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Reduction of HVAC Energy in Buildings by Incorporating Phase Change Materials

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Abstract — The effect of phase change material (PCM) integration in building components is investigated in mild climates. The incorporation of PCMs in building materials is particularly interesting since it permit to the thermal storage to become a part of the building structure and is completely passive. Simulations in a typical family house were made and the contribution of PCMs on different buildings components was analyzed. Results show important reduction in cooling energy even in those climates characterized by low day/night temperature swings. Even if large quantities of PCM are necessary, a reduction of 20% can be obtained with reasonable thickness of PCM wallboards. The best position for PCMs is found to be on surfaces that undergo large temperature variations (connected to the outdoor air) like the ceiling for example. This position present the better compromise between energy reduction and PCM quantity used.

Keywords — Low energy building, Passive building, Phase change materials, Energy conservation

1 INTRODUCTION

The IPCC (Intergovernmental Panel on Climate Change) has estimated that to limit the earth average temperature increase to a maximum of 2.4°C by 2050, the rate of greenhouse gases (in particular CO_2) should be brought back down to between 50 to 80% of their level of before 2000. The CO_2 emission is essentially due to the fossil fuel using especially for electricity generation. For example, in 2002 about 40% of the CO_2 emissions were due to electricity generation (Goswami [1]).

Roughly speaking, we can consider that the energy demand in the world falls into about a third for the building, another third for the industry/agriculture and the rest for the transport. For the transport and industry, the potential savings are low since a great effort was already made in energy conservation. On the other hand, a huge potential exists in the building because about 70% of the consumption concerns the heating/air conditioning. For example, every German low energy building 'Passivhauss' saves up to 80% on the heating energy and so avoids about 2.4 tons of CO_2 emission a year (Krarti [2]).

For the new buildings, the actual target is to reach by 2050 a quasi-null fossil energy consumption with the needs reduced by about 70% and the renewable energy contributing by 30% (Zero energy concept). However, more than a half of 2050's buildings are already built with a little energy preoccupation. Presuming a yearly renewal mean rate of 0.3%, about 600 years would be needed to replace the current park of buildings. To fulfill the Kyoto objectives for CO_2, it requires besides the transition to 'low energy' of all the new housing which will be in the meantime built, but also the renovation of the existing sector at 2 to 5% per year. Those goals are very far because numerous problems of costs and implementation.

World electricity consumption is expected to double by 2025 with a strong growth of 3.5 % year. Cooling of residential buildings contributes significantly to this increasing consumption with a peak demand in mild and hot climates. This simultaneous energy demand in summer requires utilities to build, operate and maintain peak-power plants, distribution network, with a real risk of blackouts and energy shortage. To attenuate this problem, many countries set up a differential pricing system for the peak and off peak periods of electricity use.

Houses with very low energy consumption are built today and they meet some success because the recent technical solutions can be now easily integrated. To reach this target of low energy buildings, three ways are followed:

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1- Reduction of the energy consumption: by the constructive systems, the insulation of the opaque walls and the treatment of the transparent walls (windows).

2- Use of renewable energies, PV (photovoltaic) electricity, combined heating-warm water solar systems, heat storage, micro-network heat etc.

3- Efficient use of the fossil energy, double ventilation with heat recovery, compact HVAC systems, micro-cogeneration etc.

Whatever is the model used, any action must start with an important reduction of the energy demand in the housing. In fact, by keeping the current building consumption, substituting fossil fuels by renewable energies, is technically practicable but economically illusory. Reducing energy consumption is giving a chance of success to the renewable energies.

2 PCM AND BUILDINGS

The main issue with energy conservation and renewable energies is often the heat storage since the needs are not necessarily simultaneous with the availability of the sources. Sensible storage is accomplished by increasing the material's temperature whereas latent heat storage is accomplished by changing the material's physical state. To store the same quantity of energy, smaller quantities of material are required for latent storage. For example, a common building material such as concrete, can store about 1 kJ/kg whereas a PCM such as calcium chloride hexahydrate can store/release up to 193 kJ/kg on phase transition (Kenneth [3]). The order-of-magnitude of increase in thermal storage capacity for PCMs and their almost isothermal discharge could be exploited to stabilize ambient temperatures inside buildings.

Thermal mass of buildings can be used to store energy and attenuate indoor temperature fluctuations. Nevertheless, the advantages of a thermally massive building often conflict with aesthetics and cost pressure which require buildings to be increasingly lightweight. Incorporating PCMs in buildings is a mean to increase artificially thermal mass of lightweight structures (Zhang [4]). Further, as heat storage takes place inside the building where the load occurs rather than externally, additional energy transport is not required.

Actually, the available commercial micro-encapsulated PCMs are made with paraffin waxes embedded within small polymer spheres, about 10-20 µm diameter. They can be mixed directly into the building material or facing wallboards. Significant PCM mass fractions, up to 30%, are achievable. The PCM is chosen to melt in the working temperature range of the thermal mass. The additional latent heat capacity for the distributed PCM increases the overall effective heat capacity compared with sensible storage alone (Khudhair [5]). As the interior lining is usually made with multilayer gypsum plaster, PCMs can be easily added to the plaster. They can be installed both in new constructions and during the rehabilitation process of existing buildings with no additional cost (except for the PCM material).

The incorporation of phase change materials (PCMs) in building materials to reduce the cooling needs was investigated by many studies especially these last years. An extensive literature review can be found in Zhu [6]. Experimental test-rooms with PCM wallboards were investigated by Kuznik [7], Schossig [8] and Voelker [9]. For heavy structures, Zalba [10] and Cabeza [11] tested concrete cubicles impregnated with encapsulated PCMs. But, these studies are generally with light weight constructions (wood structures) or reduced scales. The promising results cannot be generalized and do not permit to conclude about the real benefits in real buildings. In those studies, the experience conditions leads to a large indoor day/night temperature variation allowing to the PCMs to swing widely around the melting temperature. In this case, charge and discharge cycles are completely accomplished many days in the year. The night ventilation with cooler outdoor air is generally sufficient to discharge and remove heat from the PCMs. Unfortunately, those favorable conditions do not exist in mild climates where PCMs are expected to melt/solidify only partially.

Our aim is to see how PCMs can reduce thermal loads in real buildings and mild climates. These climates are characterized by tempered outdoor temperatures with a low day/night variation. In coastal cities, the temperature swings can be only 4-5°C on hot season. Therefore, night ventilation is expected to be less effective and the higher outdoor night temperature does not allow to the PCMs to discharge completely. Further, high humidity could cause a real discomfort. The resort to mechanical cooling is generally required to provide acceptable summer comfort conditions. Secondarily, we would examine in which building component, the PCMs are more efficient.

3 THE BUILDING MODEL

Among the numerous factors that influence energy consumption performance of buildings and PCM integration, we can identify the following as key parameters:

- Local construction systems.

- Local climate: solar irradiation and ambient outdoor temperature.

- Internal loads: the personal occupancy and electrical appliances (lights, TV, computers etc.).

The studied case is a typical residential single-family house of 4 rooms and about 98 m^2 total area (see fig 1). The constructive system is typical for south Mediterranean countries with a heavy envelope (solid concrete end-terrace roof and brick walls). Windows shading in summertime is by roof eaves and persian shutters (shade factor G=0.5).

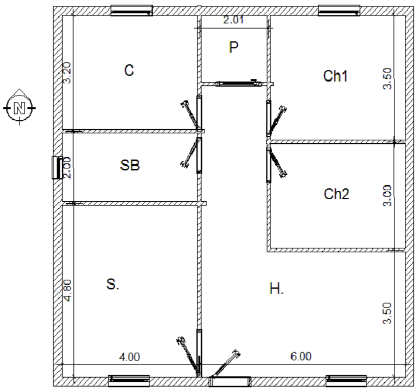

Fig 1. Sketch of the studied house case.

Exterior walls are the traditional double brick walls with an air gap (see table 1 for thermal characteristics of building components). These levels of insulation seem to be lower in comparison to continental European countries, but they are sufficient in south Mediterranean region. When present, a PCM of 26°C melting temperature is embedded in wallboards of gypsum plaster of different thickness containing 26% mass fraction of paraffin and are set to the interior wall's face and/or on the ceiling.

Table 1. Thermal characteristics of building components.

	U- roof W/m^{2}K	U-extior wall W/m^{2}K	U- floor slab W/m^{2}K
Standard house	2.80	1.55	5.60

The study is carried out for the case of Algiers, a typical coastal Mediterranean city with a mild-warm climate. The day temperatures are not very high even in the summer and the night ones are just lower. Relative humidity is often more than 60% in summer period.

A space can be considered to be thermally comfortable if the perceived temperature experienced by the occupants (operative temperature) falls within a narrow range around 23°C. Cooling is by split system room air conditioners with 100 W/m^2 power and is activated when the indoor temperature exceeds 26°C. The home furnishing is typical and internal charges are evaluated to 10 W/m^2 with typical family hourly use distribution. Natural windows ventilation is assumed for the nighttime cooling if the temperature of the room exceeds the ambient one and free ventilation is estimated to 1 volume change per hour.

4 RESULTS AND DISCUSSION

The cooling demand was determined by mean of a dynamic thermal building simulation software (Valentine®). Different cases of PCM integration are evaluated with the criterion of useful cold demand. Otherwise, the quantity of energy which needs to be removed from the building by active cooling system in order to confine indoor air temperature to a maximum of 26°C.

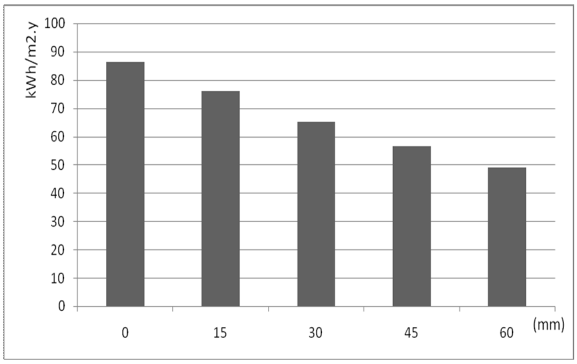

Fig 2. Effect of PCM wallboard thickness on cooling energy demand.

Figure 2 shows the cooling energies for the case where the PCM is incorporated on ceiling and on the exterior walls (interior facing) for different thickness of wallboards. The presence of PCMs reduces the cooling energy with increasing wallboard thickness so that 44% of reduction can be achieved with 60 mm of wallboards (relatively thick). But about 25% of reduction can be already obtained with 30 mm wallboards.

The energy that can be stored is directly related to the quantity of PCM contained in wallboards and then to the thickness of the wallboards. The outdoor ambient temperature variation is transmitted to the PCM, which undergoes cycles of charge/discharge many days in the year, especially in the mid-season.. In fact, PCMs are efficient only in mid-seasons (May, early June, September and early October) when daytime temperatures are still high but night temperatures become fresher. PCMs can only delay the resort to mechanical cooling for really hot days.

Figure 3 shows the reduction of energy cooling (compared to case without PCM) by incorporating PCM in different components of the house (different oriented walls, ceiling and in all the walls).

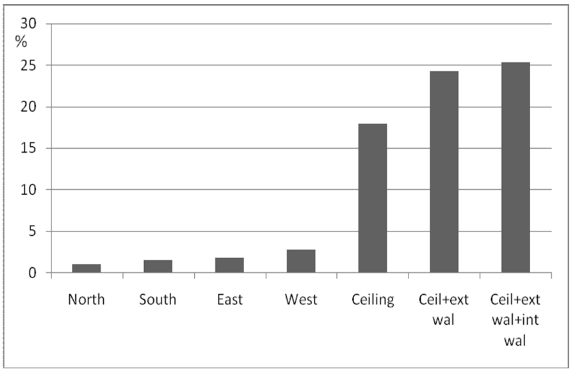

Fig 3. Cooling energy gain with PCM integrated in different building components (30mm thickness).

The main enhancement is with PCM on ceiling. Adding PCM on the exterior walls does not enhance the gain more than 6%. Adding more PCM on internal walls has practically no influence because it acts only as sensible storage. The temperature of internal walls is affected only by indoor temperature, which is almost constant at 26°C. The PCM perform more on roof (ceiling) because the main part of heat enters from there to the building. The end-of-terrace roof as a flat area is exposed all day to solar irradiation, unlike the exterior walls which are only partially irradiated, depending on their orientation. Further, the ceiling is a clear area and then exchange directly heat by convection with room air without any obstacles (like furniture for example).

The effect of PCM reduction is also lesser in exterior walls because their low U value. The air gap between the bricks and their low conductivity is a kind of insulation that makes the exterior temperature variations less transmitted to the PCM.

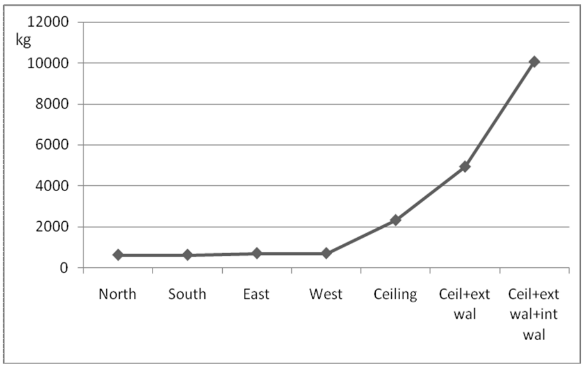

Fig 4. PCM quantities in different building components.

The amount of PCM material used (wallboards) for each position can be seen in figure 4. The investment cost is directly related to this quantity. Somewhat a great quantity of PCMs is used for about 25% reduction on cooling energy for the case where PCM is on all surfaces (exterior, interior walls and ceiling). But 18% of reduction can be obtained with about a fifth of PCM quantity (ceiling). The best gain/quantity ratio is then with PCM is incorporated on the ceiling. However, for an economic efficiency analysis and length of the payback period, rather than percentage of gains, it is the absolute saved energy quantity that is of importance.

The main problem with gypsum wallboards is their lower heat capacity which is much lower than concrete for example (Baetens [12]). However, even if the micro encapsulation of PCM in concrete is very effective, it may affect its mechanical strength. Since energy storage would be significant only in the first few centimeters (Richardson [13]) adding PCM to concrete at the walls surface seems to be a better solution. It improves the performance of energy storage without affecting the structural requirements of the building walls. PCM needs to be applied only in a thin facing layer to achieve the thermal benefits. A solution is to mix PCM with cement mortar for using as wall coating (rendering) which is a common practice in southern countries. Another problem is the weakness of the temperatures gradient between wallboard interfaces and indoor air making natural convection not very efficient to remove heat from the PCM. A solution is to increase night ventilation rates by using mechanical devices which enhance the convection coefficient by favoring the air recirculation.

5 CONCLUSION

The incorporation of encapsulated PCMs in material building as gypsum wallboards was investigated in mild climates in order to reduce cooling energy.

PCMs are found to have interesting performances even in mild climates characterized by low day/night temperature swings, which make night time ventilation less efficient for discharging the PCM. Anyway, about 20% of cooling energy is obtained but with relative large quantity of PCM. A local economic efficiency analysis must confirm the process profitability.

The PCMs have better performance on surfaces that undergo the widest temperature variation (connected to the outside air for example). Incorporating PCMs on the ceiling give the best compromise gain/cost and is relatively easy to realize even in existing houses. This shows their potential use for refurbishment of actual buildings which is the weak point of all energy conservation policies.

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