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Boosting Smart Building Energy Saving Capacity using Phase Change Materials

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***Abstract*— Energy consumption in buildings accounts for over 30% of the total energy use in the world, so it is a priority in the EU. Phase change materials (PCMs) can assist for thermal regulation, because they can save and release the heat. In smart buildings, consumers can incorporate in managing building energy systems, by Demand Response Programs (DRPs). One applicable method is to include PCM as interior coating. Two groups of tests in a test house are investigated concerning: (i) a case in which a PCM is introduced in the mortar; (ii) a base case in that a regular mortar is considered. The two cases are subjected to simulate real temperature variation (summer and winter scenarios). Temperature difference of the "measurement point" showed that the heating/cooling system is turning on for a total of 7.83h under winter scenario for the base case, whereas the PCM case allowed a decrease in the heating time to 7.75h, which represents a 1.1% saving alone. In the case of summer scenario, the heating/cooling system is turning on for 5.5h per day in the base case, whereas the PCM case allowed a decrease in the heating time to 5h, which illustrates a 10% saving alone.**

Keywords*— *Smart building, heat storage, dynamic electricity tariff, demand side management, demand response

I. INTRODUCTION

A. Motivation and Background

Energy consumption in buildings has significant portion of total demanded energy in developed countries [1], and it led to increase the energy efficiency in building sectors become of interest. In which there is wide range of research efforts on the sustainability and energy efficient systems to be used as building's element [2].

Smart grid is an idea to use the consumers' participation in order to improve the power systems efficiency from the generation side to the end user [3]. To provide the demand side activity, each Demand Response Program (DRP) is the important element of smart grids in future [4]. DPRs focus on switching the peak of the customer consumption to off-peak period in order to decrease the pressures on equipment [5]. Smart houses observe the usage and act to relieve the electricity cost. They can prepare the ground to enable demand side activities [6].

Heating and cooling equipment are the most energy consuming parts in buildings. So, the comfortable interior temperature needs to be maintained by a thermal system, with the minimum energy consumption [7]. Therefore, thermal energy storage systems have an important role in energy consumptions in buildings [8]. Also, home electricity consumption needs to track the DRPs by moving and curtailing the electricity loads to decrease electricity bills in a manner that the stage of comfort and gratification of users are accessible [9].

B. Relevant Literature

In [10,11], a household energy management (HEM) has been offered using DR strategies to bound the peak power for the smart building. In [12], optimization methods have been accessible for active operation of buildings according to the price signal based DR. In [13], a framework for HEMS is presented on the bases of an hourly measure of electricity use of appliances. In [14,15], a model is proposed to improve the load designs by using a time scheduling users. In each house presented in [14], everyday energy necessities and customer favourites were measured and their influence on peak curtailing and electricity price was studied. In [16], a scheduling problem embedded in HEMS, has been modeled and solved, that enabled users to overcome the major obstacles in implementing DRPs. In [17], they propose an association rule mining based quantitative analysis approach of household characteristics impact on residential ECPs trying to address them together.

One method that can be considered for the energy problem in buildings is thermal energy storage (TES) using phase change materials (PCMs) [18]. PCMs can assist for thermal regulation, because they can save and release latent heat through the phase change process. PCMs can be incorporated in several interior parts of the buildings to increase energy efficiency of the heating/cooling systems through reduction of their energy consumption during day and night. PCMs can be used in the structure of the building [19], interior coatings on the walls [20], building facade [21], and integrating PCMs into ventilation system as a part of building [22]. Among mentioned methods, there is one relevant way of including PCM as interior coating. The study presented in this paper focused on microencapsulated PCM incorporating into a mortar to prevent leakage of the PCM through the mortar [23]. Based on the previous works of the authors, PCM mortars can involve high amounts of PCM, reaching almost 20 wt.% of the whole mass of a mortar [24].

C. Contributions

Feasibility of incorporating PCM in the mortar may enhance energy saving during winter and summer seasons when compared to situations that PCM is not utilized. However, such PCM mortar is investigated at material level [25]. In this way, two sets of test cases in a test building are taken for the simulation regarding to the combination of the internal coating mortar of the external walls: (i) the case with a PCM mortar (SPCMM); (ii) the case with a regular mortar (REFM). These two cases are considered to simulated real temperature tolerances (both summer scenario and winter scenario), in order to evaluate thermal performance differences induced by each mortar and consequently the energy saving evaluation in real scale tests.

D. Paper Organization

The rest of the paper is organized as below. In section II, the methodology and implementation of the work is explained. In section III, numerical results are presented and finally there is section IV for the conclusion.

II. METHODOLOGY AND IMPELEMENTATION

An example for a smart home is shown in Fig. 1. It consists of some equipment as serious and manageable loads. The idea of the offered model is that the habitants utilize the heating system during the coldest times of winter days and it may rise the demand peaks.

Fig. 2 shows the heater mechanism. The bottom sensor is controlling the sensor of the heater within the prototype. The moving air in the prototype dominated by heating elements, because the existence of air convection impact should be taken into account that refers to the flow equations.

Two sets of numerical simulations are considered for this work. In fact, the effectiveness of PCM on the interior air temperature profile is assessed through simplified five storeys building located in Portugal. The entire 3rd floor is considered for the analysis. Two simulations are run in each set: summer and winter climatic conditions. The first set of simulation involved PCM where the PCM incorporated into the mortar to be used as interior lining of the walls.

A similar set of simulations is then performed with regular mortar (without PCM). Dimension of the simulated model in above sets is realistically large in term of volume of the interior air; it is a good representation of the effect of having larger surface areas of mortar with PCM participating in thermal energy storage.

The simulated flat is with interior dimension of 9.71m length, 9.71m width and 3m height (Fig. 3). The external walls considered to have a normal Portuguese layers by: a 0.02m thick of render wall (REFM), 0.1m of brick, a 0.03m of extruded polystyrene (XPS), another 0.1m thick of brick and a 0.02m of render wall (REFM or SPCMM) as inner coating. The flat had a heating/cooling system with surface area of 3.29m^2 capable power of 1500watt placed at the centre of the flat [26].

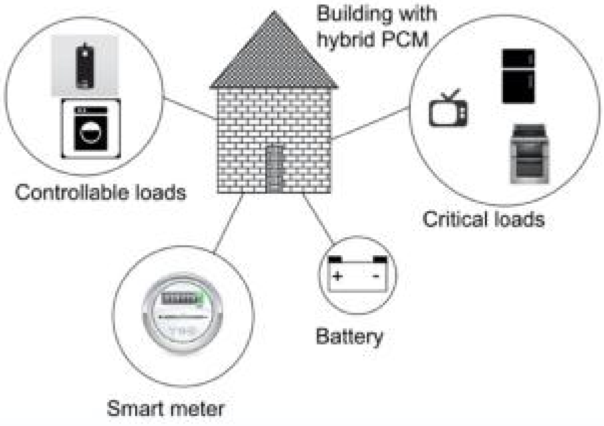


Fig. 1. Example of a smart household system.

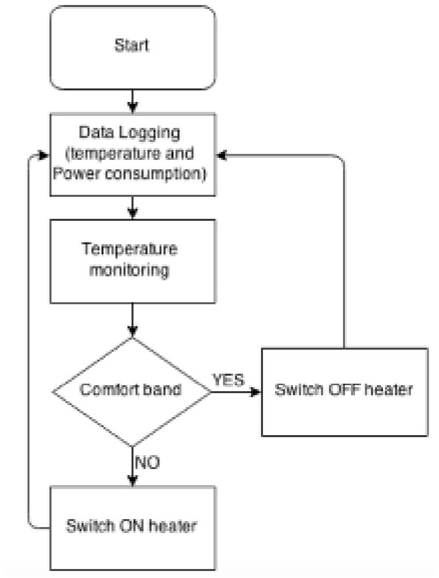


Fig. 2. Mechanism of a system with heater incorporated in the simulated model.

It is worth to mentioned that the exterior wall system have a thermal transmittance (U $\approx$ 0.7 W/m^2 K) which is less than the maximum limit regarding the Portuguese regulations for vertical elements (U = 1.45 W/m^2 K). The point labelled as X in Fig. 3 is considered as a reference point for temperature controller of cooling/heating system and for temperature analyses showed in this work. Cooling/heating system is set to 9 keep interior temperature at the desired temperature of 20ºC and 24ºC for the winter scenario and summer scenario respectively based on recommendation of the ASHRAE 55. The operation of the set point for temperature controller is ON/OFF mode depending to the defined set point (20ºC or 24ºC) for tested case upon winter or summer scenario. In principle, during winter scenario testing, when the temperature is less than 20ºC, the system is getting “on” and when it meets 20ºC, the system is getting “off”. During summer scenario testing, when the temperature is more than 24ºC, the system is getting “on” and it is getting “off” while the temperature is reaching 24ºC.

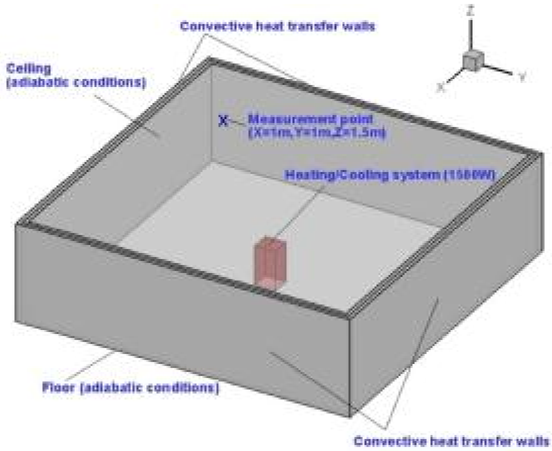


Fig. 3. Configuration of studied flat. Ceiling and floor are treated as adiabatic planes. Exterior walls boundaries are imposed to the convective

heat transfer that varied depending upon summer or winter scenario on the simulation.

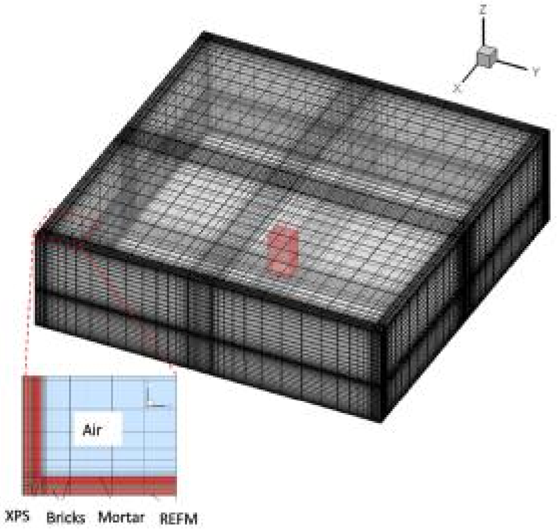


Fig. 4. The 3D model mesh and zoomed mesh.

ANSYS-FLUENT version 16.0 is used as the CFD software package to solve numerically Navier-Stokes equations. Phase changes effect of the PCM materials are handled through effective heat capacity method. In fact, specific enthalpy of phase change improves heat capacity value of the wall in heating or cooling processes. Regarding the simulation setting, the laminar model, employed for all sets of simulations.

The mesh of the model contains hexahedral cells. The mesh is considered fine at near wall distances. The present work utilizes the pointwise software to discretize the computational domain into smaller elements. The computational mesh of the model is built, being comprised of hexahedral cells (8 nodes) as shown in Fig. 4.

A pressure-based, transient, three-dimensional, viscous laminar solver with body force term, and user-defined function (UDF) assist the numerical computation. The proposed numerical solver takes into account that the air is an ideal fluid, and it is thermophysical properties are constant throughout. This is a necessary condition to appropriately recreate the heat transfer from walls to the flow when natural convection is accounted. Solar radiation effect is considering in a simple way in a sol-air temperature algorithm, regarding methodology details in reference [18].

A SPCMM with around 20% PCM in comparison with the whole mass of mortar is chosen [23]. The formulation of walls SPCMM considered here, includes PCMs with melting temperature of 24ºC [23]. The SPCMM structure generally reaches 18.34 wt% of PCM in the mortar. Some thermo-physical characteristics of materials used in both mortars, REFM and SPCMM, are presented in Table I [23]. Table I also includes data for the XPS, brick and the air which are parts of the mentioned mortar system.

III. NUMERICAL RESULTS

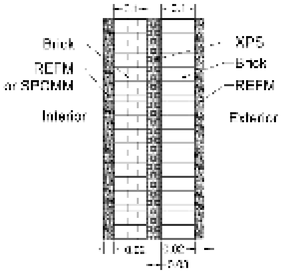
The numerical algorithim was initially validated by comparing it is predictions with experimental results available in the literature. The available experimental work by Kheradmand et al. [27] has been considered to validate the model. such experimental work encompassed similar conditions but small scale dimensions contains PCM mortar and heater device. The simulation framework adopted herein is fairly similar, and it is validation was achieved by simulating the experiments of Kheradmand et al. [27], with differences of predicted temperature bellow 0.1°C in compare with their experimental results. Such confidence in the simulation was paved the ground to remaining numerical simulation in this paper.

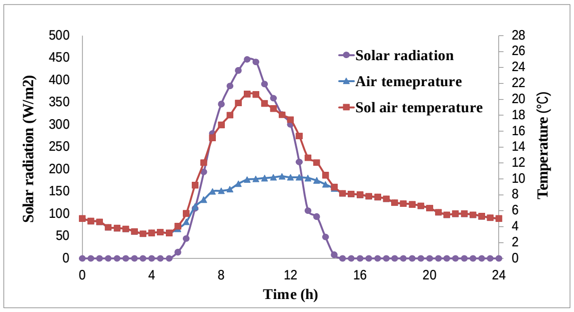
Because of the application of the sol–air temperature algorithm, the 24h cycles shown in Fig. 5 are obtained for both winter and summer scenarios from weather station from city of Covilhã located in the Centre of Portugal. All of the calculations are performed in transient model, and they are monitored until reaching a steady state. Surface convection coefficient is 20 W /m K for external wall surfaces of the flat. In the ceiling and floor planes, adiabatic boundaries are considered.

The heat fluxes of 454 W/m^2 (for heating) and 454 W/m^2 (for cooling) are used for the model system as boundary condition, with the “on” and “off” algorithm for the operation. In these cases, the models are initialized from 20ºC and 24ºC for winter and summer scenarios, respectively. The time step size is 300 s and it is considered as a constant. In momentum equation, the convergence criterion for a time step is checking below 10^{-3}. It is 10^{-2} and 10^{-5} for continuity and energy equations, repectively.

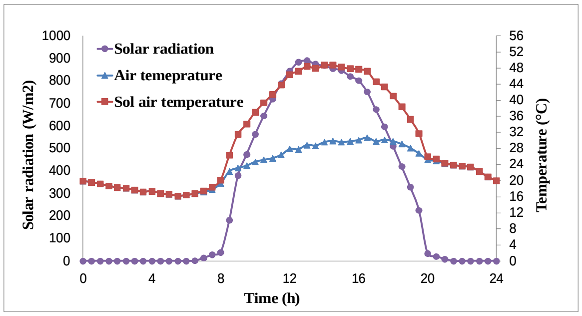
As mentioned, the specific heat capacity of SPCMM and REFM are calculated based on the methodology details obtained from [23] and they are presented in Fig. 6.

TABLE I. THERMO-PHYSICAL CHARACTERISTICS OF MATERIAL UTILIZED IN NUMERICAL SIMULATION

Properties	***REFM***	***SPCMM***	***XPS[28]***	***Brick[29]***	***Air[30]***	***Wall system configuration***
Density (kg/m^3)	1529.5	1360.9	32	1976	Ideal-gas	
Thermal conductivity (W/m K)	0.40	0.30	0.034	0.77	0.0242	
Specific heat capacity (J/kg K)	1000	According to Fig. 6	1400	835	1006.43	



(a) A winter day



(b) A summer day

Fig. 5. Environmental data in Covilhã, Portugal.

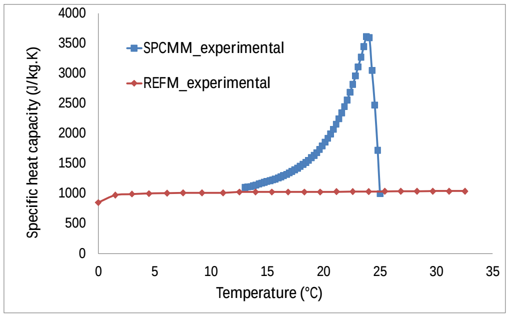
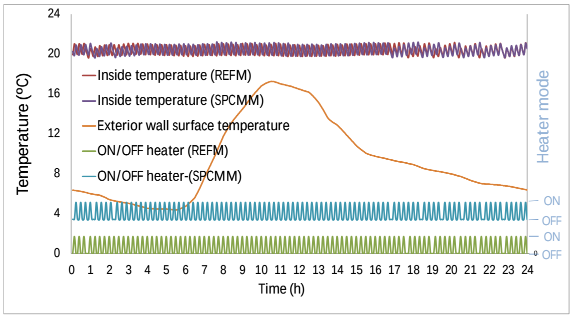


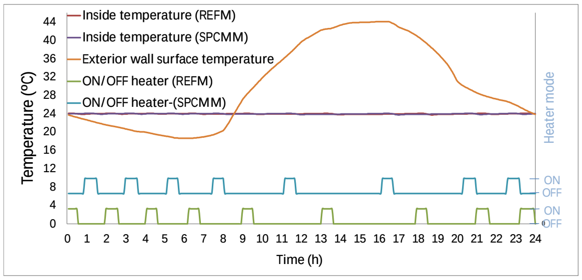
Fig. 6. Experimentally obtained specific heat capacity curve of REFM and SPCMM.

Fig. 7 represents the temperature variations of "measurement point" for both the SPCMM and REFM under winter and summer cases. Although it is not easily understandable from the figure, heating/cooling system is turning on (heating mode) for a whole 7.83h under winter scenario for the REFM case, while the SPCMM case permitted a decrease of the heating time to 7.75h, which itself represents a 1.1% saving. In the case of summer scenario, the heating/cooling system is turned on (cooling mode) for 5.5h daily for the REFM case, but the SPCMM case permitted a decrease of the heating time to 5h, which itself shows a 10% saving.

Fig. 8 shows housing electricity cost in different tariffs taken from a manufacturing company, Energias de Portugal, in Portugal. It can be seen that, only the flat rate tariff has a fixed value for an entire day. In other tariffs, energy price is different in different hours of a day. The energy stored by introducing PCM mortar in the building was estimated below, based on electricity costs in every tariffs.



(a) Winter scenario



(b) Summer scenario

Fig. 7. Internal temperature with/without PCM controlled by heating/cooling systems under realistic climatic conditions.

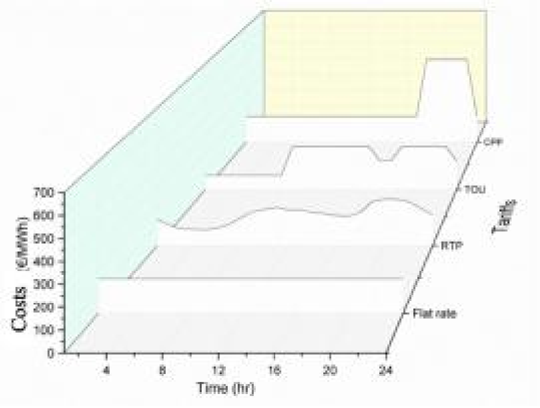
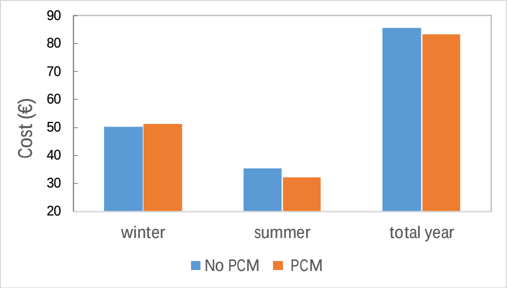


Fig. 8. Hourly price of energy for housing end-users.

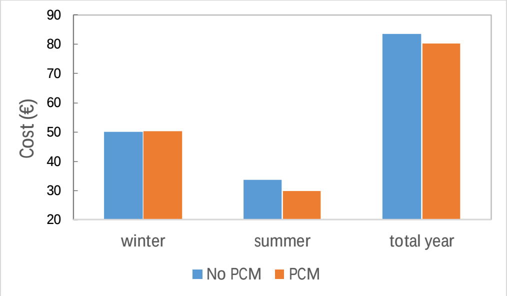
It is obvious that the electricity price is changing in different hours. These tariffs inspire customers to use electricity in reaction to the price variations by the time. They can propose motivations or charge fines to present less usage in higher electricity price. Demand response program can be categorized as : Time of Use (TOU), Real Time Pricing (RTP) and Critical Peak Pricing (CPP).

Fig. 10 indicates the influence of implementing PCM on electricity cost of the consumer in both summer and winter seasons for different DRPs.

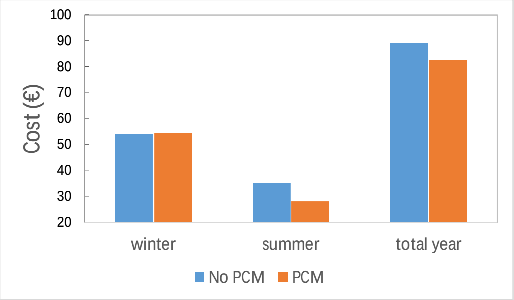
As it is shown in Fig. 9 (a-d), using PCM is not very effective in winter but in summer and also in a total year it can reduce the electricity cost. In addition, according to Fig. 10, when the TOU and CPP tariffs are considered, implementing PCMs can be more beneficial.



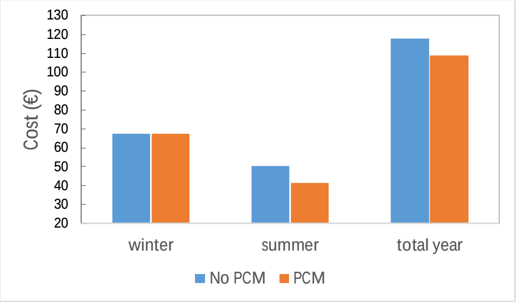
(a) Flat rate



(b) RTP



(c) TOU



(d) CPP

Fig. 9. Cost Analysis based on different tariffs

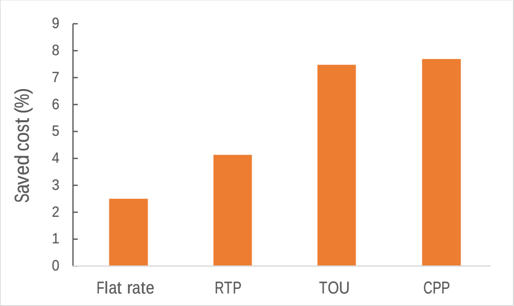


Fig. 10. Yearly energy saving

IV. CONCLUSION

This paper presented a model for DR systems with PCM to make consumers' bills minimum and to be sure about customers' comfort. Various cases showed that introducing PCM into the mortar of a building could influence the operative form of HEM system in various DRPs. The results demonstrated that introducing PCM mortar can influence on the electricity cost in most of the times. Furthermore, introducing PCM mortar could have a supplementary influence on the suggested HEM system. It can be concluded that using PCM was not very effective in winter season, but it could decrease the electricity bills in summer season. Moreover, when the TOU and CPP programs were considered, implementing PCMs could be more effective. The results showed that, by implementing the proposed model, yearly users' electricity cost can be decreased up to 7.7%.

As a final noted, it is remarked that the concept of PCM mortar has revealed promising performance capacity. The real scale simulation of this concept is bound to bring added value to thermal performance of buildings. Even though direct conclusions could be obtained in regard to the potential of energy saving harvested by the use of PCM when only a heating/cooling system is installed, no direct conclusions can be taken for the whole building due to the fact that, there are several devices installed in a real situation. Therefore, in order to obtain more definite conclusions in this concern, new further simulations are needed to performed.

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