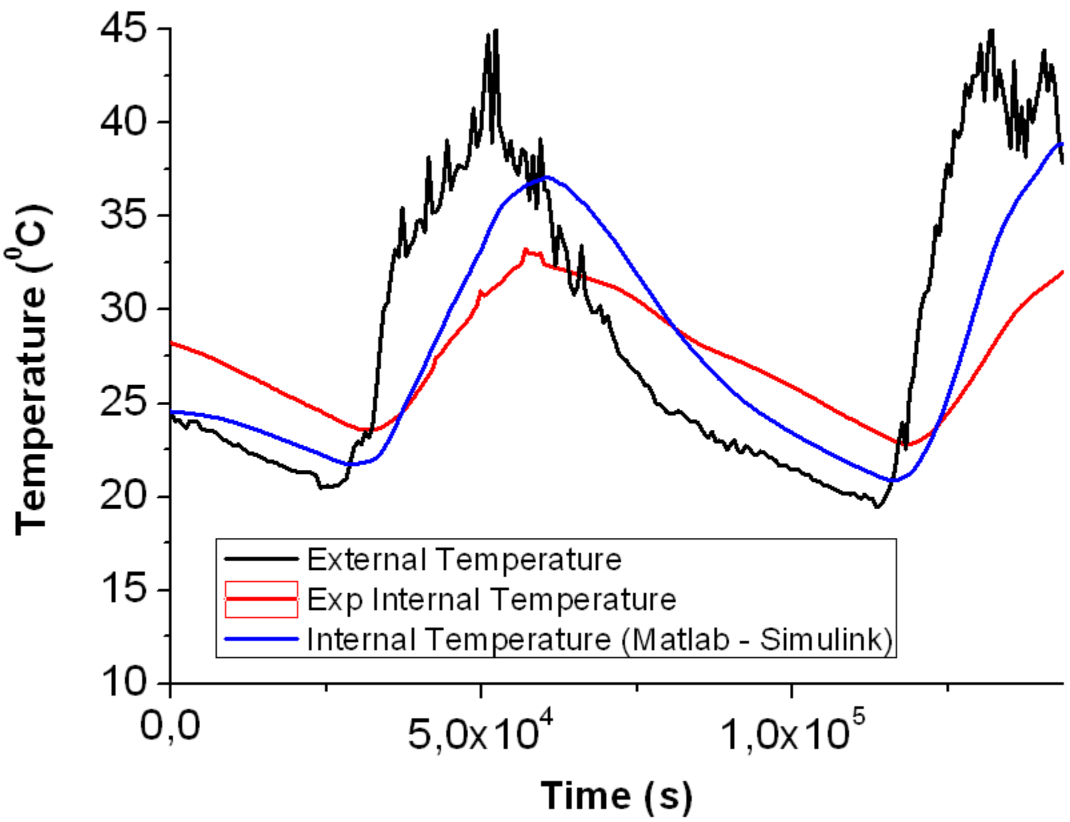

Figure 4: Temperature measurements and Matlab / Simulink model computational results – No PCM case

Fig.5 presents the internal room temperature of both pilot stations (without and with PCM) given by the numerical simulation using TRNSYS for the 2^{nd} of September, compared with measurements for the same day.

Measurements demonstrate that a small but noticeable difference is developed in internal temperatures when the pilot station case without the PCM is compared to the respective case of the PCM façade. The maximum recorded temperature in the PCM treated station is 1.2^0C lower than the respective maximum value of the station without PCM, demonstrating, at pilot scale, the application's energy storage potentials. The cooling process is smoother for the pilot station with PCM, indicating that the stored energy is being released. Minimum temperature in the PCM treated station is 0.6 ^{0}C higher compared to the station without PCM. It should be noted though that maximum recorded temperatures do not occur at the same time points as in the reference station and a small shift of approximately 2 hours is observed.

An overall good agreement is found between simulation and measurements. However, some discrepancies are evident, with computational results exhibiting a tendency to under predict the measured temperatures. These discrepancies can be attributed to the following factors: (a) the ground temperature is considered to be constant throughout the simulated cycle, (b) the inability to import the temperature variation curve of the utilized PCM's specific heat capacity (Cp) in TRNSYS. Thus a constant Cp value for the PCM wall has been considered and (c) assumptions made in the pilot house walls and door sheets material properties.

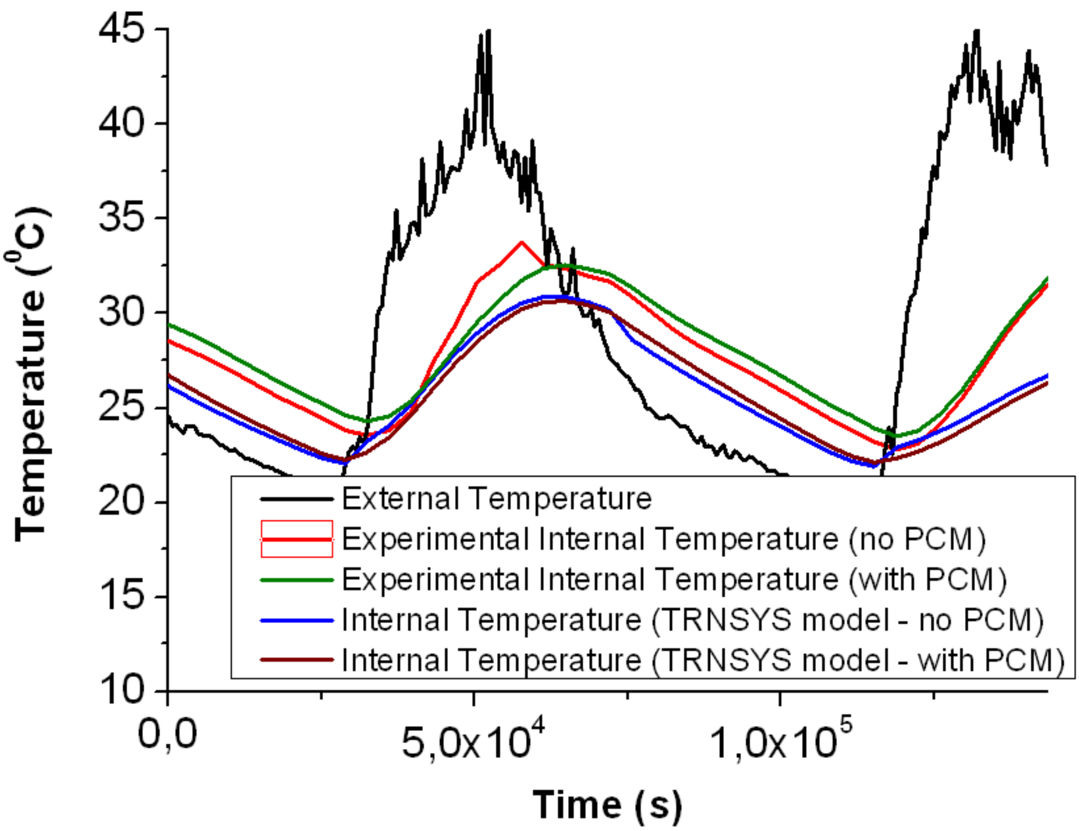

Figure 5: Temperature measurements and TRNSYS model computational results (no PCM / with PCM Cases)

The obtained results and above arguments support the development of a flexible and adjustable, coupled computational tool in a composite approach, which will be characterized by the merging of the two different computational models that have been developed in this study. Hence, the MATLAB – Simulink model will be merged with the TRNSYS software, in order to develop an efficient solver combining the advantages of both implemented components, depending on the specifications and complexities of the examined case. Consequently, the TRNSYS platform will be incorporated, in order to provide detailed information for complex building geometries and accurate predictions of HVAC systems characteristics. On the other hand and during the same simulation, MATLAB – Simulink model will be called by the TRNSYS platform, focusing on the calculation of possible thermal effects associated with PCM incorporation in structural components. Evidently, the combined computational tool will consist of two interacting parts. The first one (TRNSYS platform) will provide useful information on the thermal behaviour of buildings. The second one (MATLAB – Simulink) will concentrate on the accurate prediction of thermal characteristics at a component level.

6. Conclusions

In the present work, the thermal behaviour of two "model" pilot stations of natural stone and concrete, one of which contained phase change material in the natural stone has been experimentally and numerically investigated. The pilot houses have been selected as a simplified, standard case aiming to: (a) highlight the PCM influence when implemented in structural components and (b) be used for the validation of the developed computational tools.

Temperature sensors have been appropriately placed inside the stations, allowing the characterization of their thermal behaviour. Variations of temperature in different spots inside the "model" pilot stations have been monitored every 10 min for several day-night cycles. The resulting measurements demonstrate a reduction of temperature variations during the monitored period of time, when natural stone is treated with PCM. Hence, an improvement in human comfort and a reduction of energy consumption can be anticipated.

Two computational models have been implemented for the simulation of the model pilot houses. A MATLAB – Simulink model has been developed to calculate the energy balances defining the thermal behaviour of the pilot house without PCM. In TRNSYS, a new Type (204) has been implemented and properly modified, allowing for the simulation of the PCM wall. The predictive capabilities of both incorporated models have been assessed by comparing computational results with the aforementioned temperature measurements. In both cases, computational results show an overall satisfactory agreement with the respective measurements, however improvements are still needed.

Future work will focus on the development of an integrated computational tool merging both MATLAB – Simulink and TRNSYS models. The coupled solver will be implemented for the simulation of a demo house in Amphilochia - Greece where innovative elements will be integrated with conventional technologies, RES, and building architecture. The coupled solver will be able to simultaneously use the TRNSYS platform for the simulation of complex building geometries associated with sophisticated HVAC systems and the MATLAB – Simulink tool for the accurate prediction of thermal characteristics at a component level, when PCM are incorporated.

Acknowledgement

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