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Building integration of PCM for natural cooling of buildings

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HIGHLIGHTS

- ▶ A brief overview of PCM solutions for buildings is provided.
- ▶ Some weaknesses of existing PCM solutions for buildings were identified.
- ▶ New solutions for PCM integration in buildings are proposed.
- ▶ Proposed solutions overcome identified weaknesses of existing solutions.

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ABSTRACT

The use of night cooling ventilation in addition of phase change materials (PCMs) is a very powerful strategy for reducing the cooling demand of buildings. Nevertheless, there are inherent drawbacks in the way things have been doing so far: (a) The limited area of contact between PCM and the air; (b) the very low convective heat transfer coefficients which prevents the use of significant amounts of PCM and (c) the very low utilization factor of the cool stored due to the large phase shift between the time when cool is stored and time when it is required by the building. In this paper, we present innovative solutions using PCM to overcome the above situation. Compared with existing solutions, innovative solutions proposed, increase the contact area between PCM and air by a factor of approximately 3.6, increase the convective heat transfer coefficient significantly, and improve the utilization factor due to the inclusion of active control systems which allow the cold stored be actually used when required.

1. Introduction

Different approaches have been studied to use PCM materials for night cooling applications, depending on the building material and its location in the building (envelope, heating/cooling system, etc.), see for instance Castell [1].

The frame of the present paper is a research project called MECLIDE. The technical objective of the project is to develop PCM based night cooling solutions able to cover a significant fraction of the cooling energy needs of buildings and to identify the circumstances in which it is possible to cover 100% of cooling needs of residential buildings.

This paper deals with the reasoning and design criteria that lead to the MECLIDE solutions and the evaluation of their energy savings potential.

Other tasks of the project include:

- Selection of PCM materials and determination of thermophysical properties. Selection of encapsulation strategies.
- Modeling activities with development of detailed numerical models and simplified models able to be integrated in simulation tools.
- Experimental activities using test cubicles located in Puigverd de Lleida (Spain).
- Validation activities where the major concern is the accurate determination of convective film coefficients.
- Evaluation of the potential of the solutions developed in the frame of the project.
- Integration of a prototype in an actual building (a new office building located in Seville) where the PCM will be coupled to the HVAC system.

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- Information about the experimental activities can be seen in [2]; modeling and validation activities are described in [3].

2. Fundamentals of the potential of night cooling applications

A very powerful well known strategy for reducing the cooling demand of buildings is the use of low outdoor air temperatures during the night to cool the structures of the building. In many cases, the night-time outdoor air climatic conditions of many Mediterranean locations allow a significant compensation of the day-time solar and internal heat gains [4].

The performance of a night cooling application depends on [5]:

1. The climate, which provides the availability of the heat sink in terms of its thermal level and its variability throughout the year and on a daily basis.
2. The cooling needs of the building (absolute values and load profiles). The combination of 1 and 2, gives the extent in which the requirements can be covered by the cooling technique.
3. The efficiency of the technology used to transfer heat from the heat sink (night-time outdoor air) to the building.

The efficiency of a night cooling strategy lies in the ability of the building inertia to store cool during the night and to use it during the next day. The role of the inertia appears then double-linked to this strategy. It can be characterized by means of the storage efficiency [4,6] and the utilization factor [6].

The utilization factor characterizes the interaction between the building (cooling required) and the Natural Cooling Technique (cooling provided). The loss of usable cooling energy is due to the periods when there is an excess of the cooling produced in relation to the cooling required. It has been proved that the utilization factor is extremely low when the cooled material is in direct contact with the indoor air due to the large phase shift between the time when cool is stored (sunrise) and time when it is required by the building (around 14th solar time). "Therefore, shifting the cooling load from peak hours to hours of low demand by storing the cold is beneficial" [7].

The utilization factor depends on the building design, the position and characteristics of the storage and mainly on the existence on an eventual control strategy ([6,8]).

In the sections below we will present, first, some data of the evaluation performed regarding the interaction between the climatic potential of the Spanish locations and the cooling requirements of buildings, and next, an analysis on how the MECLIDE solutions were designed, including a comparison with related solutions.

3. Climatic potential and cooling needs of buildings in Spanish locations

A data base of buildings has been selected to evaluate the cooling needs structure of residential and non-residential buildings.

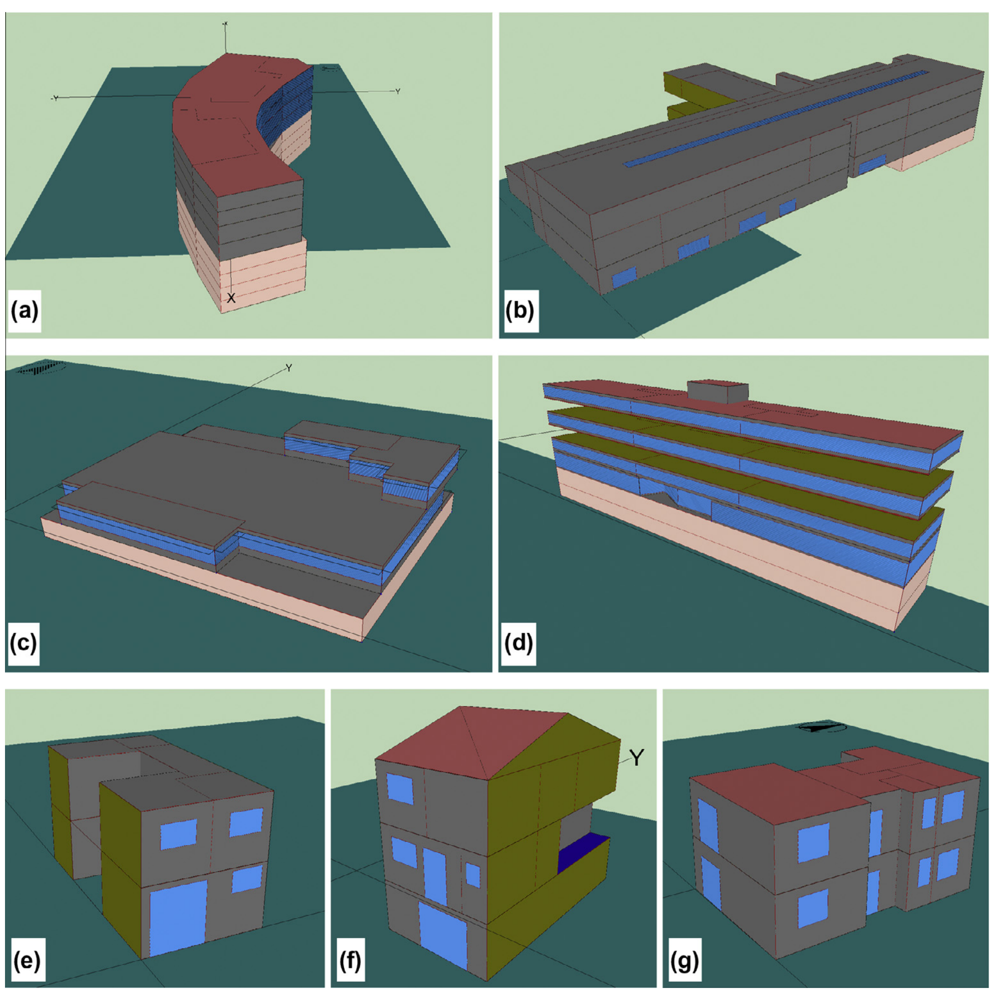

Fig. 1. Buildings used to perform the calculations.

Table 1
Brief description of buildings in Fig. 1.

Building	Description	Area (m^2)
a	Curved plan building with a highly glazed facade, and four underground floors (non-residential building)	5064
b	Building with two dominant orientations (non-residential building)	10,232
c	Low height and highly glazed building with one underground floor	1219
d	Highly glazed building in four orientations and two underground floors (non-residential building)	5544
e	Single family building (residential building)	61
f	Single family building (residential building)	166
g	Single family building (residential building)	130

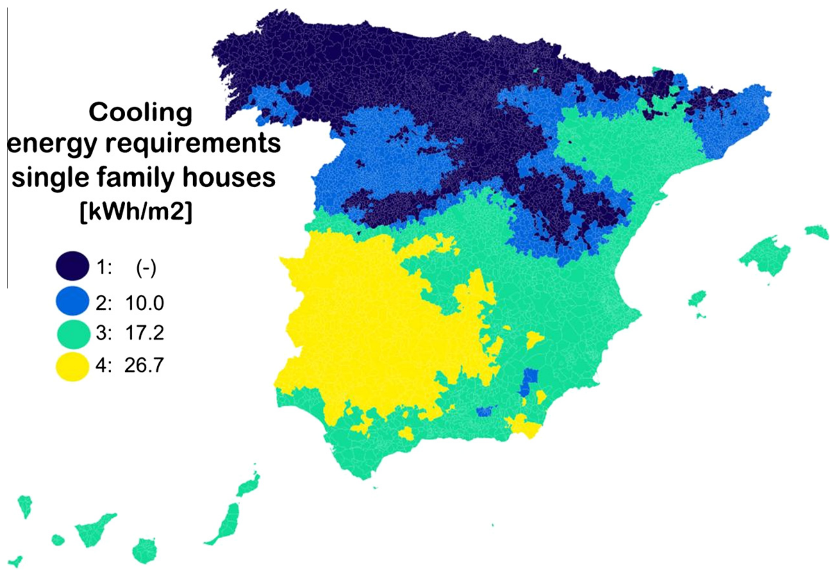

Fig. 2. Average cooling requirements of single family buildings in the Spanish summer climatic zones. Each color represents a climatic zone in Spain and the value is the average cooling needs.

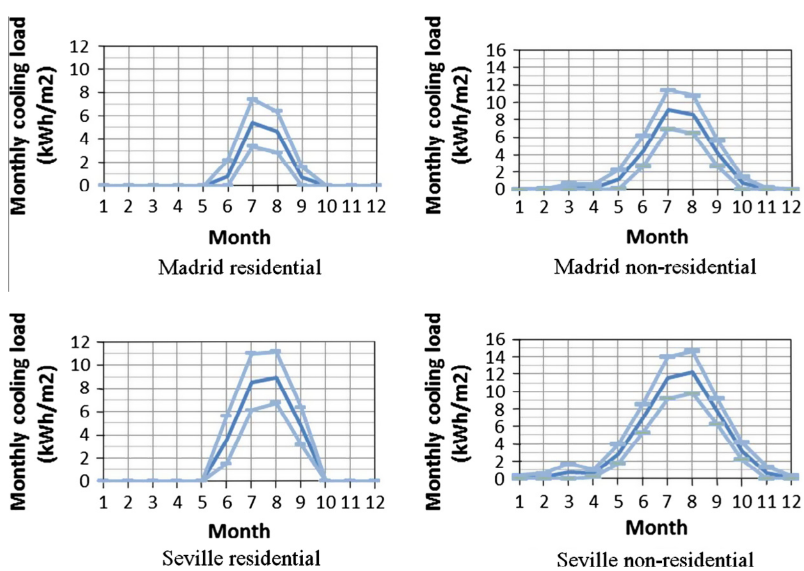

Fig. 3. Monthly cooling needs of residential and non-residential buildings for Madrid and Seville.

The building typology of the selected buildings can be seen in Fig. 1, and descriptive information of each one is shown in Table 1.

The simulation program used for the estimation of the cooling needs was the calculation engine of the Spanish national tool (LIDER) [9]; this is the official software used for regulation purposes in Spain. LIDER uses a dynamic and multizone detailed simulation model to perform calculations of heating and cooling needs of buildings. The calculation engine of LIDER, is the evolution of the simulation software "S3PAS" which was developed by some of the author of this paper. S3PAS was validated with the Building Energy Simulation Test (BESTest) [10], while Lomas et al. [11] performed an experimental validation of several dynamic thermal

Table 2
Daily cooling needs (August).

	Daily cooling needs residential (W h/m^2)	Daily cooling needs non-residential (W h/m^2)
Madrid	100–207	260–440
Seville	209–354	390–580

simulation programs proving an excellent agreement between the results predicted by S3PAS and the measured data.

Buildings shown in Fig. 1, were simulated in 8110 Spanish localities assuming that each building in each location had a construction quality according to the Spanish energy code [12]. As an example, Fig. 2 shows the climatic dependency of the average cooling needs (June to September) of single family buildings, according to the official summer climate zoning.

We have also analyzed the distribution of monthly, daily and hourly values for every location. As an example, Fig. 3 shows the monthly cooling needs (average ± standard deviation) of residential (single family) and non-residential buildings for Madrid (climate zone 3) and Seville (climatic zone 4), respectively.

From Fig. 3, the daily average cooling needs for a given month (August for instance) can be deduced. They are summarized in Table 2.

In relation to the cooling power required, Fig. 4 shows the cumulative frequency distribution of the cooling loads for an average building in Seville and Madrid.

For the two locations selected (Seville and Madrid), Fig. 5 shows the frequency distribution curves of the daily minimum outdoor temperatures during nigh-time.

Let's assume 23 °C as the suitable phase change temperature for the PCM and 5 °C as the temperature drop necessary to recharge the modules. Fig. 7 reveals that the cooling strategy can be effectively used in more than 55% and 80% of the summer days in Seville and Madrid respectively.

4. Numerical model for evaluation of thermal performance of PCM

For simulation of the elements proposed, a numerical model was developed by the authors and it is described in [3]. This numerical model uses finite differences explicit method with the effective heat capacity method [13] for the simulation of PCM. Experimental validation of this model was performed founding a good agreement between simulation and experimental data. Some results can be seen in Fig. 6.

Temperatures discrepancies are in the range of the experimental uncertainty, except in the solidification process, when subcooling in the PCM used (RT22 [14]) [14,15] appears. The simulation model does not include this characteristic. Hysteresis is presented too, but this phenomenon is hidden in part by the subcooling and it is difficult to be quantified.

Table 3 shows the correlation coefficients between experimental data and simulation results of representative variables.

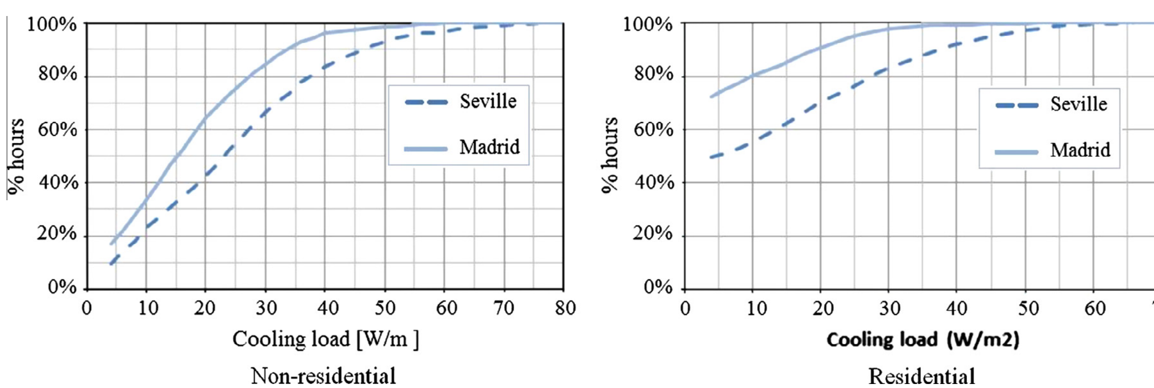

Fig. 4. Cumulative frequency distribution of cooling load of residential and non-residential buildings for Madrid and Seville.

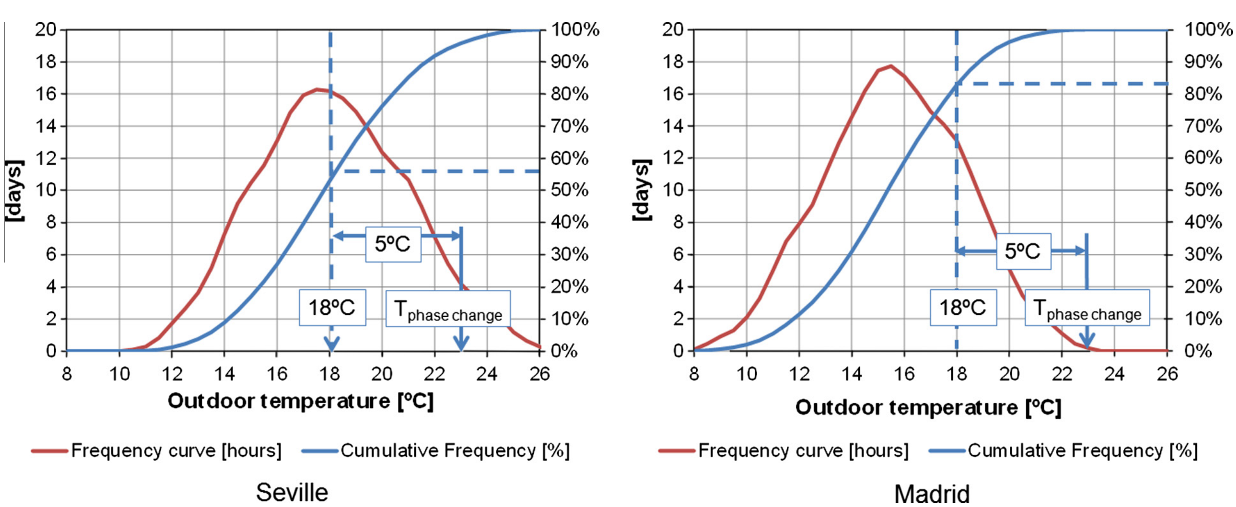

Fig. 5. Frequency distribution of outdoor temperatures at night-time for Seville and Madrid.

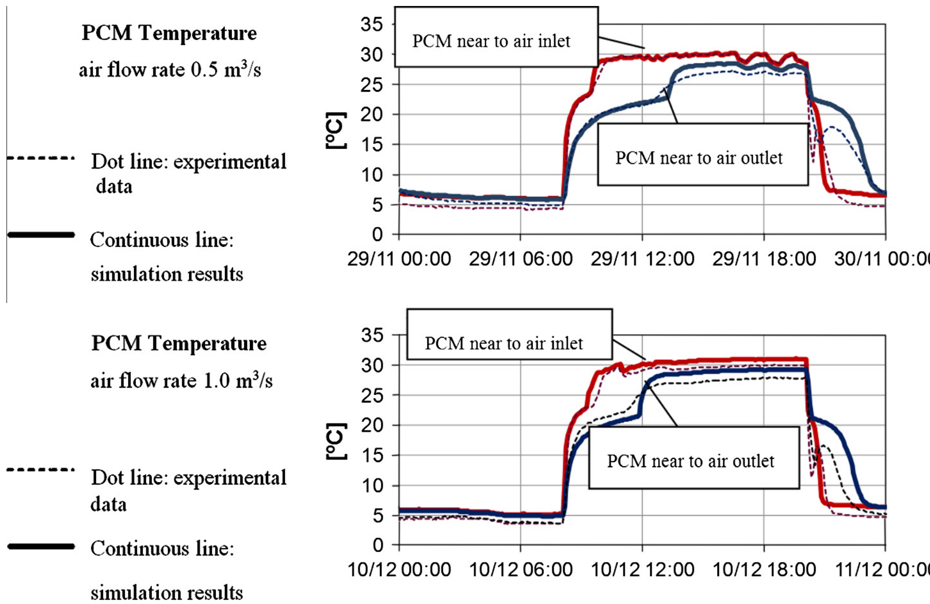

Fig. 6. Comparison between experimental and simulation results.

Table 3
Correlation coefficients between experimental data and simulation.

	Temperature outlet	Temperature PCM lower side	Temperature PCM upper side
Airflow rate = 0.5 m^3/s	0.991	0.997	0.994
Airflow rate = 1.0 m^3/s	0.999	0.994	0.985

The correlation coefficients are close to 1 which reinforces the validity of the conclusions hereinafter.

5. Design and sizing principles. Comparison with existing solutions

There are several alternatives to incorporate PCM in buildings, Tyagi and Buddhi [16] presents a classification consisting in three types:

1. PCMs in building walls.
2. PCMs in other building components (for example subfloor or ceiling systems).
3. PCMs in separate heat or cold storage systems.

Alternatives 1 and 2 directly increase the thermal inertia of the building, while Alternative three stores energy in separate equipments. Solutions proposed in the MECLIDE project are a combination of the three types because they can be understood as separate systems (type 3) that have been incorporated in the structure of the building. The advantage of this design is that the thermal inertia of the building is increased, such as types 1 and 2 do, and additionally it works as an active solution, as type 3, which can be controlled to provide cooling as required.

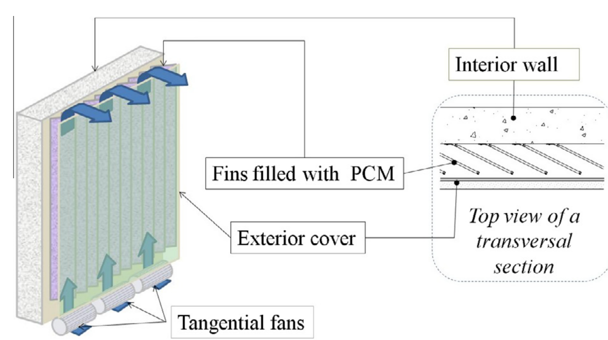

Fig. 7. Ventilated facade with fins filled with PCM.

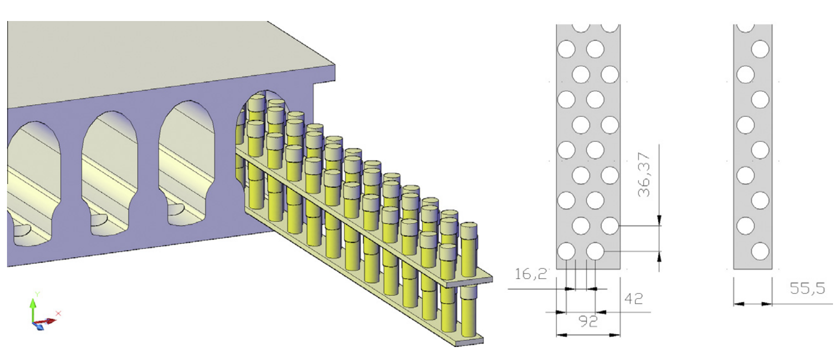

Fig. 8. PCM cylinders in hollow core slabs.

5.1. Description of the solutions

The objective of MECLIDE solutions is reducing cooling load of buildings, through a strategy of storage and a controlled evacuation of heat. The solutions of MECLIDE project use PCM in containers, which are located inside an air chamber, where air is moved by fans with variable flow (forced convection). This air flow is controlled by a control system that can change the air-flow-rate, the origin and the destination of air flow. They even can stop the system totally.

The PCM containers are sealed, made of a material which does not react with PCM contained, and its shape and its arrangement pretend to stimulate heat exchange with air around them. In principle, three basic forms have been considered: fins, cylinders and spheres.

The origin of the air flow can be: from the building or from outside. The destination of the air flow can be: to the building or to outside. These origins and destinations are changed according to climatic conditions and needs of the building.

Figs. 7 and 8 show the MECLIDE solutions used in the experiments. Fig. 7 corresponds to the ventilated facade with PCM embedded in fins. Fig. 8 corresponds to the hollow core slab where the PCM is embedded in cylinders; and an example of integration is shown in Fig. 9.

There are three operational modes in a 24 h cycle:

- Day mode: This mode recirculates hot air from inside the house with the aim of cooling it. This period may also be referred discharge period, since it is at this time, when the "cold" stored in the phase change material is discharged. The target at this stage is to use the cold stored to reduce cooling consumption (Fig. 10).
- Inactive periods: During these time intervals, the airflow stops and closes all doors. The goal is to maintain stored the accumulated cool at night or wait until outside conditions are right to extract efficiently the heat that has been stored during the day (Fig. 11).
- Night mode: Air circulation is from outside to outside. This period can be called charging period, since it is the time when the cold is stored in the PCM (Fig. 12).

A relevant characteristic of the MECLIDE solutions is that the heat transfer area of PCM with the air is higher than the area occupied by the solution. This is, the heat transfer area of the PCM in the MECLIDE facade is 3.6 m^2 per m^2 of façade. For the slab the same index number is obtained but in this case is referred to m^2 of slab.

Related solutions have been described by several authors, Lemma et al. [17], propose a solution consisting of a ventilated facade in which the PCM is incorporated as an additional layer of the exterior skin of the facade. The objective of this solution is that it can be easily incorporated in the construction of new buildings and for building refurbishment. They found that the use of this element reduces the thermal load peak and shift it several hours. Kara and Kurnuç [18] tested a facade similar to a Trombe wall with PCM in the wall and a novel triple glass unit. Faggembauu et al. [19,20] developed a numerical code to simulate double-skin envelopes that can include PCM: they found that the inclusion of PCM in the "opaque zone provokes a reduction in both the heat gains and the heat losses". Barnard and Setterwall [21] present the "CoolDeck element" that is an element using PCM in conjunction with night ventilation; they found a coefficient of performance (cooling/fan energy) in the region of 20.

The proposed MECLIDE solutions perform significantly better that the solutions previously cited as will be shown in the remaining sections.

In order to show the differences of performance two specific indicators (per m^2 of floor) will be defined: daily storage capacity

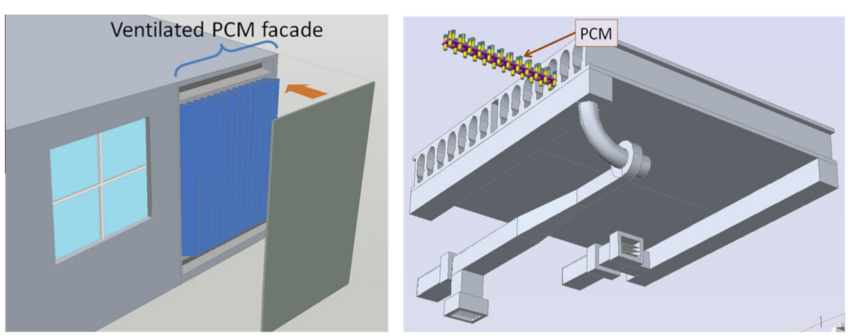

Fig. 9. Integration scheme of MECLIDE solutions.

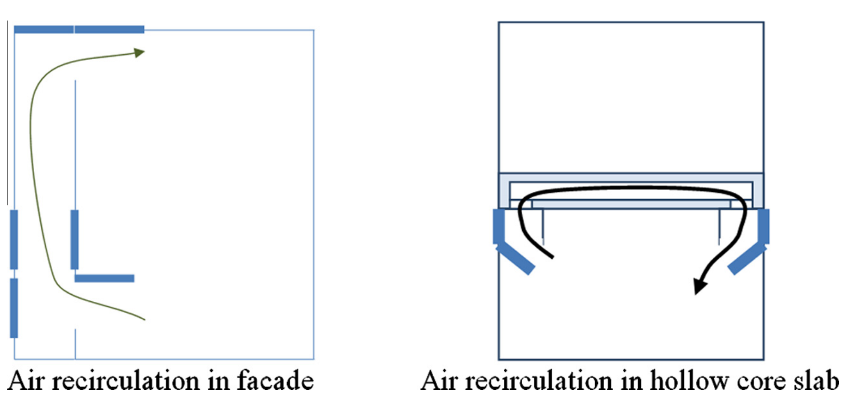

Fig. 10. Day mode or discharge period.

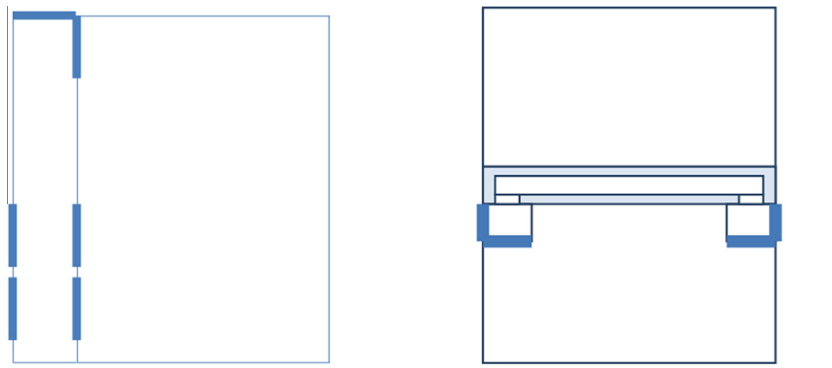

Fig. 11. Inactive periods.

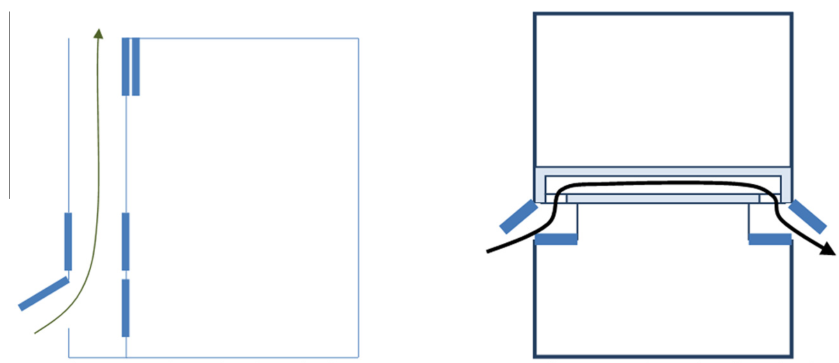

Fig. 12. Night mode or charge period.

(energy that can be stored in a day) in W h/m^2 day; and cooling power that can be dissipated in W/m^2.

The solutions to be compared are:

- Solution 1: Microencapsulated (gypsum wallboard with PCM) or macroencapsulated PCM on the interior surfaces of the building outdoor walls and partitions. See for instance some of the experiments in [1,22].
- Solution 2: Same as above but PCM on the interior surface of a ventilated facade or, alternatively a ceiling solution (CoolDeck for instance).
- Solution 3: Ventilated facade with fins filled with PCM as described in Fig. 7.
- Solution 4: PCM cylinders in hollow core slabs as described in Fig. 8.

5.2. Effective volume of PCM

For a given PCM, the storage capacity depends on the quantity of PCM that is capable to change phase during a daily cycle. This quantity is called the effective volume. The effective volume depends on:

- Amplitude of excitation for PCM.
- Duration of this excitation.
- Convection heat transfer coefficient between the air and the PCM.

In this article and for the purposes of the comparison, it is assumed that:

- Temperature range around phase change temperature: ±5 °C.
- Duration of the excitation: 5 h melting period, 5 h freezing period.
- For solutions 2, 3 and 4 an air velocity of 1.5 (m/s) has been assumed. For solution 1, natural convection has been assumed.
- PCM properties were taken from a commercial product:
  - Latent heat: 170 kJ/kg.
  - Density: 783 kg/m^3.
  - Thermal conductivity: 0.18 W/m K.

In order to calculate the effective volume of PCM that changes phase, the numerical model, described above was used.

Each of the referred solutions was exposed to a cyclic excitation of 24 h, with the following schedule: during 5 h, air temperature (temperature of excitation) was 5 °C lower than the temperature of phase change and during the remaining 19 h, the air temperature was 5 °C higher than the phase change. These cycles were repeated until a repetitive behavior was observed in the response of the PCM.

The model of solutions 1, 2 and 3, consisted of a very wide slab (semi-infinite slab) and the observed result was the maximum depth where the change of phase is performed. That depth is the effective thickness.

The model of the solution 4 was a cylinder of PCM. To determinate the effective radius, several simulations with different radius were carried on. The cylinder that performed a complete change of phase, but that any increment in its radius makes impossible a complete phase change, was selected to define the effective radius.

The effective thickness and radius obtained from the previous simulations are shown in Table 4 along with the convective heat transfer coefficients used in each case.

Table 4
Convective heat transfer coefficient and effective thickness/radius for each solution.

System	Convective heat transfer coefficient (W/m² K)	Effective thickness/ radius (cm)
Solution 1	2.5 [23]	0.2
Solution 2	12 [21], [24]	0.7
Solution 3	18/8 [2,3]	1.7/1[a]
Solution 4	35 [22], [25],	1.75

[a] In conventional solutions as wall with PCM and ventilated facade with PCM, one PCM surface is in contact with the air and the other with the wall. However, a fin has two surface of contact with the air, so the effective thickness is the double.

Table 4 shows two options in solution 3 because in the ventilated facade with fins filled with PCM there are two different zones, at the bottom, (near to the air inlet) convective heat transfer coefficient values equal to 18 W/m^2 K have been measured, but in the upper convective heat transfer coefficient values were 8 W/m^2 K [2,3].

Higher thicknesses or radius of those shown in Table 4 are useless from the point of view of energy storage since phase change will be not performed. Despite it not was considered in this work, a technique for improving the effective thickness of PCM is to increase the thermal conductivity of PCM [26].

5.3. Energy storage and cooling power potential

By referring the effective thickness and radius to the complete solutions, the effective volume and the heat transfer area can be obtained. The results are shown in Table 5 and are expressed in terms of 1 m^2 solution.

As for typical building applications for PCM in buildings, the ratio between the energy stored in PCM in the sensible range and the latent range are low (low Stefan numbers) the storage capacity can be assumed proportional to the specific volume times the latent heat.

Moreover the cooling power depends on the product of the specific heat transfer area and the convective heat transfer coefficient.

In order to calculate daily energy stored provided and cooling power provided, the next hypotheses have been made:

- In the ventilated facade with PCM fins, if the MECLIDE configuration is used, six fins can be collocated in one meter of facade.
- In the ventilated facade with PCM, the thickness of fins was considered equal to 1.0 cm with convective coefficients of 18 W/m^2 K from inlet to the middle height of facade and 8 W/m^2 K to outlet [3].
- In the hollow core slab solution, 1 m^2 of slab can be fitted with 433 PCM cylinders.
- There are no losses for solutions 1, 2 and 4.
- Losses fraction to outdoor for solution 3 is 0.3.
- Utilization factor for solution 1 is 0.6.
- Utilization factor for others solutions is 1.

The reason to assume a lower value for the utilization factor of the solution 1 is that this is a passive solution, therefore there is no control for the time when charge and discharge of PCM occurs thus, the cooling effect in the space can be produced when it is not required.

Table 5
Specific effective volume and specific heat transfer area for each solution.

System	Specific effective volume (m³/m² solution)	Specific effective heat transfer area (m²/m² solution)
Solution 1	0.002	1
Solution 2	0.007	1
Solution 3	0.031/0.018	3.6/3.6
Solution 4	0.021	3.7

Table 6
Daily cooling energy and cooling power required.

		Daily cooling energy [W h/(m² floor)]	Peak cooling load (W/m² floor)
Required	Madrid residential	100–207	40
	Madrid non-residential	260–440	60
	Seville residential	209–354	60
	Seville non-residential	390–580	80

Table 7
Daily cooling energy and cooling power provided by each solution.

		Daily cooling energy [W h/(m² solution)]	Cooling power (W/m² solution)
Provided	Solution 1	37	13
	Solution 2	246	60
	Solution 3	467	227
	Solution 4	788	632

Table 6 summarizes some of the results obtained from simulations performed in Section 3.

From the above and using the results in Tables 2, 5 and 6, the daily cooling energy and cooling power can be obtained (Table 7).

Although daily cooling energy required and provided are given in m^2 of floor and m^2 of solution respectively, MECLIDE solutions (3 and 4) prove to be significantly better than current solutions analyzed in both storage capacity and cooling power.

Most important is that the storage capacity obtained by MECLIDE solutions are able to provide a significant percentage of the cooling required by non-residential building even in the most climatically severe location in Spain.

6. Conclusions

There are inherent drawbacks in the way things have been done so far in PCM based night cooling applications:

- The limited area of contact between PCM and the air.
- The very low convective heat transfer coefficients which prevents the use of significant amounts of PCM.
- The very low utilization factor of the cool stored due to the large phase shift between the time when cool is stored and time when it is required by the building.
- The MECLIDE project aims to overcome the above situation by developing innovative integrated solutions of PCM in the building structure based on:
- Placing the PCM in the core of mechanically ventilated air layers which allows a significant increase of the convective heat transfer coefficients and the use of control strategies to fit the cooling needs of the building.
- The use of encapsulation shapes (fins, cylinder and sphere) that still increase the convective heat transfer coefficients and optimize the use of significant amounts of PCM consistent with the storage capacity required by actual buildings in summer dominated regions.

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