Potentialities of using PCM in residential buildings in Portugal

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ABSTRACT: In the past few years the energy crisis has been a big topic around the world and many studies have been made to improve the efficiency of energy use. One of the research areas is the building sector and his heating and cooling systems. Constantly changing weather has a large effect on room temperatures and thermal comfort of residents. Controlling devices and appliances are consuming a large amount of energy to keep the temperature within the comfort range. This work reviews the Phase Change Materials (PCM) use in new and refurbished buildings to decrease the energy consumption.
PCMs can be used in different structures like roofs, walls and floors and by correct placement the maximum potential may be achieved. The main objective is to stabilize the temperature fluctuations inside and reduce the energy use of heating and cooling systems. This study takes in consideration also the financial matters and additionally there is a short review of the possible application of PCM in northern countries.

1 INTRODUCTION

Energy consumption with heating and cooling systems in buildings has increased remarkably during the past few years. The constantly growing demand of energy is also increasing the fuel consumption and carbon dioxide (CO_2) emissions. To limit this instance more sustainable solutions need to be found. One reason for the increasing energy use in buildings is the growing amount of lightweight buildings that are built. They are less expensive and faster to build but at the same time they are more vulnerable for heat fluctuations. The lack of thermal mass can be recognized as high peak loads during cold and hot periods and further in high energy consumption (Cabeza et al. 2011, Castell et al. 2010, De Gracia et al. 2013, Evola et al. 2013, Farid et al. 2004, Fraser 2009, Alqallaf & Alawadhi 2010, Menoufi et al. 2013).

Thermal mass is the materials ability to store heat. For example concrete has a good ability for this because of its high density and heat capacity. Massive structures warm up and cool down slower than the surroundings and stabilize temperature fluctuations inside buildings. Phase change materials (PCMs) can be used to increase the thermal mass of lightweight buildings. PCMs can prevent overheating and lower the thermal peak loads and further decrease the demand for heating and cooling.

The system is environmentally friendly because it uses natural thermal energy to function. Because of the high safety regulations in building industry only a few PCMs can be used. Different materials and compounds are being studied to further improve potential energy saving properties of the PCMs. PCMs might be an easy and efficient solution for decreasing the energy consumption in buildings.

The objective of this work is to study the functionality of a phase change material and examine the possible benefits of using different PCMs to improve the energy efficiency of buildings.

2 PHASE CHANGE MATERIALS

2.1 *PCM Features*

A phase change material is a material that has ability to store and release thermal energy (Cabeza et al. 2011, Menoufi et al. 2013, Zalba et al. 2003). The basic idea of PCM is to reduce temperature fluctuations. PCM acts as thermal inertia without increasing significantly the weight of the building, reducing the structural needs and moderating thermal stresses. The goal is to prevent overheating, shift down peak-loads and reduce energy consumption.

PCMs efficiency is based on the latent heat method while most construction materials function with sensible heat storage (Farid et al. 2004, Tyagi & Buddhi 2007). In the latent heat method the heat storage and release occurs isothermally providing much higher storage density within smaller temperature difference than in the sensible method. Materials that have a high thermal conductivity have also high heat transfer rate. Even though most of the PCMs have low thermal conductivity enhancement applications can be used to improve heat transfer in the latent thermal storage systems.

PCM works in cycles. For applications PCMs phase transition is usually from solid to liquid and vice versa (Tyagi & Buddhi 2007). First the PCM absorbs heat from the surroundings and starts to melt, storing thermal energy. PCM compounds have different melting temperatures and the selection is done according to the requirements of the thermal operation range. On the second stage the PCM starts to solidify releasing the stored heat to surroundings. For the best functionality the cycles should be swift and completed each time. During a phase change the molecules are rearranged and enthalpy change occurs. The process enables PCMs to absorb or release thermal energy with high density and this feature is used to stabilize and control the temperature fluctuation.

PCMs are often divided into organic and inorganic compounds (Cabeza et al. 2011, Evola et al. 2013, Menoufi et al. 2013, Tyagi & Buddhi 2007, Zalba et al. 2003). Advantages for the organic PCMs are non-corrosiveness, low or none subcooling and chemical and thermal stability, but they have lower thermal conductivity, lower phase change enthalpy and present flammability risk. Inorganic PCMs have greater phase change enthalpy and conductivity but they are more vulnerable for subcooling, corrosion, phase separation and have a lack of thermal stability.

Usually PCM has to be encapsulated because during the phase change from solid to liquid the melted PCM could drain away and be misplaced (Cabeza et al. 2011). Encapsulation provides also larger heat transfer area and reduces the reactivity to outside environment. The two main encapsulation techniques are macro and microencapsulation (Farid et al. 2004, Zalba et al. 2003).

Different PCMs may have some inconvenient features that can risk the functionality or safety. Such features can be subcooling, segregation, materials compatibility or other technical problems (Cabeza et al. 2011, Farid et al. 2004, Zalba et al. 2003). The most limiting feature for the use of PCMs is the long term stability and the number of cycles that the PCMs can carry out without any decrease in thermal properties (Cabeza et al. 2011, Farid et al. 2004, Zalba et al. 2003).

The first studies using PCMs were made four decades ago with houses and storage tanks (Tyagi & Buddhi 2007). Improvements were to be made in living environment because especially lightweight residential buildings have low thermal mass and are vulnerable for high thermal fluctuations. With electrical heating and cooling systems this results in high energy demands and occasional peak-loads.

Although PCM substances are widely studied only few compounds make it through to commercial level (Cabeza et al. 2011). The materials are carefully tested to ensure safety and functionality. The materials service life is also estimated for the product to be beneficial for the consumers.

One of the major issues affecting usage and selection of PCMs is the financial matters. The cost of different PCMs vary highly and the building materials containing PCM are usually much more expensive than the ordinary ones.

2.2 *Building with PCM*

PCMs have been studied and tested for decades to be a part of heating and cooling systems in buildings and most of the results show a positive effect on energy performance. PCM usage in buildings is mainly based on solar energy that rely on the PCM’s ability to store solar energy during day time and release gained heat during night (Tyagi & Buddhi 2007). Building with PCM is one of the most foreseeable applications of PCMs and in the future the method may decrease highly the heating and cooling energy use.

2.3 *Direct and indirect gain*

Solar energy gain can be direct or indirect (Tyagi & Buddhi 2007). Direct gain comes through buildings structures such as windows, doors or glass walls. The solar radiation or insolation can also be reflected from nearby surfaces like water or plate roofs as an indirect gain. Direct gain is more efficient than indirect but direct ultraviolet radiation may cause damage to the surfaces of objects and layers. In indirect gain concept structures like Trombe walls, water walls, trans wall or solariums are used to prevent the direct radiation from entering the living space. These methods are used when the fluctuations are above the comfort level and living space is vulnerable for overheating. The idea is to store excessive heat to heavy materials and keep the temperature tolerable. PCMs are used in the same purpose. PCM does not have to be in direct contact with solar radiation because it can absorb heat from surroundings and ambient air. The heat transfer is just a little slower in indirect gain than in direct gain concept.

Insolation varies during seasons and usually the yearly quantity of radiation is estimated and utilized in the design of buildings with PCMs. The seasonal changes have a large impact on the thermal loads and for the need of thermal storage.

2.4 *Area and thickness of PCM*

When using PCMs the placing and the amount of used PCM are to be estimated for the optimal functionality. Depending on the PCM’s properties the total surface area covered with PCM and the thickness of the PCM layer are calculated to fully utilize the heat storage capacity. Some PCMs cannot function as thick layers because the heat cannot reach and activate the furthest particles and therefore these types of PCMs need a large surface area in order to fully function.

2.5 *Structures*

PCMs can be used in new and refurbished buildings and since it has a large heat capacity it is an easier option to increase the thermal mass of lightweight structures (Fraser 2009). PCMs are often used in lightweight elements to facilitate installation. This also allows the possible replacement of PCMs in case of deactivation or damage. For example wallboards are relatively cheap, easy to install and commonly used in building industry and therefore suitable underlay to attach PCMs. Other structure examples could be a Trombe wall, PCM shutters or other more complex systems that may include applications such as heat exchangers or air conditioning (Evola et al. 2013, Tyagi & Buddhi 2007, Zalba et al. 2003). The structures are prepared so that the PCM does not cause changes to the structures such as expansion or bending while operating (melting and solidifying). PCMs can be placed almost in any surface of a house: floor, walls, ceiling, doors, shutters etc. (Tyagi & Buddhi 2007). In order to ensure the optimal benefit the surface with PCM must be clear of any insulating or blocking materials that might have a negative effect on the heat transfer.

Safety issues become more and more restrained every year to prevent hazards and to ensure safety. Structures with PCMs cannot jeopardize or cause any harm to building or occupants. To carry out the building requirements PCMs are examined carefully to ensure chemical balance, fire safety, non-toxicity and to prevent any other harmful features that may risk safety (Cabeza et al. 2011, Zalba et al. 2003). Aesthetic appeal is also taken into account in the design of the space.

3 METHODOLOGY

A simple study has been made to test out the effects and possible benefits of using PCMs in buildings. The testing takes into account the placing, melting temperature and the functioning of the PCM with and without HVAC system. Also the room and appliances were optimized.

The comparison was made by examining the room temperature and energy consumption. The testing was made in three sections. First one was simulating a test capsule without any PCM. On the second and third sections two different PCMs were used to see the possible differences.

3.1 *2.1 Simulation Program*

The study was made with computer simulation of a space with and without PCM. The simulations were made with Energy Plus software (version 8.0.0.007) and the design with Google Sketch Up plug-in (version 8.0.16846). Energy Plus was used as the simulation tool for this study as it has the capability to simulate phase change material in the building envelope (Pederson, 2007).

The target area is located in the Northern Portugal and the software (Energy Plus) weather file of Porto was used as the climatic conditions. The outside temperature varies from 0ºC to 31.1ºC, the average being 14.3ºC.

3.2 *Room Specifications*

The subject was approached using a simplified model and the test simulation was made for a typical living environment. The target space is a single room flat for one person and this test capsule presents one room in a residential building or in an apartment house. This design was chosen to avoid excessive simulation run time and to perform the analysis under controlled conditions. The dimensions of the test capsule are shown in Figure 1.

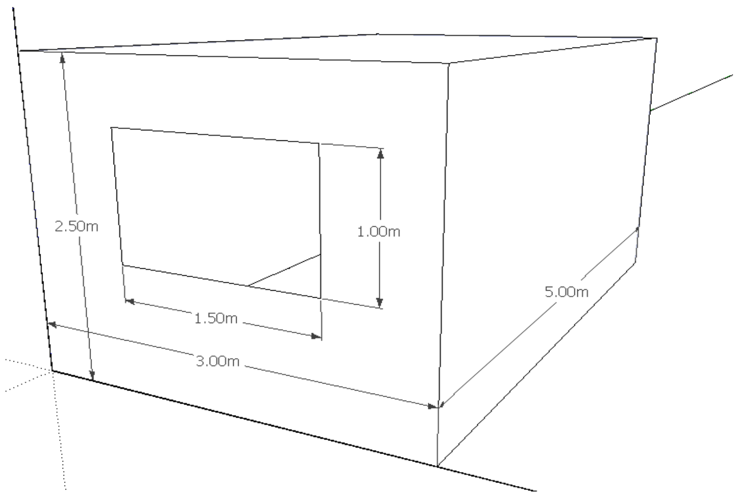

Figure 1. Test capsule sizes used in simulations (SketchUp).

The room has a depth of 5.0 m, a width of 3.0 m and height of 2.5 m. The window is 1.0 m high and 1.5 m wide facing south with a shading system for the warm periods. The construction is made with conventional structures and layer thicknesses of a residential building in the location area. All the walls and the roof are considered as exterior surfaces and the capsule is founded on ground level. The structure layers are:

- Wall: 220 mm hollow brick, 66 mm fiberglass, (PCM), 12 mm plasterboard
- Floor: 200 mm concrete, 66 mm fiberglass, (PCM), 12 mm wood cover
- Ceiling: 20 mm roof deck, 66 mm fiberglass, (PCM), 12 mm plasterboard
- Window: metallic frame with thermal cut; layers: clear 6mm glass, air 3mm and clear 6mm glass

The HVAC system for the room is an ideal system with 100% convective air system and 100% efficiency. The system does not have any duct losses or capacity limitation. The building mechanical system was set up to maintain the indoor temperatures above 18ºC (on winter) and under 25ºC (on summer). The system is running 24h per day or when needed.

3.3 *PCM Characteristics*

For the PCMs two commercialized products were chosen. The materials are placed under the surface layers. The products are introduced in the following (Delta-Cool, 2013; Dörken, 2013; Smartboard, 2013; Mariager, 2013):

- Delta-Cool by Dörken is salt hydrate that comes in small (4kg) packages and these "pouches" of PCM are usually placed on top of ceilings or under floors etc. (thickness 20 mm, density 1550 kg/m^3, specific heat 2450 J/kg-K, price 130 €/m^2).
- Smartboard from BASF (marketed by Knauf) is a gypsum board with microencapsulated paraffin and used as a wallboard itself (thickness 15 mm, density 766.7 kg/m^3, specific heat 1200 J/kg-K, price 50 €/m^2).

4 RESULTS

The results showed that it is possible to improve the thermal conditions inside the buildings.

4.1 *Placing*

For this room the optimal placing for the PCM according to the simulations performed is on the walls. The placing on the floor or ceiling results less effective. The hard floor cover is used to prevent damage but it decreases the effectiveness by 1-3% and when the PCM is placed on the ceiling the heat gathers up keeping the PCM melted.

Overall without the HVAC system the PCMs are stabilizing the thermal fluctuations and the room temperature is increasing on yearly average about 5°C regardless of the placing or the material used. The results also show that the salt hydrate has better thermal performance than the paraffin.

Figure 2 shows the temperature differences inside the room (demonstration day: 5th July). The room was set with a shading system for the window and no HVAC or ventilation system was used on the simulations. The PCMs with melting point around 24ºC are placed on the walls under the plasterboard.

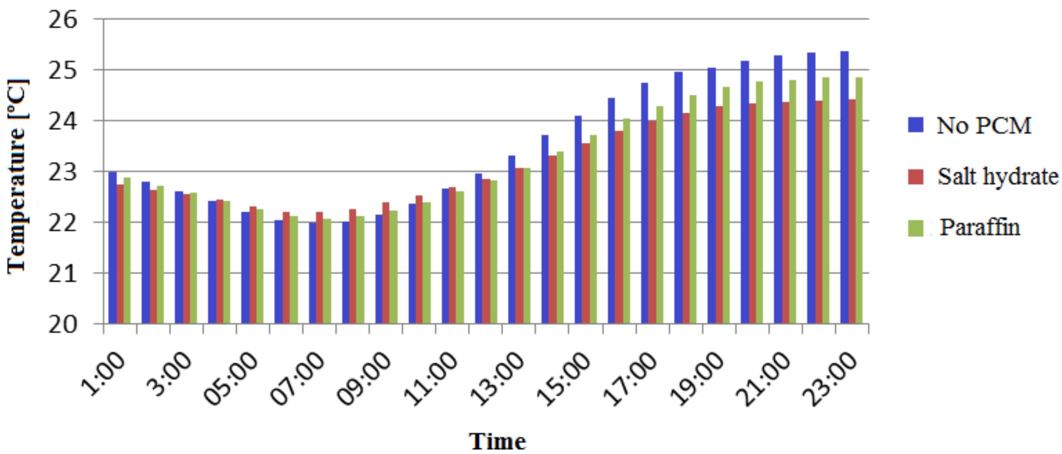

Figure 2. Temperature fluctuation in the room when the PCM is placed on the surfaces of the eastern (7.5m^2) and western (7.5m^2) walls under a 12mm plasterboard.

4.2 *Melting Point*

To reach the optimal thermal performance calculations were made to test out different melting points of the PCMs. The melting point was dropped by one degree at a time starting from 24ºC and the lowest being 19°C. At every point simulations were made and results compared to find out the optimal melting temperature.

In the test capsule the optimal melting temperature for the salt hydrate was around 21°C as for the paraffin the optimal melting point was around 23°C. The PCMs are subscribed as S21 (salt hydrate, melting point 21ºC, enthalpy of fusion 158kJ/kg) and P23 (paraffin, melting point 23ºC, enthalpy of fusion 110 kJ/kg).

4.3 *Energy comparison*

The room was set up with the original structures, shading system for the window, HVAC system set from 18°C to 25°C, ventilation set on night cooling during summer, 0.6 ACH (air changes per hour) and the PCMs placed on the walls.

The study of the test capsule showed that, in each case (test capsule with S21 and with P23 compared with the test capsule without PCMs), about two thirds of the total energy demand was cooling (66%) and one third heating (33%).

The total energy consumption for heating and cooling without PCMs was 18.6 kWh/m^{2}year. With S21 the total energy consumption decreased to 14.3 kWh/m^{2}year and with P23 to 17.4 kWh/m^{2}year. The comparison for yearly energy consumption is shown in Figure 3.

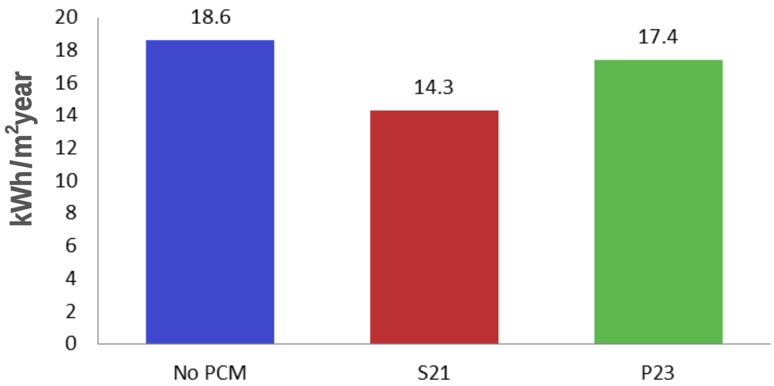

Figure 3. Energy consumption of the test capsule (kWh/m^{2}year).

As Figure 3 shows the PCMs are functioning correctly and clearly reducing the yearly energy demand. The salt hydrate (S21) reduces the energy consumption by 22.9 % and the paraffin (P23) by 6.4 % on the yearly average.

4.4 *Financial aspects*

The last evaluation was made by the material costs. The average cost found for the salt hydrate was 130 €/m^2 and for the paraffin 50 €/m^2. As the PCMs reduce the energy needs the financial savings can be calculated and compared to the market prices.

For the salt hydrate the annual savings are 8.96€ and for the paraffin 2.50€ (considering that the HVAC system is running 24h with an efficiency of 100% and the energy cost being 0.1405€/kWh in the target area).

The total cost for the salt hydrate is 1950€ and for the paraffin 750€. The prices are high when compared to the savings and it is not cost efficient to use the PCMs in the defined conditions.

Additionally calculations were made to find out what would be the reasonable price for the products to be beneficial. The expected service life for both PCMs was assumed to be 20 years and that the PCM should pay itself back in 10 years to cover the total expenses (Kosny et al.2013). The target price for S21 was 5.97 €/m^2 and for P23 1.66 €/m^2.

With the salt hydrate the real price for the product is over 20 times more expensive and with the paraffin even 30 times more expensive than the target price. This means that the payback time for each PCM would be much longer than the expected service life.

4.5 *Could the method be used in the northern countries?*

Climatic conditions in the northern countries are far more demanding than in the research location. The outdoor temperature varies highly from -30 to +28°C and for example in southern Finland the amount of months when the outdoor temperature reaches or overcomes the comfort level are limited to only three and the daily temperatures vary from +5°C to +26°C. The northern parts of the country are even cooler and there is practically no need for cooling systems in residential buildings or danger for overheating.

The building shells have thicker insulation layers and the house building standards are very strict to ensure the protective aspects of the building and the materials are chosen in different ways to withstand the climatic challenges. Mainly the structures are designed to prevent the heat leaking out. The material's R-value indicates the heat flux density (heat transfer per unit area per unit time) and it is used for a unit value of any particular material. For example the placing and the size of the windows and other structures or materials which have poor thermal resistance are chosen carefully.

As described before, the PCMs need heat fluctuations to function and as the thicker insulation and higher thermal mass stabilize the room temperature and the long winter period keeps the temperature low, thus there is a smaller rate for the PCMs to operate. The cycles are not rapid and the PCM stays in one phase for longer periods making the functioning less efficient.

However, instead of placing the PCMs on structures they could be combined with some other solar gain systems for example water tanks of thermal solar panels and associated to heating systems to increase their thermal capacity. These solutions might be more efficient and the PCMs could be used also in the northern climates.

5 CONCLUSION

Studies show that PCMs have a clear positive effect on the room temperature stabilization and energy saving. It is an easy way to add thermal mass to buildings without increasing the total building weight and onwards lower the heat fluctuations. However, the energy storage system development still has some major practical difficulties such as long term thermal behavior and stability. The problems with the cycling, phase segregation and subcooling are not yet completely solved and the low thermal conductivity and suitable melting temperatures limit the usable amount of the PCMs.

Altogether the PCMs stabilize the room temperature and facilitate thermal stresses. The placing and volume of the used PCMs should be carefully designed and optimized depending on the target space and heating and/or cooling needs. Also the functionality should be secured and the estimated service life should be taken into account.

In households without HVAC systems PCMs increase the average room temperature and reduce high thermal fluctuations. The results show 5 ºC increases in the average room temperature. In households with HVAC systems the PCMs reduce peak loads and decrease the energy consumption in both heating and cooling demands. The results show a clear decrease in the energy consumption (salt hydrate 22.9%, paraffin 6.4%). However, the PCMs cannot function during cold periods if the melting point is not reached especially in houses without heating system. Also, to prevent overheating and to ensure proper cycling shading systems and/or ventilation/night cooling are recommended on hot periods.

The results also show that the purchase prices are higher than the annual savings and the payback time is far too long to benefit financially from the use of the PCMs.

Thus, the main problem with PCM use in building industry is the financial matters. Even though the commercialized materials are safe and easy to place or combine with building materials they multiply the material costs making the total prices too high for the consumers. The companies guarantee long life expectancy for the products but as the payback time is long and the possible damage or decrease in the functioning the investment might not be reasonable.

However, it is important to get the consumers interested in these energy saving matters and possibilities with new materials. The next step is to further study PCMs, get the prices more accessible, get the products used in the building industry and with sales get more feedback of the materials and functioning.

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