Università degli Studi di Catania
Scuola Superiore di Catania

International PhD

in

ENERGY

XXIV cycle

New technologies for energy savings in the refurbishment of existing buildings

Maria Novella Papa

Coordinator of PhD
Prof. Alfio Consoli

Tutor
Prof. Luigi Marletta

a.a. 2008/2011

Acknowledgements

I would express my thanks to the people who have given me their support during the writing of this thesis and during all the Ph.D. course.

Firstly I thank my Ph.D. Tutor Prof. Luigi Marletta for his encouragement to start this activity and for his great efforts to solve clearly and simply my many doubts.

Then I would thank my Ph.D. Coordinator Prof. Alfio Consoli who has constantly followed the research activity urging to do better and giving useful advices.

I'm also grateful to the Ph.D. researchers Fabio Sicurella and Gianpiero Evola for their support with writing e-mails, giving wise advices and answering my numerous questions.

I would also express my gratitude to Etienne Wurtz, Research Director of CNRS-INES, who gave me the opportunity to carry out a part of my research activity at the INES laboratories in Chambéry.

My sincere thanks to my colleagues with whom I shared not only study experiences but also many pleasant time.

I'm also very grateful to the staff of Scuola Superiore, especially to Dr. Bice Immè for assisting me many times with kindness.

Finally I would express my most important thanks to my family: my dear parents and my brother, for their loving support and a special thank to my beloved Mario for his encouragement, understanding and great patience.

To them I dedicate this thesis.

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PART II

Abstract

The building sector is responsible for many environmental problems mainly because of the energy consumptions for heating, cooling, lighting, ... during the whole life cycle of a building.

The refurbishment of the existing building stock offers an opportunity to take effective and environmentally friendly solutions.

A thermal energy storage system is very effective item to reduce the energy consumptions because it allows the possibility of using solar energy continuously, reducing the internal temperature fluctuation and improving the thermal comfort.

The most used heat storage materials for building application are the Phase Change Materials (PCMs) which store solar energy during the day and release it during the night.

The aim of this work is to test the usefulness of PCMs for improving summer thermal comfort in lightweight buildings. In order to evaluate the performance of PCMs we carried out simulations using EnergyPlus, a building simulation tool based on the finite difference method.

For the assessment of the optimal thermal comfort conditions we considered the adaptive comfort method and we introduced some new thermal comfort indicators.

The results of simulations show a very significant effect of PCMs during the summer season. In particular the application of a PCM panel with a ventilated air gap proves to be beneficial for the indoor thermal comfort, due to a consistent decrease of the air temperature fluctuations and the reduction of the maximum operative temperature without using any cooling system.

The present work is intended to give a contribution to optimize building components incorporating PCMs for thermal storage, in an energy savings and thermal comfort perspective.

Introduction

The importance of energy use in buildings is a topic widely covered and studied; many policies and regulations have been introduced in order to reduce the energy consumption and improve the energy efficiency.

The energy consumption is produced mainly by the residential and tertiary sector, which is responsible for about 40% of the total final energy demand. In particular in the EU residential sector, more than 50% of the total final energy consumption is used for space heating, 25% for domestic hot water and 11% for electricity.

As a result, it is one of the sectors with the highest potential for improvement.

In this case the improvement may involve both the building envelope and the energy technologies at the building service (heating , cooling, lighting, etc...).

A new and attractive system for space heating and cooling of buildings is based on thermal energy storage which allows the possibility of using solar energy continuously, storing solar energy during the day and releasing it during the night reducing the internal temperature fluctuation and improving the thermal comfort sensation.

The storage of thermal energy can be done in relation to the sensible and latent heat. Sensible heat storage means are standard materials such as concrete, brick, plaster, etc.... which need a heavy mass for storing thermal energy; contrariwise latent heat storage materials are more advantageous because they have a large energy storage capacity associated with a very small thickness (few centimeters).

In the latent heat thermal energy storage, the most used materials are Phase Change Materials (PCMs), like paraffin wax and hydrate salts, due to a larger storage density compared to sensible heat storage materials.

In fact, an ideal material without phase change, i.e. the standard construction materials, heats up when the heat is stored and cools down when the heat is released. A phase change material stores a large amount of thermal energy during its melting phase without changing its temperature and, when the phase change is completed, the temperature starts rising.

Besides, a standard material such as concrete may cause larger fluctuations of indoor temperature, while the PCMs provide large latent heat storage over the narrow range of temperatures typically encountered in buildings, thus they can improve the thermal comfort level.

In the last years the PCMs are becoming very attractive and required materials for building application due to their possibility to be easily compounded with common building materials and manufactured into various composite building elements and components, such as laminated boards or panels. Particularly these last ones are very suitable to be incorporated into the envelope in the case of building refurbishment because they can be easily installed and differently arranged.

However, the latent heat storage in buildings and even the PCMs induced many investigations in the last decades because there are still several difficulties concerning some practical issues. So, more surveys are still required on these field to apply this concept in a reliable and practical way.

This research activity wants to provide new assessments on PCMs efficacy on the summer indoor thermal comfort in the case of application for building refurbishment.

The project consists of two main parts: the first is an overview on important topics related to the research activity, such us the Energy Performance Directives in the building sector, the indoor thermal comfort, the thermal energy storage methods, the various typologies, properties and application systems of the phase change materials.

In the second part, we carried out numerical simulations with the software tool EnergyPlus which allows the building energy analysis and its thermal load simulation taking into account the building's physical description (location, materials, construction, etc...). By varying the thickness of the PCM panel, embedded in the internal partitions of a test building, as well as the intensity of the night mechanical ventilation, some interesting results arise as far as thermal comfort is concerned.

The analysis is supported by new indicators, which help quantify the intensity and the duration of the potential thermal discomfort as well as the actual duration of PCM activation phase.

The main goal of this research work is to demonstrate how the PCM are helpful for energy savings in the building sector by reducing operational energy consumptions during the summer period and realizing an effective solution for the improvement of the building thermal comfort.

PART I

1. Energy Performance of building.

1.1. State of the art.

The problem of energy efficiency of buildings has been at the centre of a broad scientific and technical debate in the last years; in fact the building sector is responsible for many environmental problems because of the exploitation of non-renewable resources, the use of soil and the energy consumptions during the whole life cycle of a building.

Consequently, an increase of building energy performance can constitute an important instrument in the efforts to alleviate the EU energy import dependency and help to comply with the Kyoto Protocol to reduce carbon dioxide emissions.

The new European Directive 2010/31/EC on the Energy Performance of Building (EPBD), which replaces the Directive 2002/91/EC, is also aimed at energy conservation and at improvement of energy efficiency of buildings.

In fact, given the long life-span of buildings (50 to more than 100 years) and the high number of existing buildings, it is clear that the largest potential for energy conservation measures is related to the existing building stock; in fact about 70% of the residential buildings are over 30 years old and about 35% are more than 50 years old. Also, considering that most national building regulations concerning the thermal insulation of building envelopes were introduced after the 1970s following the energy crisis and the ageing technical installations (it is estimated that about 10 million residential boilers are older than 20 years old), we can understand how much the thermal performance of the old building is low.

Most energy consumption in existing building sector is due to the heating, lighting and cooling, and also an increasing percentage is consumed by domestic appliances, computers and other electrical equipment.

So, changes and innovations of materials, elements, systems... and new installations could give a good contribute to the reduction of energy needs.

The refurbishment of the existing building stock offers an opportunity to take cost-effective measures and make them efficient and environmentally friendly, with an increased social and financial value. Similar opportunities may exist even during building renovations (i.e. repairs and restorations to good condition). Protecting the architectural heritage is a primary benefit, but it may also be financially attractive.

In many cases, building refurbishment costs are lower (even for high investment retrofit operations) than demolition and reconstruction costs (about half to one-third of the cost). In light of sustainability it makes more sense than ever to renovate or refurbish old buildings.

Several efforts have been made by the EU Member States to develop methodologies and software tools in order to enable architects and engineers during their decision-making process for building refurbishment.

A number of decision support softwares have been developed in the framework of European projects over the past few years, for the assessment of different scenarios during renovation or refurbishment of buildings.

Due to the rapid increase in the living standard together with climate changes and economic development, the growing trend of energy use in buildings might be continuously experienced in the future. Promoting energy efficiency and conservation in buildings is therefore becoming one of major issues of concern to governments and society today.

1.2. Regulations about Energy Performance of Buildings.

The European Directive 2010/31/EC on the Energy Performance of Buildings (EPBD) requires that an energy performance certificate is made available when buildings are constructed, sold or rented out. The certificate has to express the energy performance (EP) of the building and it has to be accompanied by recommendations for the cost effective improvement of the energy performance. The calculation of the energy performance should be carried out according to a methodology based on a general framework set out by the EPBD.

The "energy performance of a building" is defined as '*the amount of energy actually consumed or estimated to meet the different needs associated with a standardized use of the building'*. This amount shall be reflected in one or more numeric indicators, which have been calculated, taking into account:

- insulation,
- technical and installation characteristics,
- design and positioning in relation to climatic aspects, solar exposure and influence of nearby structures,
- own-energy generation,
- other factors, including indoor climate, that influence the energy demand.

The European Energy Performance Directive has the aim of promoting the reduction of carbon dioxide emissions, according to the limits established in the Kyoto Protocol. In order to reach this target each State of European Union must to provide regulations to improve energy performance of buildings (e.g. Italy transposed the EPBD through Legislative Decree n. 192/2005 then updated by the Legislative Decree n. 311/2006 and the following Decree n. 54/2009 concerning the National guide lines for building energy certification).

However, actions provided by any regulation are the following:

- adoption and application of a methodology to evaluate the energy performance of buildings (i.e. primary energy use for heating, cooling, ventilation, hot water supply and lighting);
- the adoption of the necessary measures to ensure the minimum amount of energy for building requirements;
- the integration with technologies producing energy from renewable sources;
- the adoption of an energy certificate that includes reference values and recommendations for the improvement of the energy performance of building;
- the adoption of measures to establish a regular inspection of boilers and air-conditioning systems.

The Directive 2010/31/EC, notably in accordance with article 1, "promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness".

In particularly the new Directive provides requirements about:

- the methodology for calculating the energy performance of buildings and building units;
- the application of minimum requirements to the energy performance of new buildings and new building units;

- the energy certification of buildings and building units;
- independent control systems for energy performance certificates and inspection reports of heating and air-conditioning systems in buildings;
- national plans for increasing the number of nearly zero- energy buildings.

The European member states must define a methodology for calculating the energy performance of buildings in accordance with the criteria set out in Annex I "*Common general framework for the calculation of energy performance of buildings*".

Besides the Directive establishes that, in order to contain the energy demand, each member states have to define the requirements for technical building systems in respect of:

- the overall energy performance,
- the proper installation and sizing,
- the appropriate regulation and control.

So, according with the requirements of the new European Directive and considering the great importance of the building sector in the field of energy savings, the refurbishment of existing buildings assumes a very important role and represents a good opportunity to satisfy the legislative prescriptions.

1.3. Methodology for calculation of Energy Performance.

The European Directive prescribes that EU Member States shall apply a methodology at national or regional level, for calculation of the energy performance of buildings on the basis of a general framework.

Some European regulations define the methodologies to calculate the energy performance of buildings and for evaluation of building energy flows:

- European Standard EN ISO 15603 proposes different energy rating methods;
- European Standard EN ISO 13790 provides the methodology for calculation of energy use for space heating and cooling;
- European Standard EN 15316 defines how to use renewable energy sources and other methods in order to generate space heating and product warm water.

Many Italian norms (expressed through the acronym UNI) about energy in building consist of the adoption or transposition of European (EN) and/or International (ISO) standards. Italy transposed the regulations mentioned above through a new set of norms called UNI TS 11300 to calculate the energy performances of building. These norms are the following:

- Technical Sheet UNI/TS 11300:1 for evaluation of energy need for space heating and cooling;
- Technical Sheet UNI/TS 11300:2 for evaluation of primary energy need and of system efficiencies for space heating and domestic hot water production;
- Technical Sheet UNI/TS 11300:3 for evaluation of primary energy need and system efficiencies for space cooling;
- Technical Sheet UNI/TS 11300:4 for using of renewable energy sources and of other technologies for space heating and domestic hot water production.

Every methodology shall include at least the following aspects: thermal characteristics of the building (envelope and internal partitions, etc.) and these characteristics may also include air-tightness; heating installation and hot water supply, including their insulation characteristics; air-conditioning installation; ventilation systems; built-in lighting installation (mainly the non-residential sector); position and orientation of buildings; passive solar systems and solar protection; natural ventilation; indoor climatic conditions including the designed indoor climate.

In this calculation other positive and relevant aspects shall be taken into account, like active solar systems and other heating and electricity systems based on renewable energy sources; electricity produced by CHP (Combined Heat and Power); district heating and cooling systems; natural lighting.

The energy certification of buildings requires a method that is applicable both to new buildings and to the existing ones, focusing attention more on building features than on their management. Many studies have been developed on energy ratings, by creating and applying methods to predict annual building energy costs, to evaluate the quality of the given results and the process, to establish energy benchmark values and to plan energy efficiency improvements of the building stock.

The main inputs needed for this standard are the followings: the transmission and the ventilation properties; the heat gains from internal heat sources; the solar and climatic data; the description of the whole building and its components, systems and uses; the comfort requirements (set-point temperatures and ventilation rates);

the length of the heating and cooling seasons; the data related to the heating, cooling, hot water, ventilation and lighting systems; the partition of building into different thermal zones for the calculation (different systems may require different zones); the energy losses dissipated and recoverable or recovered in the building; the air flow rate and temperature of ventilation supply air.

The main outputs of the standard calculation methodology are the annual energy needs for space heating and cooling, the annual energy needs for hot water, the annual primary energy consumption. Other outputs are the monthly values of energy needs and energy use and monthly values of the main elements in the energy balance such as. the transmission heat losses, the ventilation heat losses, the internal heat gains, the solar heat gains. Additional outputs are the contribution of passive solar gains and system losses (from heating, cooling, hot water, ventilation and lighting systems) recovered in the building.

2. Indoor Thermal Comfort

2.1. An overview on indoor thermal comfort.

The first recognized model for thermal comfort was proposed by Fanger about thirty years ago and it had a wide scientific consensus so that it was included, several years later, in the ISO Standard 7730 (ISO, 1994). Fanger's method introduced two comfort indicators the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied); the first index is obtained combining four physical variables (air temperature, air velocity, mean radiant temperature and relative humidity) and two personal variables (clothing insulation and activity level). The index provides a score that corresponds to the ASHRAE thermal sensation scale and represents the average thermal sensation felt by a large group of people in a space. The second index is calculated from PMV and predicts the percentage of people who are likely to be dissatisfied with a given thermal environment. The PMV and PPD can be represented by a function where the percentage of dissatisfied increases for PMV values above and below zero (thermally neutral).

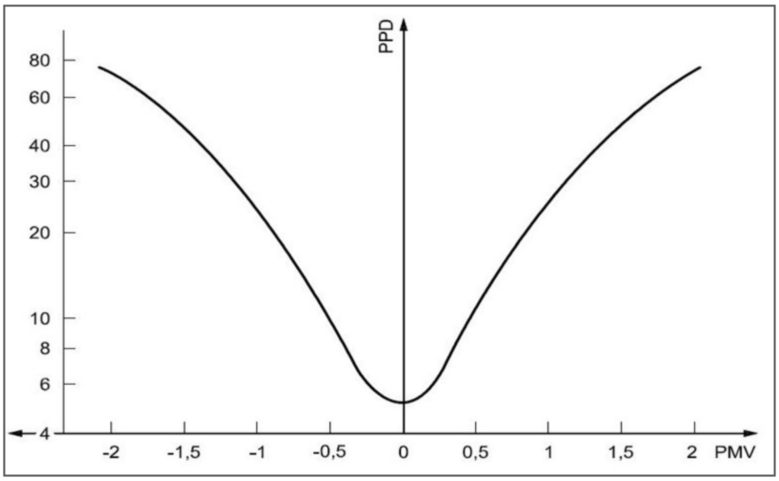

Fig. 1 Relation between PPD and PMV

However it is important to note some considerations with respect to this method: the PMV model is designed to predict the average thermal sensation for a large group of people but it also implies that not all occupants are thermally satisfied; in fact the PMV is an index based on thermal sensation, so the evaluation can be different from an occupant to another. Besides this model has been developed considering a building under controlled micro-climate condition, so it cannot manage transient situation that occurs, for instance, in naturally ventilated buildings, in buildings without HVAC systems or where occupants vary their behaviour and activity. This means that, for most of bioclimatic buildings as well as for a large number of renovating buildings, the Fanger's approach cannot be undertaken.

So in the above mentioned cases it is possible to consider another thermal comfort approach, proposed by Nicol and Humphreys and called "adaptive comfort".

The adaptive model is based on the following principle: "*If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" (Humphreys). This principle states that people have the capability to adapt themselves to the climate conditions of an environment in order to achieve their well being conditions; besides it allows to relate the comfort sensation to people's action and to define a "comfort temperature", that is the result of the interaction between the occupants and the building considering the climate conditions. So, it signifies that the operative temperature is continually changing and the rate and time of these changes can significantly affect the indoor thermal comfort conditions.

For example, occupants of naturally ventilated buildings have the possibility to increase the air velocity in the room by operating windows and, doing this, they can still create a comfortable environment in higher indoor temperatures having a direct contact to the weather outside. While Fanger's PMV-model can only take the effects of behavioral adaptation into account: the adjustment of clothing and the level of activity or the regulations of the air velocity through the HVAC system. Therefore this model is only truly appropriate for sealed air-conditioned buildings.

In a number of studies on the adaptive comfort approach it is demonstrated that the comfort temperatures and clothing insulation are more strongly correlated to the '*running mean outdoor temperature*' (Θ_{rm}) than to the actual or mean outdoor temperature during the day. This implies that not only today's weather but also the weather of the past few days has influence on the clothing values and the perception of comfort temperature.

The running mean outdoor temperature is an exponentially weighted mean outdoor temperature and is expressed by the equation:

$$\Theta_{rm} = (1-\alpha)\cdot\{\Theta_{ed-1} + \alpha\cdot\Theta_{ed-2} + \alpha^2\cdot\Theta_{ed-3} + \alpha^3\cdot\Theta_{ed-4} + \ldots\ldots\} \quad (1)$$

where:

Θ_{rm} is the external running mean temperatures [°C]

Θ_{ed-1} is the daily mean external temperature for the previous day [°C]

Θ_{ed-2} is the daily mean external temperature for the day before and so on [°C]

α is a constant between 0 and 1 (the recommended value is 0.8)

The importance of the adaptive approach increased in the last ten years, so that it was first included in the ASHRAE Standard 55 and more recently in the EN Standard 15251. These standards provide the method for determining acceptable thermal conditions for buildings without mechanical cooling systems. Particularly the Annex A of the EN Standard 15251 reports the summer temperature limits for design buildings with an air-conditioned system and without a mechanical cooling system (this last typology is the one that we took into account for the case-study considered in this work).

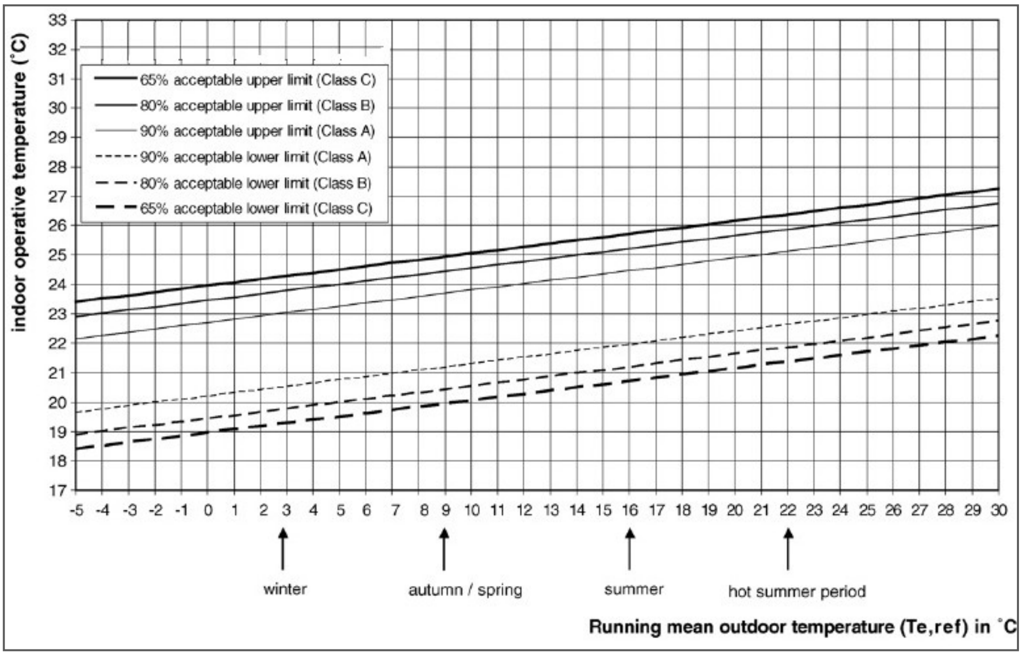

Fig. 2 Temperature limits of thermal comfort categories of the adaptive approach.

These limits are calculated as a function of the Θ_{rm} and allow to define three comfort categories: I,II and III. The class II represents a situation which could generally be considered acceptable; the other two classes around class II refer to an extra high quality building (class I) or a building with an indoor climate that is less acceptable as such (class III).
For each type of building or space, the Standard EN 15251 recommends a specific design value of the indoor temperature of the building and HVAC systems; in particular for buildings without mechanical cooling systems the acceptable indoor temperatures are defined by the following functions:

Category I $\quad \Theta_{i\max} = 0.33 \cdot \Theta_{rm} + 18.8 + 2$

$\Theta_{i\min} = 0.33 \cdot \Theta_{rm} + 18.8 - 2$

Category II $\quad \Theta_{i\max} = 0.33 \cdot \Theta_{rm} + 18.8 + 3$ (2)

$\Theta_{i\min} = 0.33 \cdot \Theta_{rm} + 18.8 - 3$

Category III $\quad \Theta_{i\max} = 0.33 \cdot \Theta_{rm} + 18.8 + 4$

$\Theta_{i\min} = 0.33 \cdot \Theta_{rm} + 18.8 - 4$

2.2. The indoor thermal comfort indicators.

For a free running building where no HVAC system controls the microclimatic conditions, it is necessary to define some indicators which take into account the most important physical parameters for thermal comfort i.e. the operative temperature. In the following we introduce some new indicators defined on the basis of the operative temperature and which can help in the assessment of the optimal thermal comfort conditions for an indoor environment.

- *Frequency of the monthly thermal comfort conditions (**FMTC**),* represents the time fraction within a month during which temperatures are falling in the comfort/discomfort thermal ranges. Temperature values delimiting the three ranges are the following:

- T_{over} as upper limit

- T_{under} as lower limit

When the operative temperature is over the upper limit, the risk of hot sensation occurs; on the contrary if the operative temperature is below the lower limit the risk of cold sensation occurs. When operative temperature falls within the range $T_{under} < T_{op} < T_{over}$ the thermal comfort condition occurs.

For most of practical applications the upper and the lower limit can be assumed as constant values, such as:

T_{over} = 27 °C

T_{under} = 22 °C

But for more accurate comfort estimation, these limits should vary according the variations of the running mean outdoor temperature as defined previously in § 2.1. In the present work we considered this last calculation method.

- *Intensity of thermal discomfort (**ITD**)* is the sum, during a month, of the degrees of temperature that exceed the upper limit of comfort temperature or that fall below of the lower limit of comfort . It is defined as follows:

$$ITD_{over} = \int_{year} \left(T(t) - T_{over}\right) dt \tag{3}$$

$$ITD_{under} = \int_{year} \left(T(t) - T_{under}\right) dt \tag{4}$$

where:

$T(t)-T_{over} = T(t)-T_{over}$ if $T(t) > T_{over}$ otherwise is equal to 0

$T(t)-T_{under} = T(t)-T_{under}$ if $T(t) < T_{under}$ otherwise is equal to 0

The two parameters describe the indoor discomfort sensation felt by the occupants in the building during the winter and the summer season.

When the indoor environment of a building without HVAC system is characterized by the condition $ITD_{over} \approx ITD_{under} \approx 0$, it means that the indoor temperature are falling in the comfort range all year without heating or cooling.

The graphical interpretation is given in *Fig. 3*.

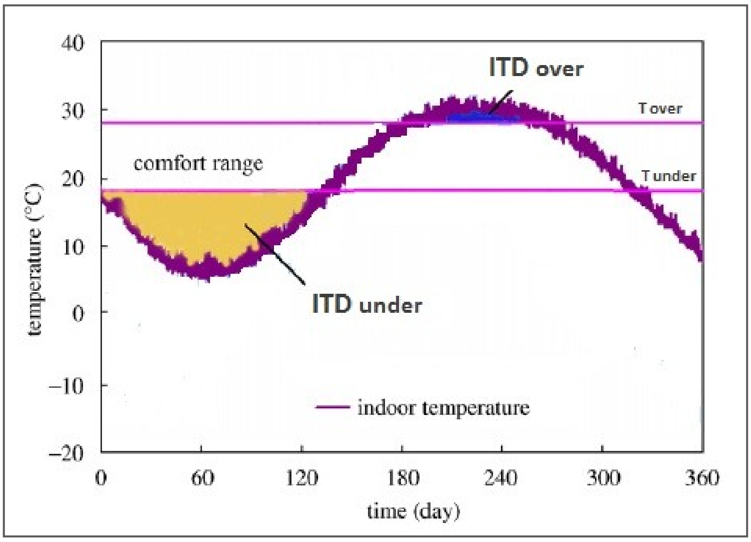

Fig. 3 The Intensity of discomfort parameters for winter and summer period.

3. Thermal energy storage methods

The energy storage plays an important role in conserving the energy because it could alleviate the mismatch between supply and demand but also could improve the performance and reliability of energy systems. Besides, it leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost.

Energy can be stored according different forms, such as mechanical, electrical, thermal and chemical. In particular in this work we are going to consider the storage of thermal energy.

Thermal energy can be stored as a change in internal energy of a material as sensible heat or latent heat.

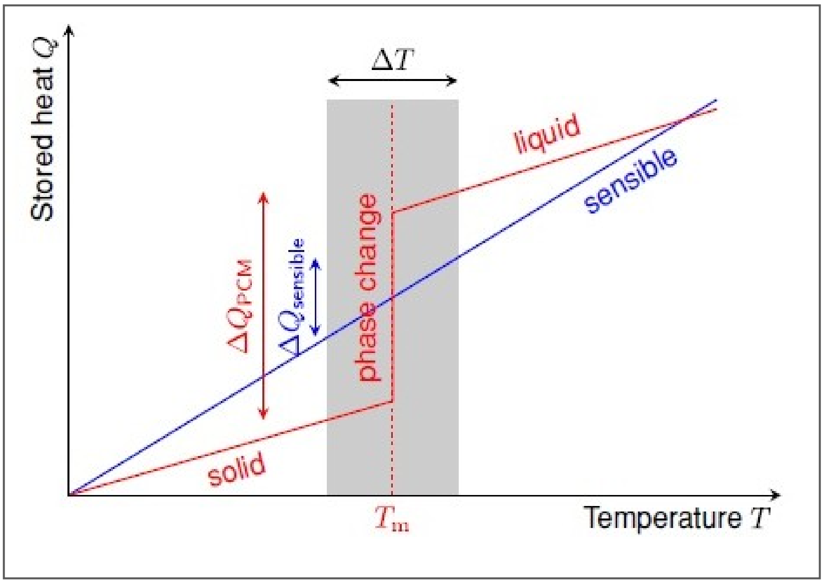

Fig. 4 Comparison of thermal energy stored by a Sensible Heat Storage (SHS) and a Latent Heat Storage (LHS).

2.1. Sensible heat storage

The sensible heat storage (SHS) consists in storing the thermal energy by raising the temperature of a solid or liquid (*Fig. 4*). In a sensible thermal energy storage system, energy is stored by changing the temperature of the storage medium.

This storage method is based on the heat capacity of the material and on the difference of temperature during the process of charging and discharging.
The amount of heat stored is defined by the following equation:

$$Q = \int_{Ti}^{To} mC_p dT = mC_p (T_o - T_i) \qquad (5)$$

The thermal energy stored is proportional to the difference between the storage input and output temperatures (T_i and T_o), the mass of the material used as storage medium (m)and its heat capacity (C_p).
The highest sensible heat storage capacity belongs to the water which represents the best sensible heat storage material. Other selected solid or liquid materials such as construction materials (concrete, rock and brick) have a minor heat storage capacity; whereas organic liquid substances (ethanol, proponal, butanol, octane,...), molten salts and oils have a fairly high heat capacity and a temperature range above 100°C (*Tab. 1*).

Medium	Fluid type	Temperature range (°C)	Density (kg/m^3)	Specific heat (J/kg K)
Rock		20	2560	879
Brick		20	1600	840
Concrete		20	1900–2300	880
Water		0–100	1000	4190
Caloriea HT43	Oil	12–260	867	2200
Engine oil	Oil	Up to 160	888	1880
Ethanol	Organic liquid	Up to 78	790	2400
Proponal	Organic liquid	Up to 97	800	2500
Butanol	Organic liquid	Up to 118	809	2400
Isotunaol	Organic liquid	Up to 100	808	3000
Isopentanol	Organic liquid	Up to 148	831	2200
Octane	Organic liquid	Up to 126	704	2400

Tab. 1 Thermal capacity of some common sensible energy storage materials

2.2. Latent heat storage

The latent heat storage (LHS) is an energy storage method which allows to store a larger amount of energy than a sensible heat storage (see *Fig. 4*) because the charge of thermal energy occurs at a constant temperature; so it could be very suitable and advantageous for solar energy applications, for instance.

Latent heat storage can occur through solid-liquid, liquid-gas and solid-gas phase transformations but considering the building application the first ones are the most suitable because of their feasibility and effectiveness.

In fact although liquid-gas and solid-gas transition have higher latent heat of fusion, they can cause some practical problems relating to their large volume changes on phase transition and lose a large part of their potential utility in thermal storage systems because the system becomes complex and impractical.

In particular, in this work we'll analyze latent heat storage systems realized with storage material which make a phase change from solid to liquid and vice–versa.

The storage capacity of the LHS system with a storage material is given by the following equation:

$$Q = \left[\int_{Ti}^{Tm} mC_{sp}(T)dT + m\Delta h + \int_{Tm}^{To} mC_{lp}(T)dT \right] \quad (6)$$

Where:

m = mass of heat storage medium [kg]

C_{sp} = specific heat in the solid phase [J/kgK]

C_{lp} = specific heat in the liquid phase [J/kgK]

Δh = heat of fusion per unit mass [J/kg]

T_i = initial temperature [°C]

T_m = melting temperature [°C]

T_f = final temperature [°C]

In the latent heat storage system the thermal energy is charged when the material achieves its melting temperature (solid to liquid phase) and it is discharged when material temperature decreases (liquid to solid phase). A latent storage material could store 5–14 times more heat per unit volume than a sensible storage material such as water, masonry, or rock.

Very effective latent heat storage materials are Phase Change Materials (PCMs) which are known to melt with a heat of fusion in any required range. However, for their employment as latent heat storage materials, it is necessary to know their thermodynamic, kinetic and chemical properties.
In the follow a wide review on PCM properties and applications is exposed.

4. Phase Change Materials (PCMs)

4.1. Properties of PCM

Due to their application as a thermal storage material, the PCMs are characterized by many interesting properties that we can classify in four main groups:

- *Thermal properties*
- *Physical properties*
- *Kinetic properties*
- *Chemical properties*

As a single material can't have all the required properties to be an ideal thermal storage media, it is possible to add others substances in order to make up for the missing properties or optimize the existing ones. For example, metallic fins can be used to increase the thermal conductivity of PCMs (as we shall see), super-cooling (see § 4.1.3) may be suppressed by introducing a nucleating agent in the storage material, and incongruent melting can be inhibited by the use of a PCM of suitable thickness.

Furthermore some economic considerations should be taken into account in order to carry out a wider and more complete survey, but this topic is not covered in this work.

4.1.1. Thermal Properties.

The most obvious thermal properties for a PCM for building application is a suitable phase change temperature and a high latent heat of transition. The first requirement is very important to ensure an effective charge and discharge cycle; the choice of the melting temperature depends on the PCM application and, above of all, on the weather conditions of the building location.

For a given climate condition and building, if the melting temperature is too high, PCM can't fully achieve its working phase and the amount of the stored heat will be too low in the daytime; on the contrary, if the melting temperature is too low, the

PCM can't carry out completely its charge-discharge cycle and it could remain in the same phase.

As concerns to the second property, the latent heat should be as high as possible, in order to reduce the container size.

As well as the latent heat, the thermal conductivity of a PCM should be quite high in order to ensure a better heat transfer within the material and so a more effective charge and discharge cycle.

4.1.2. Physical Properties.

The small volume variation during the phase transformation is one of the main physical characteristics of a PCM for building application; in fact smaller changes in volume can reduce the containment problems and consequently make it possible the application of a phase change medium with a smaller thickness.

Others physical properties which can make more desirable a PCM for thermal energy systems are a high density (the higher the density the larger is the quantity of the latent heat stored) and a low vapor pressure at operating temperatures in order to reduce the mechanical stability on a medium containing the PCMs.

4.1.3. Kinetic Properties.

The kinetic properties are related to the mechanism of the phase transition. In particular the kinetic properties required for a PCM are:

- a little or no supercooling during the cooling phase
- high rate of crystal growth (nucleation rate)

The supercooling (also called subcooling) is the effect during which a temperature significantly below the melting temperature is reached until a material begins to solidify and release heat. If that temperature is not reached, the PCM will not solidify at all and thus it only stores sensible heat. The *Fig. 5* shows the effects of subcooling on heat storage.

During the phase transition from liquid to solid state, the latent heat is not released when the melting temperature is reached due to subcooling.

The effect of subcooling makes it necessary to reduce the temperature well below the phase change temperature to start crystallization and to release the latent heat stored in the material. If nucleation[1] does not happen at all, the latent heat is not released at all and the material only stores sensible heat.

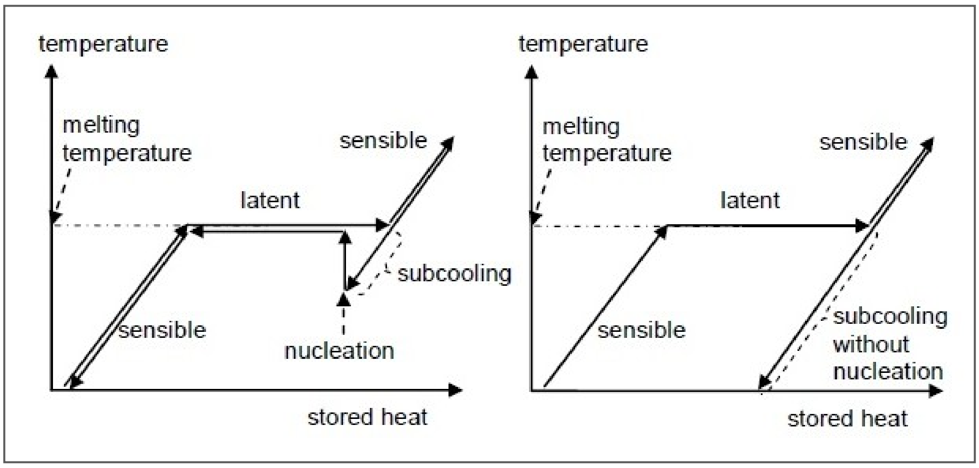

Fig. 5 Effect of little subcooling and nucleation on heat storage (left) and effect of a large subcooling without nucleation.

The PCMs, in particular salt hydrates, have the tendency to supercool and not melt in a congruent way; so this can cause some segregation problems, i.e the components of the PCM with different composition are separated from each other macroscopically and the those ones with a composition different from the correct initial composition optimized for heat storage then show a significantly lower capacity to store heat.

This process can have some important and also deleterius effects on the overall characteristics of PCMs and affects their effectivness in storing heat.

In order to prevent segregation problems and to enhance the nucleation rate some nucleasting and thickening agents [2] are added to PCM compounds.

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[1] The nucleation is the initial process that occurs in the formation of a crystal from a solution (liquid or vapour) in which a small number of molecules become arranged in a pattern characteristic of a crystalline solid forming a site upon which additional particles are deposited as the crystal grows.

[2] Thickening means the addition of a material to the PCM to increases its viscosity. Due to the high viscosity, different phases cannot separate far until finally the whole PCM is solid.

4.1.4. Chemical Properties

Regarding the chemical properties, PCM should be:
- chemical stable,
- compatible with the construction materials,
- non-degradable after melt/freeze cycles,
- non-toxic, non-flammable, non-explosive.

The chemical stability of the PCM can ensure a long lifetime of the material especially when it works in difficult conditions (exposition to high temperatures, gases, radiation,...).

The cyclic stability means that the phase change has to be reproducible, i.e. the use of the material many times for storage and release of heat as required by an application. The number of cycles varies from only one, when the PCM is used for heat protection in the case of a fire, to several thousand cycles when it is used for heating or cooling of buildings. This property depends on the phase separation (see § 4.1.3) which can change the initial PCM composition and reduce over time the effectivness of the heat capacity.

4.2. Classification of PCM

The first classification of phase change materials is probably made by Steiner et al. in 1980. Then several publications could be mentioned: Abhat in 1983 (*Fig. 6*), Lane in 1983 and in 1986, and recently Hiebler and Mehling 2001, Zalba et al. 2003, Sharma et al. 2004, Farid et al. 2004, and Kenisarin and Mahkamov 2007.

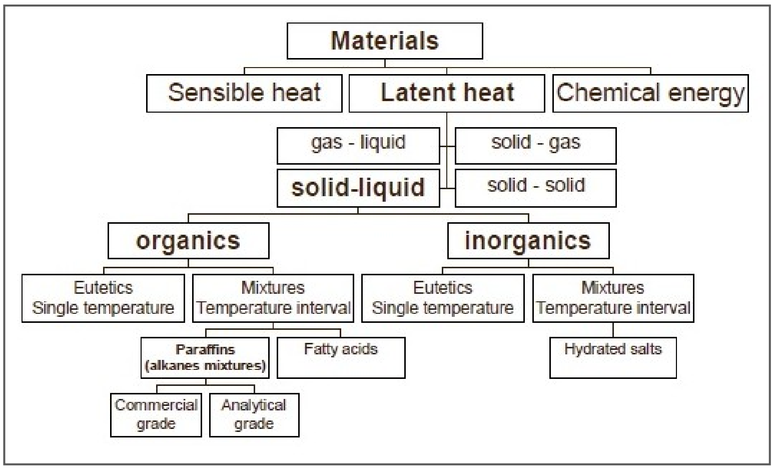

Fig. 6 Classification of phase change materials.

Considering the PCM based on latent heat storage, it is possible to account three most important classes: organic, inorganic and eutectics compounds.

Organic materials, like paraffins, alkane mixtures, fatty acids and their derivatives, are mostly used for many applications in the field of energy conservation in building; while inorganic compounds (especially hydrate salts) cover a wider temperature range than organic materials and have a higher enthalpy per volume due to their higher density. The inorganic PCM are mostly considered for solar energy storage in tanks.

At present, most of the commercial phase change materials suitable for building construction are paraffins and hydrate salts. The inorganic PCMs are much cheaper than the organic ones, but these last ones could cause some leakage problems in the solid-liquid phase change. So they are less suitable to be used in building envelope.

PCMs eutectics are commonly organic-organic, organic-inorganic and inorganic-inorganic compounds.

4.2.1. Organic substances.

The most known and used organic materials for energy storage application are the paraffins and the non-paraffins.

The common paraffins (of type C_nH_{2n+2}) belong to the family of saturated hydrocarbons; they consist of mainly straight chain hydrocarbons which have a melting temperature between 23 - 67 °C (Abhat 1983) and, during the crystallization of the (CH_3) chain, they release a large amount of latent heat. Paraffins between C5 and C15 are liquids and the rest are waxy solids. These last ones are the most-used commercial organic PCMs.

Commercial-grade paraffin wax is obtained from petroleum distillation and is not a pure substance, but a combination of different hydrocarbons. In general, the longer the average length of the hydrocarbon chain, the higher the melting temperature and heat of fusion.

The paraffin waxes represent very suitable materials for thermal energy storage applications especially in the building sector thanks to their several properties: a quite wide melting temperature range, the safety, the reliability, the noncorrosivity, the chemical inertia, the stability below a certain temperature, etc... Besides they show little volume changes on melting and have low vapor pressure in the melt form. For these properties, the system that uses paraffins usually has very long freeze–melt cycle.

However, these materials present some drawbacks, such as the low thermal conductivity and a moderately flammability, but all these undesirable effects can be partly eliminated by slightly modifying the wax and the storage unit.

The non-paraffin materials (such as fatty acids, alcohols and glycols) are more numerous than paraffin materials. In spite of these last ones, which have similar properties, each non-paraffin material have its own properties. Some properties of these materials are as follows: high heat of fusion, inflammability, low thermal conductivity, low flash points, varying level of toxicity and instability at high temperatures.

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Paraffin C_{14}	4.5 [1]	165 [1]	n.a.	n.a.
Paraffin C_{15}–C_{16}	8 [1]	153 [1]	n.a.	n.a.
Polyglycol E400	8 [4,11]	99.6 [4,11]	0.187 (liquid, 38.6 °C) [4,11] 0.185 (liquid, 69.9 °C) [11]	1125 (liquid, 25 °C) [4,11] 1228 (solid, 3 °C) [4,11]
Dimethyl-sulfoxide (DMS)	16.5 [28]	85.7 [28]	n.a.	1009 (solid and liquid) [28]
Paraffin C_{16} –C_{18}	20–22 [29]	152 [29]	n.a.	n.a.
Polyglycol E600	22 [4,11]	127.2 [4,11]	0.189 (liquid, 38.6 °C) [4,11] 0.187 (liquid, 67.0 °C) [11]	1126 (liquid, 25 °C) [4,11] 1232 (solid, 4 °C) [4,11]
Paraffin C_{13}–C_{24}	22–24 [1]	189 [1]	0.21 (solid) [1]	0.760 (liquid, 70 °C) [1] 0.900 (solid, 20 °C) [1]
1-Dodecanol	26 [9]	200 [9]	n.a.	n.a.
Paraffin C_{18}	28 [1] 27.5 [30]	244 [1] 243.5 [30]	0.148 (liquid, 40 °C) [30] 0.15 (solid) [1] 0.358 (solid, 25 °C) [30]	0.774 (liquid, 70 °C) [1] 0.814 (solid, 20 °C) [1]
1-Tetradecanol	38 [9]	205 [9]		
Paraffin C_{16}–C_{28}	42–44 [1]	189 [1]	0.21 (solid) [1]	0.765 (liquid, 70 °C) [1] 0.910 (solid, 20 °C) [1]
Paraffin C_{20}–C_{33}	48–50 [1]	189 [1]	0.21 (solid) [1]	0.769 (liquid, 70 °C) [1] 0.912 (solid, 20 °C) [1]
Paraffin C_{22}–C_{45}	58–60 [1]	189 [1]	0.21 (solid) [1]	0.795 (liquid, 70 °C) [1] 0.920 (solid, 20 °C) [1]
Parffin wax	64 [4,11]	173.6 [4,11] 266 [6]	0.167 (liquid, 63.5 °C) [4,11] 0.346 (solid, 33.6 °C) [4,11] 0.339 (solid, 45.7 °C) [11]	790 (liquid, 65 °C) [4,11] 916 (solid, 24 °C) [4,11]
Polyglycol E6000	66 [4,11]	190.0 [4,11]	n.a.	1085 (liquid, 70 °C) [4,11] 1212 (solid, 25 °C) [4,11]
Paraffin C_{21}–C_{50}	66–68 [1]	189 [1]	0.21 (solid) [1]	0.830 (liquid, 70 °C) [1] 0.930 (solid, 20 °C) [1]
Biphenyl	71 [4,11]	119.2 [4,11]	n.a.	991 (liquid, 73 °C) [4,11] 1166 (solid, 24 °C) [11]
Propionamide	79 [11]	168.2 [11]	n.a.	n.a.
Naphthalene	80 [4,11]	147.7 [4,11]	0.132 (liquid, 83.8 °C) [4,11] 0.341 (solid, 49.9 °C) [4,11] 0.310 (solid, 66.6 °C) [11]	976 (liquid, 84 °C) [4,11] 1145 (solid, 20 °C) [4,11]
Erythritol	118.0 [31]	339.8 [31]	0.326 (liquid, 140 °C) [31] 0.733 (solid, 20 °C) [31]	1300 (liquid, 140 °C) [31] 1480 (solid, 20 °C) [31]
HDPE	100–150 [32]	200 [32]	n.a.	n.a.
Trans-1,4-polybutadiene (TPB)	145 [33]	144 [33]	n.a.	n.a.

n.a.: not available.

Tab. 2 Organic substances with potential use as PCM.

The larger group of non-paraffin compounds is represented by the fatty-acids which have the following chemical formula: $CH_3(CH_2)_{2n}COOH$. The fatty acids realize sharper phase change transformations than paraffin materials but, in spite of them, their cost is much higher; in fact they are 2–3 times more expensive than the technical grade paraffin's.
The table 2 shows some organic materials and their properties.

4.2.2. Inorganic substances.

The two most important sub-groups of inorganic materials are salt hydrates and metallics. Regarding the second group, although these materials have a high heat of fusion per unit volume and a high thermal conductivity, they are not very used and suitable as PCM technology because of weight penalties and a series of unusual engineering problems.
The first category, salt hydrates, could be considered as alloys of inorganic salts and water forming a typical crystalline solid. The solid–liquid transformation of salt hydrates is actually a dehydration process although this process happens with a thermodynamic melting or freezing action. During the melting phase the hydrate crystals breakup into anhydrous salt and water or into a salt hydrate with fewer moles of water. However this phase could cause a significant problem because the released water of crystallization is not sufficient to dissolve all the solid phase and so an incongruent melting occurs. It signifies that the lower hydrate or anhydrous salt rests on the bottom of the container with an evident separation between the solid and liquid material; so a recombination with water is unavailable. This means that the melting–freezing of the salt hydrate goes on decreasing with each charge–discharge cycle until it becomes irreversible.
However, thanks to their high storage density with respect to mass, the salt hydrates represent the most studied group of PCMs above of all for their use in latent heat thermal energy storage systems. Contrariwise their application for the energy storage in the building sector is less suitable due to their instability in the phase change process.
The most important properties of salt hydrates are: high latent heat of fusion per unit volume, relatively high thermal conductivity (almost double of the paraffin's),

small volume changes on melting, they are not very corrosive, compatible with plastics and only slightly toxic. Moreover many salt hydrates are sufficiently inexpensive for the use in storage.

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
H_2O	0 [1,5]	333 [1] 334 [5]	0.612 (liquid, 20 °C) [1] 0.61 (30 °C) [5]	998 (liquid, 20 °C) [1] 996 (30 °C) [5] 917 (solid, 0 °C) [1]
$Mn(NO_3)_2 \cdot 6H_2O$	25.8 [18]	125.9 [10]	n.a.	1738 (liquid, 20 °C) [10] 1728 (liquid, 40 °C) [10] 1795 (solid, 5 °C) [10]
$CaCl_2 \cdot 6H_2O$	29 [4,11]	190.8 [4,11]	0.540 (liquid, 38.7 °C) [4,11]	1562 (liquid, 32 °C) [4,11]
	29.2 [7]	171 [1,9]	0.561 (liquid, 61.2 °C) [11]	1496 (liquid) [1]
	29.6 [6] 29.7 [1,9] 30 [8] 29–39 [12]	174.4 [12] 192 [6]	1.088 (solid, 23 °C) [4,11]	1802 (solid, 24 °C) [4,11] 1710 (solid, 25 °C) [1] 1634 [12] 1620 [6]
$LiNO_3 \cdot 3H_2O$	30 [6]	296 [6]	n.a.	n.a.
$Na_2SO_4 \cdot 10H_2O$	32.4 [1,7,9] 32 [13] 31–32 [12]	254 [1,9] 251.1 [12]	0.544 [1]	1485 (solid) [1] 1458 [12]
$Na_2CO_3 \cdot 10H_2O$	32–36 [12] 33 [6,7]	246.5 [12] 247 [6]	n.a.	1442 [12]
$CaBr_2 \cdot 6H_2O$	34 [4,7,11]	115.5 [4,11]	n.a.	1956 (liquid, 35 °C) [4,11] 2194 (solid, 24 °C) [4,11]

Tab. 3 Some inorganic PCMs.

4.2.3. Eutectics susbstances.

Eutectic systems are mixtures of chemical compounds or elements that have a single chemical composition that solidifies at a lower temperature than any other composition.

Any components of the eutectic compound melts and freezes congruently, forming a mixture of the component crystals during crystallization (Lane, 1989).

On the phase diagram of an eutectic system, at a certain value of pressure, the intersection of the eutectic temperature and the eutectic composition corresponds to an equilibrium point (*Fig. 7)*. Eutectics nearly always melt and freeze without segregation because they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate.

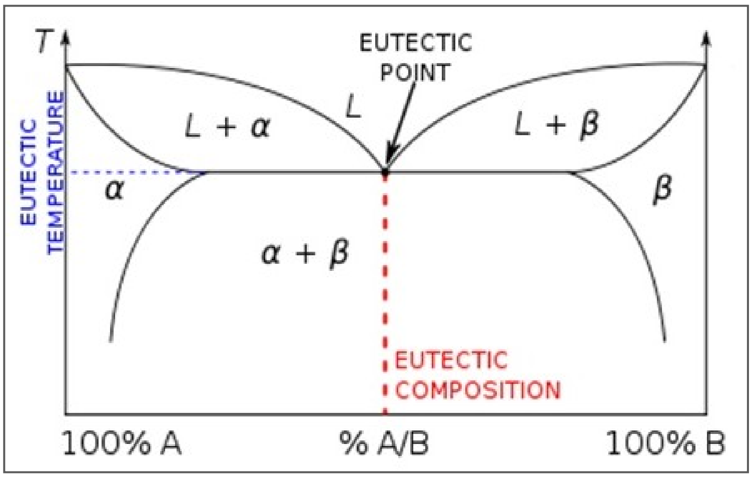

Fig. 7 A phase diagram of a fictitious chemical mixture of two components denoted by α and β .

Eutectic materials are metallic alloys especially those ones composed of tin (Sn), zinc (Zn), lead (Pb), copper (Cu), sodium (Na), potassium (K),....

In the following table some eutectic PCMs are reported.

Name	Composition (wt %)	Melting Point (°C)	Latent Heat (kJ/ kg)
Na_2SO_4+NaCl+KCl+H_2O	31+13+16+40	4	234
Na_2SO_4+NaCl+NH_4Cl+H_2O	32+14+12+42	11	n.a.
$C_5H_5C_6H_5$+ $(C_6H_5)_2O$	26.5+73.5	12	97.9
Na_2SO_4+NaCl+H_2O	37+17+46	18	n.a.
Na_2S_4+$MgSO_4$+H_2O	25+21+54	24	n.a.
$C_{14}H_{28}O_2$+$C_{10}H_{20}O_2$	34+66	24	147.7
$Ca(NO)_3$.4H_2O+$Mg(NO)_3$.6H_2O	47+53	30	136
NH_2CONH_2+NH_4 NO_3	–	46	95
$Mg(NO_3)_2$.6H_2O+NH_4 NO_3	61.5+38.4	52	125.5
$Mg(NO_3)_2$.6H_2O+$MgCl_2$.6H_2O	58.7+41.3	59	132.2
$Mg(NO_3)_2$.6H_2O+$Al(NO_3)_2$.9H_2O	53+47	61	148
$Mg(NO_3)_2$.6H_2O+$MgBr_2$.6H_2O	59+41	66	168
Napthalene + Benzoic Acid	67.1+32.9	67	123.4
$AlCl_3$+NaCl+$ZrCl_2$	79+17+4	68	234
$AlCl_3$+NaCl+KCl	66+20+14	70	209
NH_2CONH_2+NH_4Br	66.6+33.4	76	151
$LiNO_3$ + NH_4 NO_3+$NaNO_3$	25+65+10	80.5	113
$AlCl_3$+NaCl+KCl	60+26+14	93	213
$AlCl_3$+NaCl	66+34	93	201
$NaNO_2$+$NaNO_3$+KNO_3	40+7+53	142	n.a.

n.a.: not available.

Tab. 4 List of some eutectic compounds.

4.3. Commercial Products

Phase change materials are present in the market as commercial PCM (pure), composite or encapsulated materials. Most commercial PCMs are based on materials from the material classes of the salt hydrates, paraffins, and eutectic water-salt solutions. They are however not identical with these materials. In the case of salt hydrates often the composition is changed because a nucleator is added, the material is gelled or thickened or the PCM is a mixture of different base materials. With paraffins, commercial grade paraffins usually contain a mixture of different alcanes because pure alcanes are expensive. Commercial PCMs cover the temperature range from – 40 °C to +120 °C. Even though many materials have been investigated for higher temperatures, none of them is available commercially because there has been no market yet.

Many companies have exploited the potential of the PCMs according to the various forms that they can assume; for example some companies use the PCM in a powder form then encapsulated to realize PCM elements (bags, balls, capsules,....) or some companies integrate the PCM in their products (tanks, panels for partitions, ceiling, floor,....) in order to produce a PCM system. A good example of specific PCM products are the ice packs which are used to keep food cold.

Today more than 50 PCMs are commercially available and the number is growing from year to year. So, it is not possible to list all available commercial products because the companies produce several PCMs that are often similar one from each other. In the follows we reported some typical PCMs mostly used and known.

Fig. 8 Some typologies of commercial PCMs: compound material in powder form (a,b,f), bags (c), balls (d), panels (e), capsule strips (g).

For other detailed information we refer to the respective websites of the companies listed in the reference section at the end of this work.

Some of the most important and known companies which are engaged in the development and trade of PCMs are: Climator, Cristopia, EPS Ltd., Mitsubishi Chemical Corporation, Rubitherm, DuPont de Nemours and BASF. Some commercial PCMs available in the market are showed in the *Tab.* which includes their thermal and physical properties, as reported in the datasheets provided by the companies (melting point, heat of fusion and density), and the name of the company that produces them.

PCM name	Type of product	Melting temperature (°C)	Heat of fusion (kJ/kg)	Density (kg/L)	Source
RT20	Paraffin	22	172	0.88	Rubitherm GmbH [75]
ClimSel C 24	n.a.	24	108	1.48	Climator [76]
RT26	Paraffin	25	131	0.88	Rubitherm GmbH [75]
STL27	Salt hydrate	27	213	1.09	Mitsubishi Chemical [77]
AC27	Salt hydrate	27	207	1.47	Cristopia [78]
RT27	Paraffin	28	179	0.87	Rubitherm GmbH [75]
TH29	Salt hydrate	29	188	n.a.	TEAP [79]
STL47	Salt hydrate	47	221	1.34	Mitsubishi Chemical [77]
ClimSel C 48	n.a.	48	227	1.36	Climator [76]
STL52	Salt hydrate	52	201	1,3	Mitsubishi Chemical [77]
RT54	Paraffin	55	179	0,90	Rubitherm GmbH [75]
STL55	Salt hydrate	55	242	1,29	Mitsubishi Chemical [77]
TH58	n.a.	58	226	n.a.	TEAP [79]
ClimSel C 58	n.a.	58	259	1,46	Climator [76]
RT65	Paraffin	64	173	0,91	Rubitherm GmbH [75]
ClimSel C 70	n.a.	70	194	1,7	Climator [76]

n.a.: not available or not known at the time of writing

Tab. 5 Commercial PCMs available in the market.

4.4. Application of PCMs in a building system.

Thanks to the properties previous exposed, the phase change materials can be used for several applications; in particular many surveys have demonstrated that they can be very suitable for building applications in order to reduce the energy consumption and improve the indoor thermal comfort for occupants due to the lowering of the temperature variations.

The use of PCMs in buildings provides different functions for different applications: they can be used for free cooling or heating of buildings, for shifting the building peak load, for using the solar energy, for recovering the waste heat, etc...

In general we can recognize two different ways to use the PCMs inside a building:

- combination of PCMs with heating or cooling equipment (*active system*)
- integration of PCMs into the building envelope, such as walls, ceilings, floors,.... (*passive system*).

An active system means that the stored heat or cold is in a container thermally separated from the building and the charging and discharging process is achieved with the help of mechanical or electrical equipment.

The second system (passive) means that the stored heat or cold is automatically released when indoor or outdoor temperature rises or falls beyond the melting point; in this case the PCMs are integrated in the structure of buildings and the melting and freezing of PCMs is realized without using any mechanical equipment.

Anyway, many factors affect the effectiveness of PCM system in a building: the type and amount of PCMs used, the PCM's encapsulation method, the location of PCMs in building structures, the building design and orientation, the equipment design and selection, the climate condition, the occupancy schedule, the system control and operational algorithms, etc...

Now we reported an overview of the most used solutions for PCM building application, but in the second part of this study we only considered the application according a passive method.

4.4.1. Active PCM systems.

The application of PCM according an active system has the goal of enhancing the heat transfer of a PCM storage. This system consists of a PCM storage unit integrated into other mechanical or electric systems, such as solar heat pump systems, heat recovery systems, floor heating systems, etc... in order to make a more complex solution that can increase the indoor thermal comfort with maximizing the performances of PCMs.

Many studies and experiments have been carried out on the various typologies of PCM application as active building systems, such as:

- *electrical under-floor heating system with PCM storage* that charges heat during the nighttime, when the electricity cost is cheaper, and discharges thermal energy during daytime (see Farid and Chen, Lin);
- a *roof integrated with solar heating system with PCM storage* which utilizes the existing roof as a solar collector/absorber incorporating PCMs (see Bruno);
- *combined solar heat pump with energy storage* (see Kaygusuz and Ayan);
- a *solar space heating system incorporating PCMs* that consistis of an array of solar flat plate collectors which deliver heated water to a storage tank, and a number of PCM filled panels melting the PCM (see Kenneth);
- *phase change material combined with a night ventilation system*, such as an array of PCM bags applied in the ceiling (see Kang) or PCMs embedded in a wall surface in combination with a night ventilation plant (see Zhong);
- a *heat recovery system using PCMs*, which recovers rejected heat of air conditioning systems in order to produce low temperature hot water for washing and bathing (see Gu).

4.4.2. Passive PCM systems.

A passive system consists of the integration of PCMs into the components of the building envelope (i.e. walls, roofs and floors) as part of building materials or structures to increase the building thermal mass. This system works according this procedure: during the daytime the PCM absorbs melting heat from indoor air until it reaches its melting point in temperature; during the night the PCM releases the stored heat at the indoor space through the building structure until it decreases to the solidification temperature. A passive system could be very effective on indoor thermal comfort because it reduces the indoor overheating during the daytime in hot summer, provides heat for space heating during night in cold winter, increases the thermal capacity of the light building envelopes and also reduces the room temperature fluctuation. This implies none or less demands of energy and a lower energy consumption.

As we just said, a PCM passive system can be made by embedding PCMs into the building materials (such as bricks, concrete, plaster,...) or by integrating them into the building components (such as walls, ceilings, floors, windows,...).

Some examples of PCM applications as passive building systems are the following:

- *trombe wall integrated with PCM*, which consists of a wall filled with PCMs standing on the south side of a house and facing a double-layer of glass. The incoming solar radiation is collected in the space between the wall and the glazing and it produces the melting of PCMs; at night the heat is released to the indoor environment in order to warm the house.
- *wallboards incorporating PCMs* which consist of the encapsulation of PCMs (the effectiveness depends on the PCM's quantity) into a thin panel which allows an easy installation in any typology of building, particularly in the case of building retrofit. This system can also be installed on the floor or ceiling .
- *PCM incorporated into building materials (bricks, concrete, gypsum,...).* This method represents a suitable way to use PCMs thanks to lower costs, easier fabrication and widespread application. This solution achieves interesting results but the better performance can be obtained by incorporating PCMs into porous materials, such as plasterboard or gypsum.

These are some of the several applications of PCMs as active or passive storage systems; many other solutions have already been studied and experimented, but many surveys about the various possible PCM-technologies are in progress.

In the second part of the present work we only considered the application of a passive energy storage system consisting of the application of the PCM panels in the interior partitions of a room.

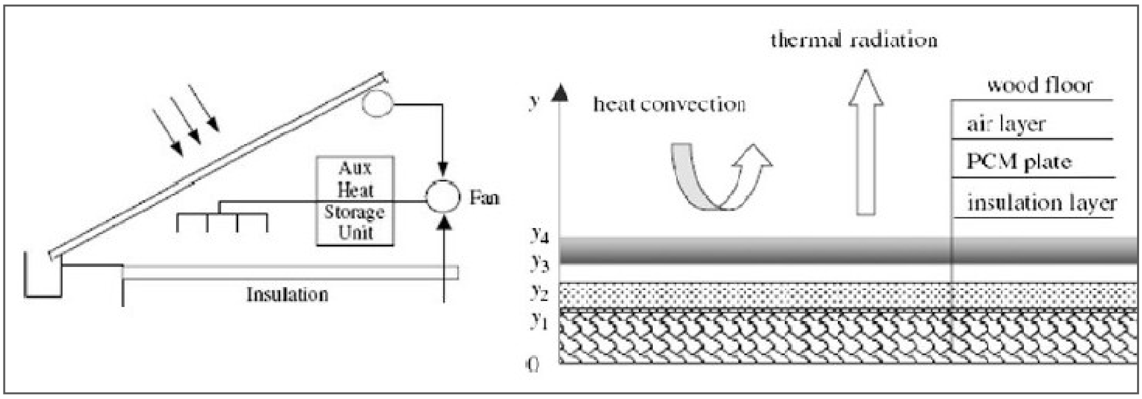

Fig. 9 Scheme of a system incorporated PCM: roof integrated with solar heating devices (left) and electrical under floor heating system (right).

PART II

5. The simulation tools.

In order to achieve the purposes of the present study, we used the building simulation software *EnergyPlus*. This program is developed by the United States Department of Energy and allows the building energy analysis and its thermal load simulation (heating and cooling loads) taking into account the building's physical description (location, materials, construction, etc...) and its mechanical systems.
This software is based on the previous programs BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 (Department Of Energy), which were two of the most important simulation programs developed in the 1970's in order to carry out a load and energy simulation of a building. The main difference between these two programs is the load calculation method: DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach.
Each program comprises hundreds of subroutines working together to simulate heat and mass flows throughout a building. In some cases, subroutines in DOE-2 were more accurate. In other cases, subroutines in BLAST were more accurate.
In 1996 the Department of Energy of United States developed a new simulation tool named EnergyPlus, which is based on the merging of the two above mentioned programs. So, EnergyPlus results from the combination of many features of BLAST and DOE-2 but with more and new capabilities.

5.1. Structure of EnergyPlus

EnergyPlus is a simulation program based on a modularity system; it runs according sub-hourly calculations and considers, at the same time, the load and system dynamic performance into the whole building energy balance.
The program consists of three modules: a simulation manager that incorporates the heat and mass balance simulation module and the building system simulation modules (the scheme of the program is shown in *Fig. 10*).
The first component (simulation manager) controls the entire simulation process, such as the interactions between all simulation loops (environment, day, hour and

sub-hour) and simulation period (whether day, month, season, year or several years). Actions among individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, record keep, or report.

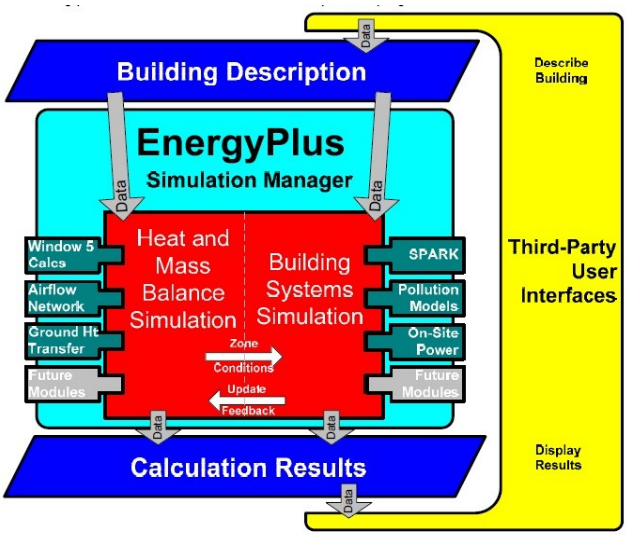

Fig. 10 EnergyPlus structure.

The second module, heat and mass balance simulation, consists of two modules: a surface heat balance module and an air heat balance module. The surface heat balance module simulates inside and outside surface heat balance, interactions between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapor) effects. The air heat balance module acts as an interface between the surface heat balance and the building systems simulation; it takes into account the thermal mass of zone air and evaluates the direct convective heat gains in the building loads simulation.

This model considers these assumptions:

- the air mass balance is calculated considering all mass streams (ventilation air, exhaust air and infiltration);

- the air in each thermal zone is considered as well mixed element with uniform temperature throughout;

- room surfaces (walls, windows, ceilings and floors) have uniform surface temperatures, uniform long and short wave irradiation, diffuse radiating surfaces and internal heat conduction.

The building systems simulation module controls the communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans and other equipment/components.

5.2. EnergyPlus calculation methodologies.

The heat balance on the zone air is expressed by the "Zone Air Heat Balance Algorithm" object; it allows to choose the type of solution algorithm that will be used to calculate zone air temperatures and humidity ratios.
The basic equation for the zone air and heat balance is the following:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \,(T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{\inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \qquad (7)$$

where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads.

$\sum_{i=1}^{N_{surfaces}} h_i A_i \,(T_{si} - T_z)$ = convective heat transfer from the zone surfaces.

$\dot{m}_{\inf} C_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air.

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing.

$\dot{Q}_{sys} = \dot{m}_{sys} C_p (T_{\sup} - T_z)$ = air system output.

$C_z \frac{dT_z}{dt}$ = energy stored in the zone air.

The filling of the "Zone Air Heat Balance Algorithm" as EnergyPlus input is optional. To the purpose of this work, we have to take special care of the thermal behavior of the construction materials when they are subjected to a heat flow transfer; so, first we considered very important to understand how EnergyPlus works during the "surface heat balance" processes in order to use the most suitable heat transfer algorithm according test conditions. To this aim we used the "Heat Balance Algorithm" to carry out the simulations.

The "Heat Balance Algorithm" object represents the heat and moisture transfer algorithm that is used across the building construction calculations.

The types of calculation are the following:

- *Conduction transfer function* (CTF);
- *Effective Moisture Penetration Depth with Conduction Transfer Function* (EMPD);
- *Conduction Finite Difference* (CFD);
- *Conduction Finite Difference Simplified* (CFDS);
- *Combined Heat And Moisture Finite Element* (HAMT).

In this work we have utilized two kinds of heat transfer equation: the Conduction Transfer Function (CTF) and the Conduction Finite Difference (CFD).

5.2.1. Conduction Transfer Function.

The first method represents a traditional way of simulating the heat transfer, such as the time series coefficients that describe the transient conduction process with an algebraic equation.

The equations that represent the conduction heat transfer are the following:

- for the inside flux

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \quad (8)$$

- for the outside flux

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \quad (9)$$

where:

q''_{ko} = Conduction heat flux on outside face

q''_{ki} = Conduction heat flux on inside face

X_j = Outside CTF coefficient, j= 0,1,...nz.

Y_j = Cross CTF coefficient, j= 0,1,...nz.

Z_j = Inside CTF coefficient, j= 0,1,...nz.

Φ_j = Flux CTF coefficient, j = 1,2,...nq.

T_i = Inside face temperature

T_o = Outside face temperature

The first term in the equation (8) is separated from the rest in order to simplify solving for the current temperature in the solution scheme. The subscript following the comma indicates the time period for the quantity in terms of the time step δ.

EnergyPlus uses a "state space method" to calculate the CTF coefficients. The use of the state-space method in solving the equations (8) and (9) was introduced by Seem (1987). The state-space expression is formulated by using either finite difference or finite-element methods to discretize the CTF equations. The expression relates the interior and exterior boundary temperatures to the inside and outside surface heat fluxes at each node of a multi-layered slab as shown in the following system of linear matrix equations:

$$\frac{d[x]}{dt} = [A][x] + [B][u] \tag{10}$$

$$[y] = [C][x] + [D][u] \tag{11}$$

where:

[x] = vector of state variables (nodal temperatures)

[u] = vector of inputs (interior/exterior temperatures)

[y] = vector of outputs (heat fluxes at both surfaces)

t = time

A,B,C,D = coefficients of matrices

Another form of the previous matrix equations is the following:

$$\frac{d\begin{bmatrix} T_1 \\ \cdots \\ \cdots \\ T_n \end{bmatrix}}{dt} = [A]\begin{bmatrix} T_1 \\ \cdots \\ \cdots \\ T_n \end{bmatrix} + [B]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} q''_i \\ q''_o \end{bmatrix} = [C]\begin{bmatrix} T_1 \\ \cdots \\ \cdots \\ T_n \end{bmatrix} + [D]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \tag{13}$$

These relations can be used to solve the transient heat conduction equation by enforcing a finite difference grid over the various layers in the building element being analyzed. In this case, the state variables are the nodal temperatures, the environmental temperatures (interior and exterior) are the inputs, and the resulting heat fluxes at both surfaces are the outputs.

For instance, in the case of a simple one layer structure (*Fig. 11*), it is possible to consider two interior nodes and the finite different equations are the following:

$$\begin{cases} C\dfrac{(dT_1)}{dT} = hA(T_0 - T_1) + \dfrac{T_2 - T_1}{R} \\[2ex] C\dfrac{(dT_2)}{dT} = hA(T_i - T_2) + \dfrac{T_1 - T_2}{R} \\[2ex] q''_i = h_i(T_i - T_2) \\[2ex] q''_o = h_o(T_1 - T_o) \end{cases} \tag{14}$$

where:

R = thermal resistance of the mass layer [W·m^{-2}·K^{-1}]

C = thermal heat capacity of the material [J·K^{-1}]

A = area of the surface exposed to the environmental temperatures [m^2]

h = film coefficient [W·m^{-2}·K^{-1}]

T_1,T_2= surface temperatures

In the matrix form the previous relations are given by:

$$
\begin{cases}
\begin{bmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC}-\frac{hA}{C} & \frac{1}{RC} \\ \frac{1}{RC} & -\frac{1}{RC}-\frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + \begin{bmatrix} \frac{hA}{C} & 0 \\ 0 & \frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_o \\ T_i \end{bmatrix} \\
\begin{bmatrix} q''_o \\ q''_i \end{bmatrix} = \begin{bmatrix} 0 & -h \\ h & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + \begin{bmatrix} 0 & h \\ -h & 0 \end{bmatrix} \begin{bmatrix} T_o \\ T_i \end{bmatrix}
\end{cases}
\tag{15}
$$

The heat fluxes are represented by the conductive flux through the material and convective fluxes (at the inside and outside).

So, in the resulting finite difference equations there are two state variables (T_1, T_2), two inputs temperatures (T_i, T_o) and two heat fluxes as outputs (q_i", q_o"). The CTF coefficient are obtained solving the A,B,C,D matrices.

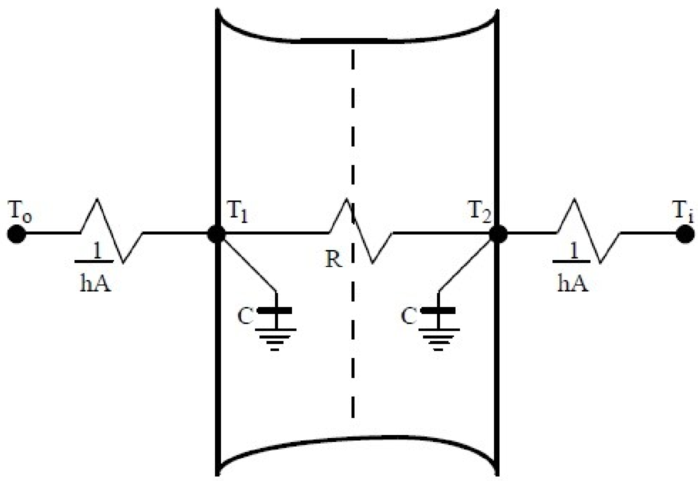

Fig. 11 Example of a simple layer structure

The state space method doesn't allow to consider the state space variables (nodal temperatures) but to calculate a matrix equation where the outputs (heat fluxes) can be calculated only as a function of the inputs (environmental temperatures).

So CTF method used in Energy Plus determines the conduction heat transfer with a simple and linear equation with constant coefficients. This is the advantage of this calculation form because the coefficients could be determined once for each construction type; furthermore this method allows to calculate heat flux without knowing temperature and fluxes within the surfaces.

Thus this feature could represents an important constraint of the calculation's method when we want to perform an accurate evaluation of the heat transfer; if the coefficients are constant it is not possible to take into account temperature dependency for thermal properties of the materials. Besides, by decreasing the time step, the conduction transfer functions become progressively more unstable causing an increase in the number of terms in the series and a divergence of the entire simulation.

5.2.2. Conduction Finite Difference.

In the cases of more complex and advanced buildings or materials (such as the Phase Change Materials) the Conduction Transfer Function are not suitable because they are based on constant properties and fixed value of some parameters. The Conduction Finite Difference is a calculation method based on an implicit finite difference procedure taking into account the layer by layer formulation of the CTF equations and also the true thermal properties of each layer. This algorithm allows to carry out a high performance simulation such as that requested for using phase change materials.

CFD procedure is based on two coupled equations: an implicit finite difference formulation related to a specific node of the building element and an enthalpy-temperature function.

$$\frac{\rho C_p \Delta x (T_{i,new} - T_{i,old})}{\Delta t} = \frac{k(T_{i-1,new} - T_{i,new})}{\Delta x} + \frac{k(T_{i+1,new} - T_{i,new})}{\Delta x} \quad (16)$$

$$h_i = f_{ht}(T_i) \quad (17)$$

where:

T = node temperature

Δt = calculation time step

Δx = finite difference layer thickness (always less than construction layer thickness)

Cp = specific heat of the material

ρ = density of the material

f_{ht} = enthalpy-temperature function

subscripts:

i = node being modeled

i+1 = adjacent node to interior of construction

i-1 = adjacent node to exterior of construction

new = new temperature at end of time step

old = temperature at end of previous time step

In a building element it possible to determine four types of nodes: external surface node (a), internal surface node (c), internal nodes (d) and nodes occurring at the material interfaces (b) (*Fig. 12*).

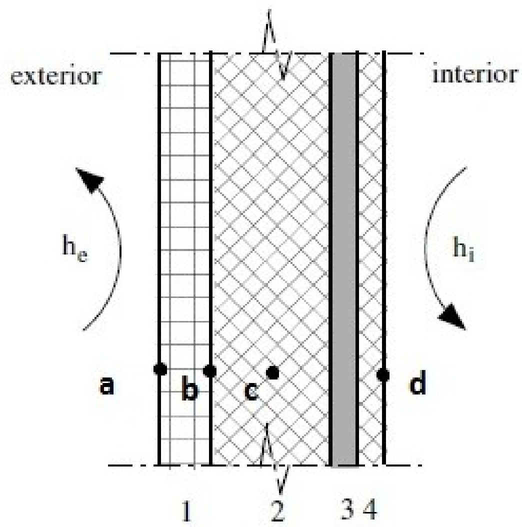

Fig. 12 Nodes on a building element.

The equations (16) and (17) can be applied for all nodes in the construction.
Equation used for each node is the same; temperatures of each node are updated according an iteration scheme (Gauss-Seidel) and consequently node enthalpies get updated in each time step. Temperature and enthalpy variable allow to calculate Cp value.

$$C_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \tag{18}$$

When we use this algorithm, it is necessary to specify the correspondent properties (thermal conductivity, enthalpy and temperatures).

The behavior of the phase change materials or those one with a variable thermal conductivity, are described in the EnergyPlus schedule called "*Material Property: Phase Change*" in which the equation (17) that relates enthalpy and temperature is defined (a graph of this relation is represented in *Fig. 13*). The values of temperature and enthalpy are put in a two-column table so that the function covers the entire temperature range that will be seen by the material in the simulation. It is assumed as standard setting of the function a starting point at a low temperature and a final temperature at about 100 °C.

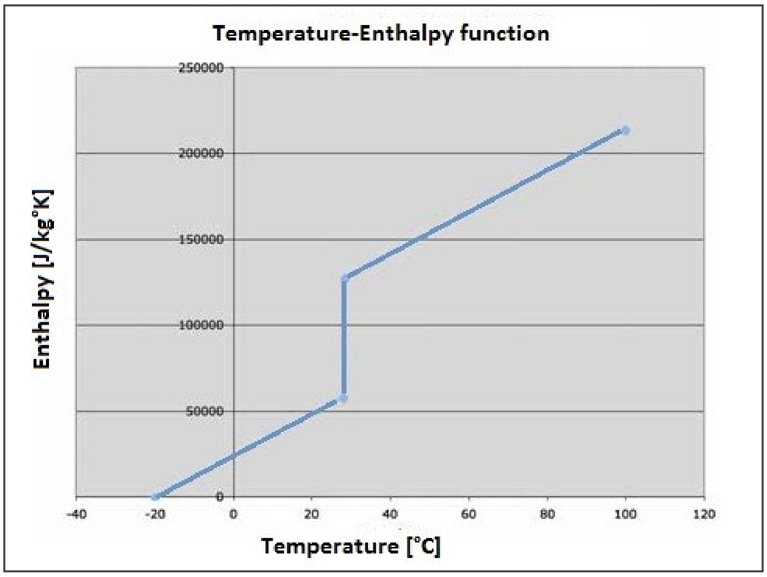

Fig. 13 Temperature-Enthalpy function.

The lowest slope of the relation represents the base material specific heat, the vertical section corresponds to the phase change during which the latent heat energy increases to a constant temperature (melting temperature) and the enthalpy contributions are always added to the enthalpy that would result from a constant specific heat base material.

The finite difference procedure allows to follow the layer-by-layer heat transfer considering the variability of material properties; in fact the temperature-enthalpy function for the material is followed exactly by updating the effective material specific heat during each iteration only considering enthalpy and node temperature values.

5.3. Setting an EnergyPlus simulation

In order to start an EnergyPlus simulation, the user create an IDF (*Input Data File*) entering with the IDD (*Input Data Dictionary*), or else a series of "objects" that allow to have a description of the building and its systems. So "object" is a pre-defined word denoting a component or element which helps to completely develop the building model, such as location, run period, surfaces, materials, occupancy, lighting, HVAC system, etc... This word is followed by a list of data values and terminates with a semicolon. These data describe performance characteristics and intended use for that object in the simulation. Unlike BLAST and DOE-2, the input file must explicitly provide all information-there are no default assumptions.

A simpler method to create an IDF for an EnergyPlus performance is the use of "OpenStudio Plug-in" toolbar of Google SketchUp, a 3-D drawing program with a quite friendly interface.

The user creates the input for EnergyPlus simply drawing the building model (all construction elements) in SketchUp. A support tool called OpenStudio Plug-in allows the data interchange between SketchUp and EnergyPlus, so that EnergyPlus can read the file as IDF and the user can complete it adding new elements for a more accurate description.

Thus the user's inputs as the simulation settings play a significant role in the efficacy of a simulation run. Main and indispensable settings for simulation in EnergyPlus include the length of the run period, the number of calculation time steps per hour, the choice of solution algorithms, the convergence resolutions, and output variables.

Another important input data is the weather. Rather than a binary file created by a separate weather processor, again we use a simple text-based format, similar to the input and output data files. The weather data format includes basic location information in the first eight lines: location (name, state/province/region, country), data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, typical and extreme periods, two lines for comments, and period covered by the data.

So, using the same building prototype, the user can develop different simulation cases with very different results simply changing few simulation settings such as the weather or calculation methodology or materials.

In this work we used the CTF calculation's method only for preliminary simulations in order to calculate the heat transfer through the building construction elements and evaluate the complete thermal behavior of the basic building model. Indeed, as the simulations with PCMs require a more precise and accurate calculation, the CTF method is not sufficient to describe completely the PCMs behavior. Thus the CFD procedure will be used for following simulations where the phase change materials are introduced.

6. The simulation phase.

6.1. Preliminary activities.

The aim of this second part of the work is to evaluate the effectiveness of a PCM panel using the simulation tool EnergyPlus.

Before going into detail it is necessary to specify that this activity is included in the context of the research project called "SIRTERI" ("Système Industrialisé de Rénovation du TERtiaire par l'Intérieur" - Industrialized System for Tertiary Sector's Renewal by Inside) still in progress with the goal of improving the thermal efficiency of the existing buildings by using passive systems as the PCM panels. SIRTERI is a French project which sees the collaboration of four partners, two industrial enterprises and two scientific centers (CSTB and CNRS-INES).

The aim of Sirteri is the refurbishment of existing building by applying the principle called "bôite dans la bôite" ("the box in the box"), that is the realization of an envelope inside the building structure.

The intervention provided by the project Sirteri regards a part of a real building of the "Cité Administrative Dode" which is a tertiary center located in Grenoble (Rhône-Alpes, France).

Particularly thanks to CNRS-INES it was possible to carry out an important part of this research activity at the laboratories of the INES center in Chambéry.

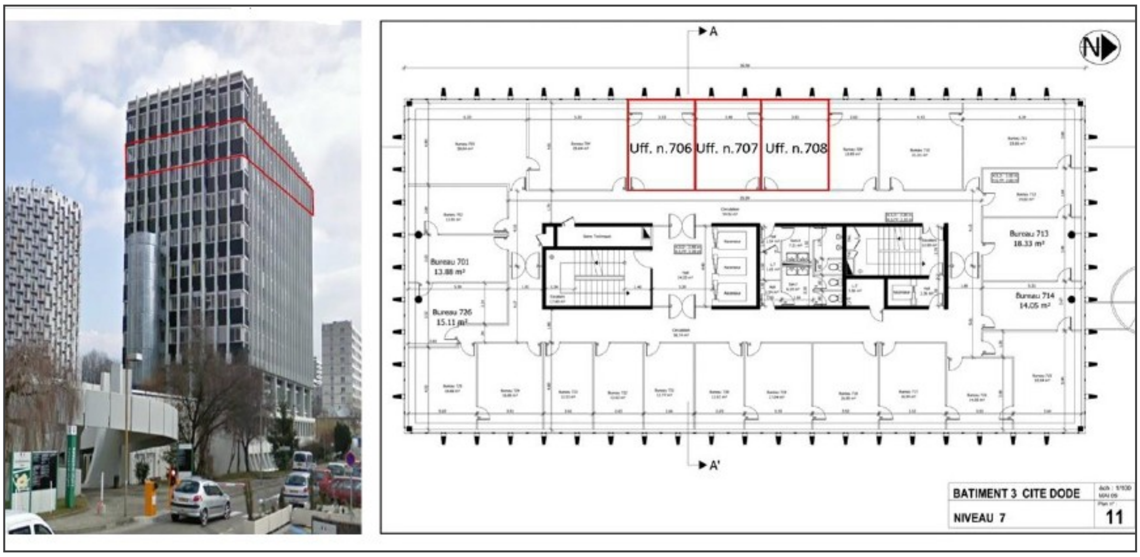

Fig. 14 The building considered for the project Sirteri and floor map of the rooms that are subjected to the PCM intervention.

Firstly this second part reports two preliminary and important phases:
- the experimental measurements.
- the characterization of the materials.

6.1.1. *The experimental set-up.*

The first phase is carried out at the CSTB (Scientific and Technical Centre for Building) located in the city of Grenoble where an experimental installation was realised in order to submit the sample of phase change material to experimentations on different scales. The PCM was firstly tested by calorimetric measures with the Differential Scanning Calorimetry method (DSC) and with other various systems of measurement. During this step, the PCMs were stressed by a solicitation rate as close as possible to the real one when the material is used in the building; so it allows to reduce the gap between experimental results and real conditions.

The phase change material chosen for the experimental tests is the Micronal PCM produced by the chemical company BASF. It has a melting point at 23° C, a powder form and specifically it contains in the core of the polymer microcapsule (5μm) a latent heat storage material made from a special wax mixture. This encapsulation system allows to maintain the size of the PCM building materials as the change in volume in the melting process occurs in each capsule and it not visible externally.

The sample tested is a 1 m^2 x 1 m^2 panel which has a thickness of 2 cm (*Fig. 15*).

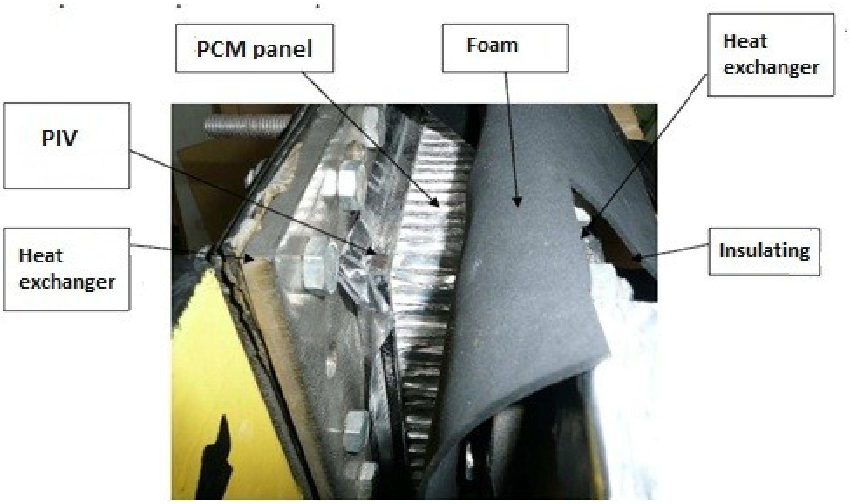

Fig. 15 Sample Panel tested by the CSTB.

It consists of an aluminium honeycomb matrix that contains the phase change materials. The encapsulation in the honeycomb matrix allows to increase the conduction process across all directions thanks to the high conductivity of the aluminum and also to improve the effectiveness of the panel which can fully perform its cycle. At last the panel is closed by two thin aluminum sheaths.

The test facility scheme is represented is similar to the one already described by Maha Ahmad et al. (*Fig. 16*). It consists of the sample of PCM panel (1) above described between two heat exchangers (2) and each heat exchangers are fed by two thermoregulated water flows (3,4) which can be programmed to produce a prescribed variation of the water temperature. In particular one of them is set to perform a sinusoidal variation to simulate daily temperature variations (in particular it imposes a temperature variation from 15° C to 35° C) while the other one is maintained at a constant temperature (T = 23° C) in order to reproduce the ambient air temperature. The rate of the temperature change is 0.03° C/min which approximates to the temperature variations inside a building.

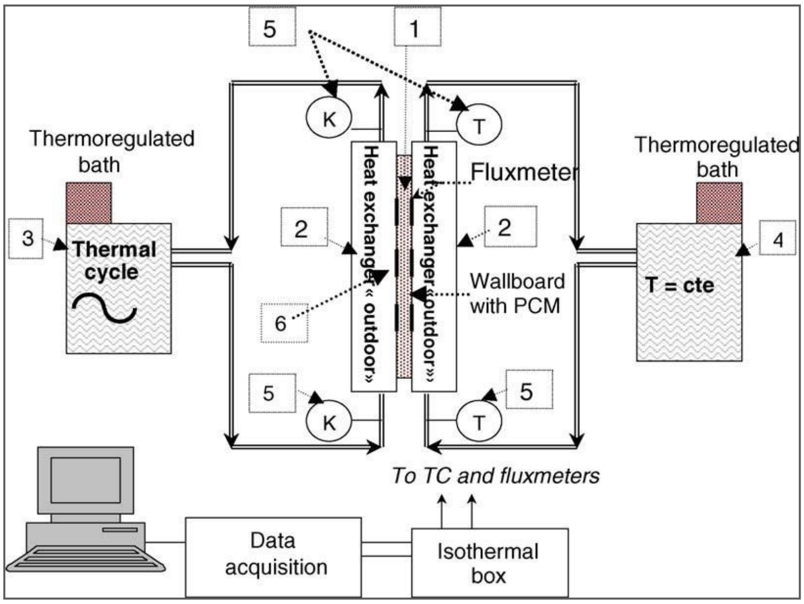

Fig. 16 Scheme of the installation for testing PCM

The water inlet and outlet temperatures and water flow rates were measured with thermocouples (5) and fluxmeters (6). Thermocouples and fluxmeters were calibrated with a specific device.

A thin conductive rubber foam was placed between the panel and the heat exchangers to ensure a good thermal contact without deteriorating the fluxmeters.

Between the PCM panel and the heat exchanger there is a Vacuum Insulation Panel (VIP) which has an insulation capacity several times higher than traditional insulating materials.

The experimental tests evaluated the following parameters: temperature variations of the water as the external temperature (T_e), the temperature variation on the external wallboard surface as external surface temperature (T_{se}) and on the internal wallboard surface as the internal surface temperature (T_{si}). The water temperature on the other side represents the internal temperature (T_i) and is kept constant. Heat flux (φ_e) is positive when heat penetrates the panel on the external side and (φ_i) is positive when heat leaves the panel on the internal side. Results of the measurements obtained by the experimental tests are reported in the *Fig. 17*.

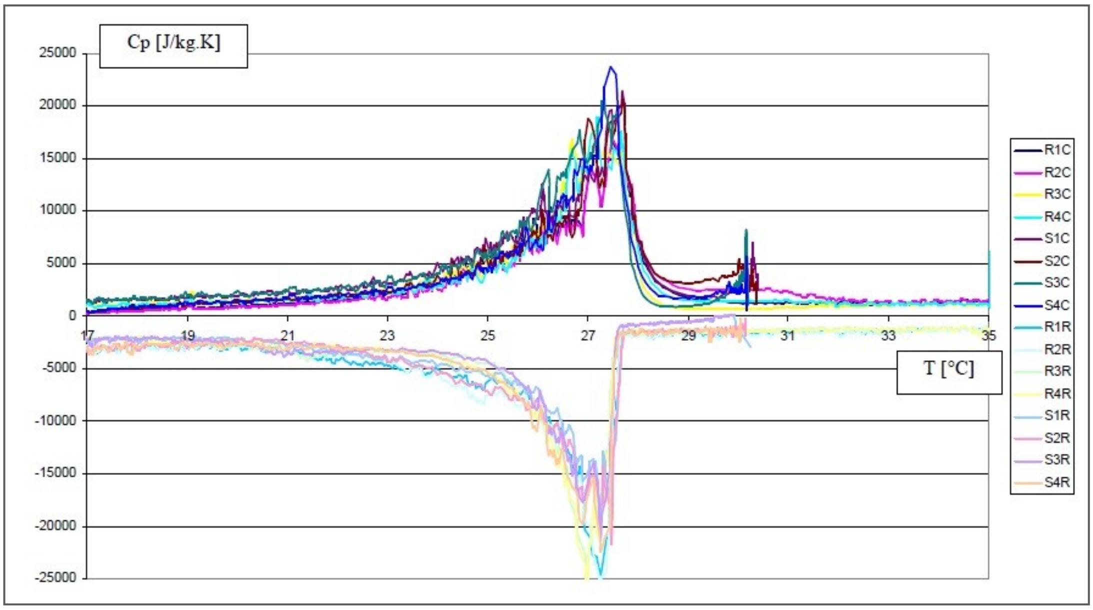

Fig. 17 Results of heat specific function after the experimental measures.

The graph indicates the thermal heat energy stored and released by the PCM sample. The curves represented in the upper part of the graph correspond to the heating phase while the curves of the cooling phase are plotted in the pastel colors. It is possible to notice that the curves haven't a symmetrical trend in the range T=27°÷28° C where the heat capacity achieves its maximum value; besides it is important to notice that, even if the melting phase of the PCM starts at a temperature T=23° C, the effective fusion of the material happens at a higher temperature. The two picks are related to the variation of the heat flux and represent the maximum quantity of energy stored and released.

6.1.2. The characterization of the Phase Change Material.

The second preliminary activity regards the characterization of the material which was possible considering results of the previous phase.

This step was carried out at the LOCIE (Optimization Laboratory of the Environment Conception and Engineering) of the University of Savoy. The above mentioned work used an inverse method based on a heat conduction transfer through wall in order to evaluate its thermal properties. The "inverse" procedure, developed by Chahwane et al. (2009), is a numerical model that enables to estimate the heat capacity of the material as an output, keeping the rest of the system parameters as known values. This method is simulated in the environment SIMSPARK that is a tool allowing to solve highly non linear problems.

In order to model the PCM system it was necessary to report the results obtained in the previous phase in analytical form. In fact "experimental" results are used as input to the inverse model simulation in order to find the heat capacity of the PCM panel at each time step. So, according to the inverse method, the equivalent heat capacity fits a Gaussian curve and is described by Eqn. (19) with a maximum heat capacity occurring at the peak melting temperature T_P.

$$C(t) = \begin{cases} C_0 + C_1 \cdot e^{-\left(\frac{T_P - T}{\Delta T}\right)^2} & \text{if} \quad T < T_P \\ C_\infty + C_2 \cdot e^{-\left(\frac{T_P - T}{\Delta T}\right)^2} & \text{if} \quad T \geq T_P \end{cases} \tag{19}$$

The coefficients C_0, C_1, C_2 and C_∞ are appropriate constants determined through experimental data.

The *Fig. 18* shows the curve describing the equivalent heat capacity according to the experimental tests conducted at CSTB; the corresponding mathematical formulation is reported in Eqn. (20):

$$C(t)=\begin{cases}1200+18800\cdot e^{-\left(\frac{T_P-T}{1.5}\right)^2} & if \quad T<T_P \\ 1300+18700\cdot e^{-4(T_P-T)^2} & if \quad T\geq T_P\end{cases} \tag{20}$$

Such an equation, obtained through best-fit techniques from the experimental data, does not actually correspond to the general model described in Eqn (19).

The melting process starts at around 22°C and ends at 28.5°C; the PCM sample has a peak melting temperature T_P = 27.6°C, after which the melting process is completed quite rapidly. The equivalent thermal conductivity of the panel corresponds to 2.8 W·m^{-1}·K^{-1}; the volumetric mass is 545 kg·m^{-3}.

These data represent the PCM properties that we used in the following phase.

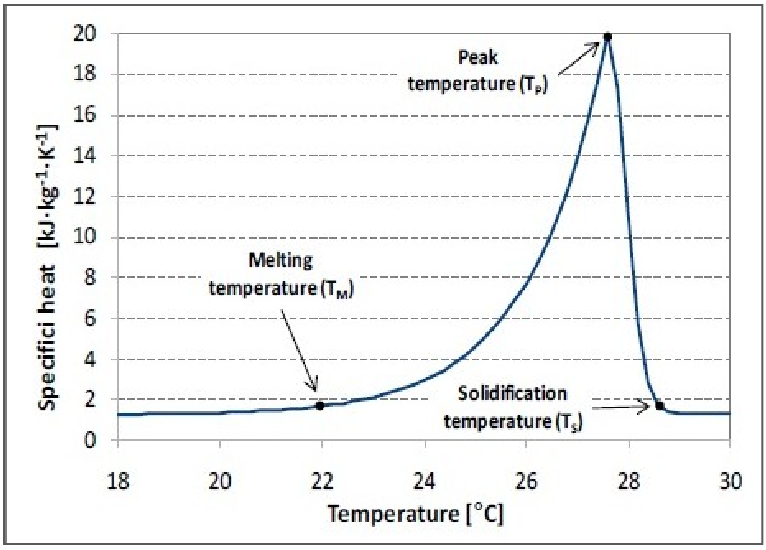

Fig. 18 Representation of the specific heat of the PCM by using the inverse method equations.

6.2. PCM simulations with EnergyPlus

In order to simulate the behavior of a phase change material on EnergyPlus, it is first necessary to introduce the PCM properties and, above of all, the curve describing its specific enthalpy as a function of the temperature.

So, the PCM insertion is made in the same manner as the other materials. We entered the characteristics of the PCM in the specific schedule "Material" (*Fig. 19*).

[0003] ScheduleTypeLimits
[0005] Schedule:Compact
[0014] Material
[0001] WindowMaterial:Glazing
[0001] WindowMaterial:Gas
[0002] WindowMaterial:Shade
[0001] WindowMaterial:Blind

Regular materials describ
ID: N4
No default value availabl
Range: 0 < X but no ma
This field is required.

Field	Units	Obj4
Name		MCP_Abeille
Roughness		MediumRough
Thickness	m	0.02
Conductivity	W/m-K	2.8
Density	kg/m3	540
Specific Heat	J/kg-K	1400
Thermal Absorptance		0.9
Solar Absorptance		0.5
Visible Absorptance		0.5

Fig. 19 Material's schedule in EnergyPlus.

Thanks to the activity carried out in the previous phases, the specific heat capacity of the PCM panel could be known. So, considering the Eqn. (5), the enthalpy can be determined as:

$$h(T) = \int_{T_0}^{T} C_{eq}(T)dT \qquad (21)$$

The values of temperature and enthalpy must be introduced in a two-column table through not more than 16 assigned points so that the function covers the entire temperature range that will be seen by the material in the simulation (*Fig. 20*).

Field	Units	Obj1	Obj2
Name		MCP_Abeille	MCP_Energain
Temperature Coefficient for Thermal Conductivity	W/m-K2	0	0
Temperature 1	C	0	0
Enthalpy 1	J/kg	0	0
Temperature 2	C	20	15
Enthalpy 2	J/kg	24240	63750
Temperature 3	C	22	20
Enthalpy 3	J/kg	27135	86070
Temperature 4	C	24	21
Enthalpy 4	J/kg	31420	93610
Temperature 5	C	25	22
Enthalpy 5	J/kg	35040	105310
Temperature 6	C	25.6	23
Enthalpy 6	J/kg	38210	120000
Temperature 7	C	26	24
Enthalpy 7	J/kg	40960	132800
Temperature 8	C	26.6	245
Enthalpy 8	J/kg	46450	136540
Temperature 9	C	27	25
Enthalpy 9	J/kg	51350	140810

Fig. 20 Input values for h(T) function.

On EnergyPlus, such a continuous function must actually be introduced.

However, this representation is largely sufficient to describe the function of Eqn. (21), as shown in *Fig. 21* where the correspondence between the continuous line (equation) and the dotted line (function introduced on EnergyPlus) is shown to be very high.

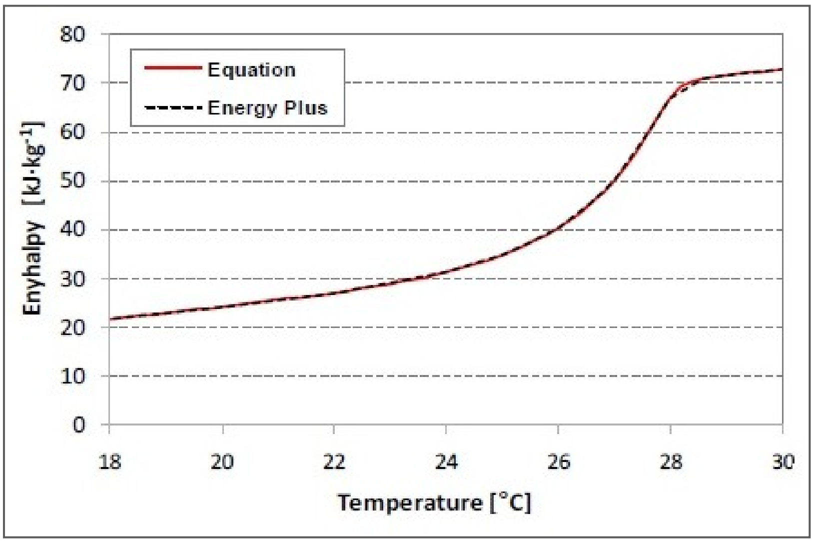

Fig. 21 Enthalpy as a function of temperature.

Unfortunately, on EnergyPlus it is not possible to include the effect of hysteresis on the heat capacity; actually, according to experimental measurements, during the solidification phase the curve shown in *Fig. 18* shifts towards lower temperatures. However the shift is limited to 0.5°C.

Furthermore, under EnergyPlus, the PCMs are simulated using the "Conduction Finite Difference algorithm", which is able to account for the variation of the thermophysical properties (thermal conductivity, heat capacity) with temperature. The finite difference procedure allows to follow the layer-by-layer heat transfer considering the variability of material properties; in fact the temperature-enthalpy function for the material is followed exactly by updating the effective material specific heat during each iteration only considering enthalpy and node temperature values.

7. The case study

7.1. The building model

In order to test the usefulness of PCMs for improving summer thermal comfort in lightweight buildings, a case study is considered.

The building model simulated on EnergyPlus is shown in *Fig. 22*. As we said previously, it corresponds to a portion of a real office building located in Grenoble (France); this building is going to be undertaken a renovation intervention by using honeycomb PCM panels.

The main façade of the building faces west; the room size in 4.83 × 3.52 m^2, with a height of 2.50 m. Floors and ceilings are made by a concrete slab 200 mm thick; the internal walls made of by 7 cm thick gypsum boards. The façade has an internal 100 mm layer of concrete, insulated on the external side by a 7 cm layer of glass wool. The windows are provided with a wood frame and double-glazing (6 mm glass plus 15 mm air gap). Internal venetian blinds are also available; in the simulation, they are normally open, unless the solar radiation incident on the external glazing gets higher than 200 $W{\cdot}m^{-2}$.

All rooms are geometrically identical, but we focused attention on a reference office room (the one standing in the center of the model) that we called "TEST ROOM" and which was subjected to the investigation referred to as.

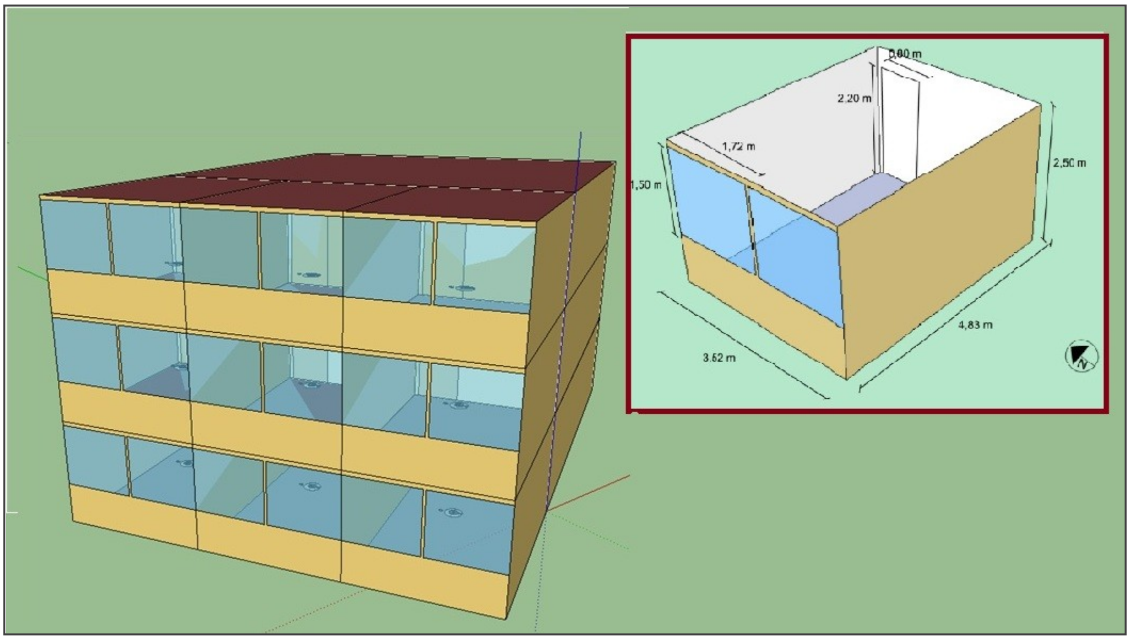

Fig. 22 Building model created in Sketch-up and introduced in EnergyPlus.

The space behind the rooms at each floor is occupied by a large corridor and by a series of identical rooms facing east. As far as ventilation is concerned, a constant rate corresponding to 0.5 ACH is considered for hygienical purposes. However, in order to test the effect of night ventilation on PCM performance, an additional mechanical ventilation rate is also introduced from 09:00 p.m. to 06:00 a.m. Several simulations are performed by varying such an air flow rate in the range 2 ÷8 ACH.

The run period of simulation goes from the 1st of January to the 31st of December, but the graphs and diagrams that we will present in the follow refer to the summer period, that is from the month of June to the month of September.

For the building configuration and for thermo-dynamic simulations the following assumptions are made:

- the external air temperature and solar radiation as outdoor boundary conditions;
- indoor thermal loads are specified (people, equipments, lights);
- the room has not a heating/cooling systems. So indoor air temperatures change in time according to outdoor conditions, internal loads and building structure.

In order to choose the suitable solution, it has been necessary to carry out a preliminary study during which we analyzed the building in "standard" conditions, that is without PCM panels but considering the actual conditions. Thus these kind of simulations can enable to understand how the choice of PCM (its thickness, its extension and the way it is installed) can affect its efficacy and, in particular, what is its usefulness on the improvement of summer thermal comfort in the building.

Then, in the next phase, we considered the installation of the honeycomb PCM panel on the inner faces of the internal walls of the test room. This second phase is performed according to different solutions (for example considering different thickness or applying it according to a different scheme). The comparison of the results of the various cases can enable us to define the suitable conditions and installation scheme in order to obtain the best thermal performance of the panel and the best summer indoor thermal comfort conditions.

In order to fully test the efficacy of the phase change materials on summer indoor thermal comfort, we decided to apply the same procedure just described in a different location such as Catania which represents a typical city with a Mediterranean climate. For carrying out these simulations we used the same building just described and the same phase change material system but with a different melting temperature.

In summary we will describe two kinds of case study:

- *Case a)* Simulations of the real building in its location (Grenoble).
- *Case b)* Simulation of the real building in a Mediterranean location (Catania).

Reference data of all simulations are summarized the following table:

Weather Data *- Case a* *- Cases b*	 Lyon[3] Catania	
Zone volume:	4.83 x 3.52 x 2.50	m^3
Thickness of exterior wall	20	cm
Thickness of interior partition	7	cm
Thickness of ceiling/floor:	20	cm
Window	6 - 15 - 6	mm
Internal loads: *- 2 persons* *- equipment* *- lighting*	 130 10 8	 W /p W/m^2 W/m^2
Ventilation: *- natural ventilation* *- mechanical ventilation*	 0.5 2÷4÷6÷8	 air changes/h air changes/h
Run Period	1st January ÷ 31st December	

Tab. 6 Basic simulation's settings

[3] The real building analyzed is located in Grenoble, but as the corresponding weather data are not available in EnergyPlus we considered the city of Lyon which is close to Grenoble and which has a similar weather conditions.

7.2. Composition of building elements

7.2.1. Exterior wall

The external wall consists of an internal 100 mm layer of concrete, a 70 mm layer of glass wool thermal insulation and 15 mm of plaster on the internal and external side.

The layers of the wall structure are the following (from the outside layer to the inside layer):

	Material	*Thickness [cm]*
Layer 1	Exterior plaster	1.5
Layer 2	Glass wool insulation	7
Layer 3	Concrete structure	10
Layer 4	Interior plaster	1.5
Whole structure		*20*

7.2.2. Interior partition without PCM

The interior partition consists of a single layer of gypsum boards:

	Material	*Thickness [cm]*
Layer 1	Gypsum	7

7.2.3. Ceiling and Floor

The ceilings and the floors are made similarly by a concrete slab with a linoleum coat for the floor and a plaster layer on the internal side for the ceiling.

The composition is the following (from the outside layer to the inside layer):

- Floor:

	Material	*Thickness [cm]*
Layer 1	Plaster	1
Layer 2	Concrete	20
Layer 3	Linoleum	1
Whole structure		22

- Ceiling:

	Material	*Thickness [cm]*
Layer 1	Linoleum	1
Layer 2	Concrete	20
Layer 3	Plaster	1
Whole structure		22

7.2.4. Window

The building presents two large windows for each room. Each window has a double-glazing (6 mm glass plus 15 mm air gap), a wood frame and a shading system consisting of internal venetian blinds. In the simulation we considered that the shading devices are normally open unless the solar radiation incident on the external glazing gets higher than 200 $W \cdot m^{-2}$.

The window's construction is the following (from the outside layer to the inside layer):

	Material	*Thickness [mm]*
Layer 1	Glass	6
Layer 2	Air gap	15
Layer 3	Glass	6
Layer 4	Blinds	30

7.2.5. PCM system

The application of the phase change materials regards only the central room that we called "Test room". We considered two different solutions:

1) the application of the PCM panels on the interior surfaces of the internal walls (*Fig. 23*).

2) the application of the PCM panels with a ventilated air gap between the internal wall and the PCM. (*Fig. 24*). This second system is under development and improvement in the framework of the ongoing project SIRTERI. These simulations allowed us to have a preliminary evaluation of this solution.

The composition of the solution *1)* is the following (from the outside to the inside):

	Material	*Thickness [cm]*
Layer 1	Gypsum	7
Layer 2	PCM panel	2

The composition of the solution *2)* is the following (from the outside to the inside)

	Material	*Thickness [cm]*
Layer 1	Gypsum	7
Layer 2	Air gap	2
Layer 3	PCM panel	2

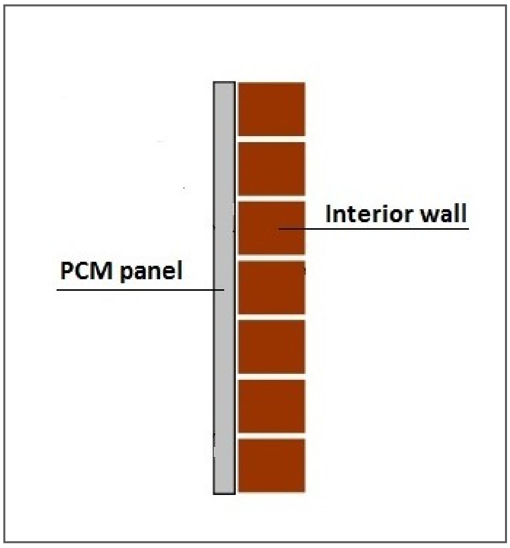

Fig. 23 Solution 1: application of the PCM panels on the inner surfaces of the room.

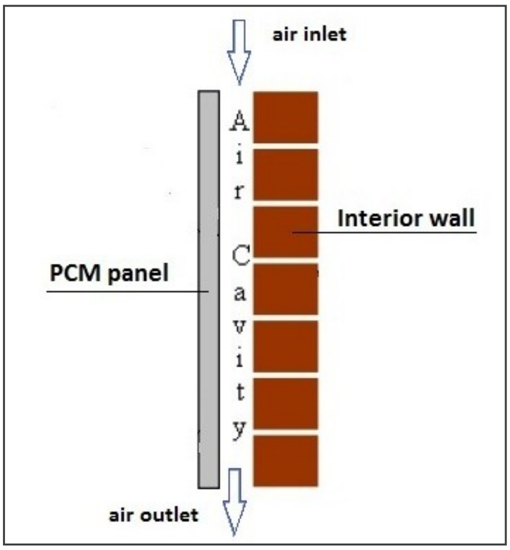

Fig. 24 Solution 2: air gap between the PCM panel and the interior wall.

7.3. Output parameters of the simulations.

For comparing results of the various simulation cases we considered the following parameters and indicators:

- Operative temperature (T_o)
- Surface inside temperature (T_{si})
- Frequency of the Thermal Comfort conditions (FTC)

- Intensity of Thermal Discomfort (ITD)
- Frequency of the Activation temperature (FA)

The *Operative temperature* is defined as a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment.
The operative temperature can be approximated by the equation:

$$T_{op} = \frac{T_{mr} + T_a}{2}$$

where:
T_{mr} = mean radiant temperature[4]
T_a = air temperature

The *Surface temperature* represents the temperature measured on the inner side of a wall which is subjected to a heat transfer. This parameter is automatically calculated and reported as output by EnergyPlus according to the specific heat transfer algorithm which is chosen for the simulations.

The last four indicators concerning the thermal comfort are recently introduced on the basis of the adaptive comfort theory. Some of them are previously defined in chapter 2; briefly we state again that the Intensity of Thermal Discomfort describes the intensity of an uncomfortable thermal sensation due to overheating in a living space and the Frequency of Thermal Comfort represents the percentage of time within a given period (we considered the summer season) during which the indoor thermal comfort conditions are achieved.
The indicator called *Frequency of Activation* is a new parameter that is introduced in this research work in order to better describe the behavior of the PCM and assess its efficacy. This parameter is defined as the percentage of time within a given period during which the PCM is actually activated, i.e. it undergoes phase-

[4] The mean radiant temperature is simply the area weighted mean temperature of all the surfaces surrounding the body.

change. The frequency of activation could assume a significant role in the design of PCM panels because it tells when the PCM is "activated" and so when the material works effectively over a long-lasting period.

Thus if the value of Frequency of Activation is too low and then the PCM keeps in its liquid or solid phase for a too long time, it means that it is not used in a correct way and its latent heat capacity is not exploited. An ideal PCM should have FA = 100%. Anyway this is not always occurring, as the activation of the PCM is highly linked to the climatic conditions. As an example, in a fresh and cloudy day, the PCM will hardly undergo melting, and it will behave like an additional layer of solid lining.

In order to calculate the FA of the PCM in our simulation cases, we considered as an activation interval the temperature range between the starting point of the melting phase (about 22°C) and the solidification temperature (28.5°C) and then we calculated how many times the material's temperature, provided by EnergyPlus as an output, falls within this range (*Fig. 25*).

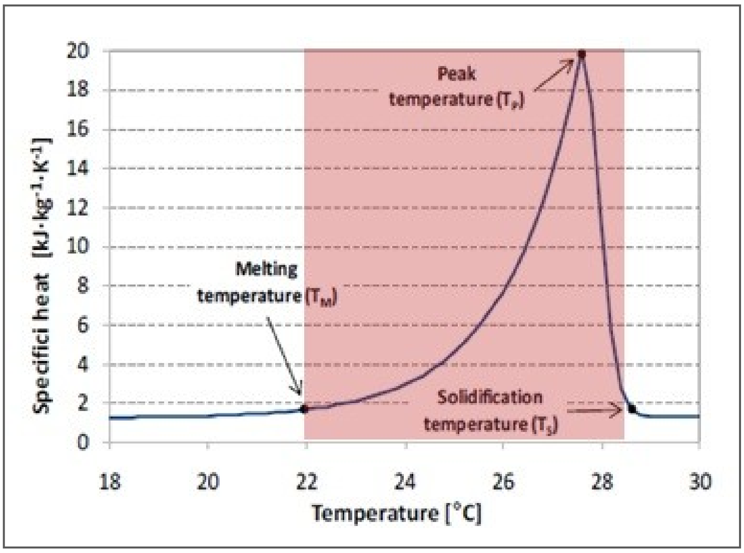

Fig. 25 Range of FA for the tested panel.

8. Case a

8.1. Base case.

In order to assess and understand how much the use of phase change materials is effective for building application, we have to compare the indoor thermal conditions occurring in the building before and after the intervention of PCMs. Firstly it is important to perform an evaluation of the physical parameters, such as the indoor air temperature, the operative temperature and the surface temperature, which allow us to assess the thermal behavior of the building and calculate the subsequent indicators.

Considering the temperature trend during a short period of summer (from 2nd to 6th of July) we can notice that all three physical parameters previously mentioned have a very similar trend (*Fig. 26*). The indoor air temperature deviates more than the others at the maximum and minimum values, but both the operative, the indoor and the surface temperature fluctuate in the range between the 28°C and 32°C. It's obvious that the variations of the internal temperatures are influenced by the swing of the external temperature.

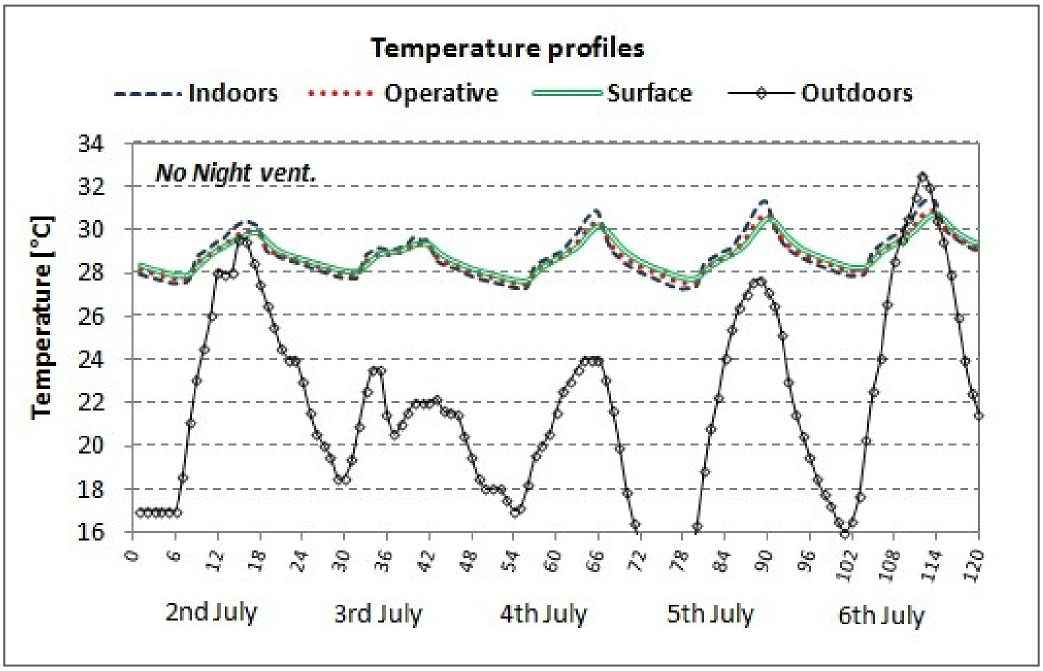

Fig. 26 Temperature profiles without night ventilation during a summer period (from 2nd to 6th of July) in the case a.

Also looking at the temperature profiles in the cases of activation of the night ventilation system (with 4 ACH and 8 ACH), we can notice a fair lowering of the curves at the peak conditions and a more evident separation during the night period when much lower values are achieved.

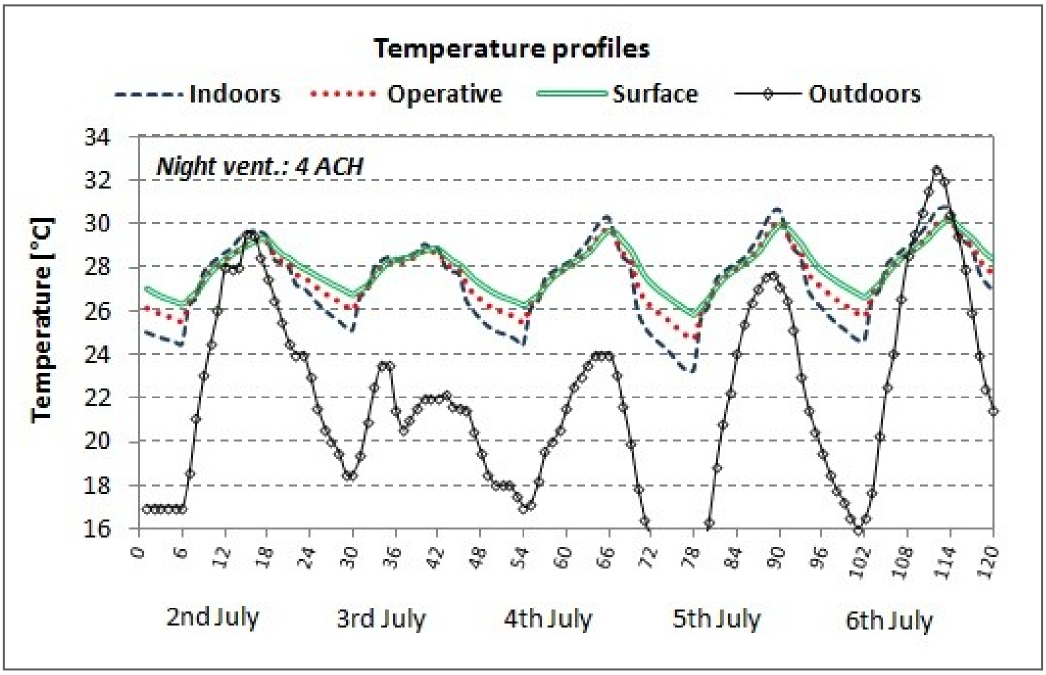

Fig. 27 Temperature profiles with 4 ACH by night during a summer period (from 2nd to 6th of July)in the case a.

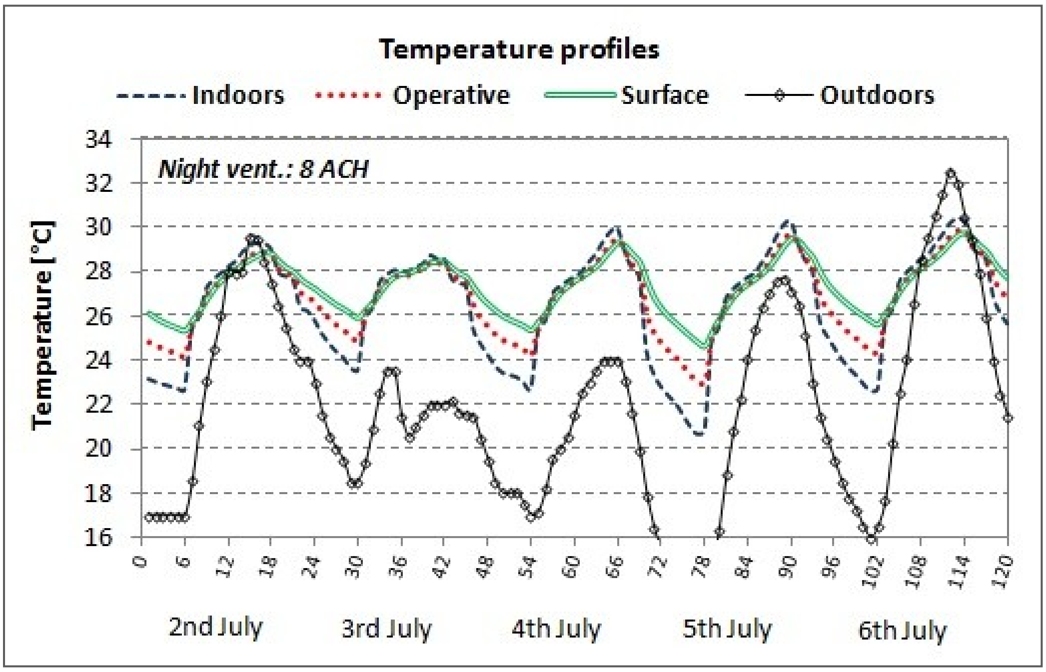

Fig. 28 Temperature profiles with 8 ACH by night during a summer period (from 2nd to 6th of July) in the case a.

This different variation produces a wider range of the temperature fluctuations. The temperature reduction occurs mostly during the night when the building is uninhabited (*Fig. 27*-*Fig. 28*).

In order to better investigate the thermal conditions, we focused the attention on a daily trend of temperature (*Fig. 29*).

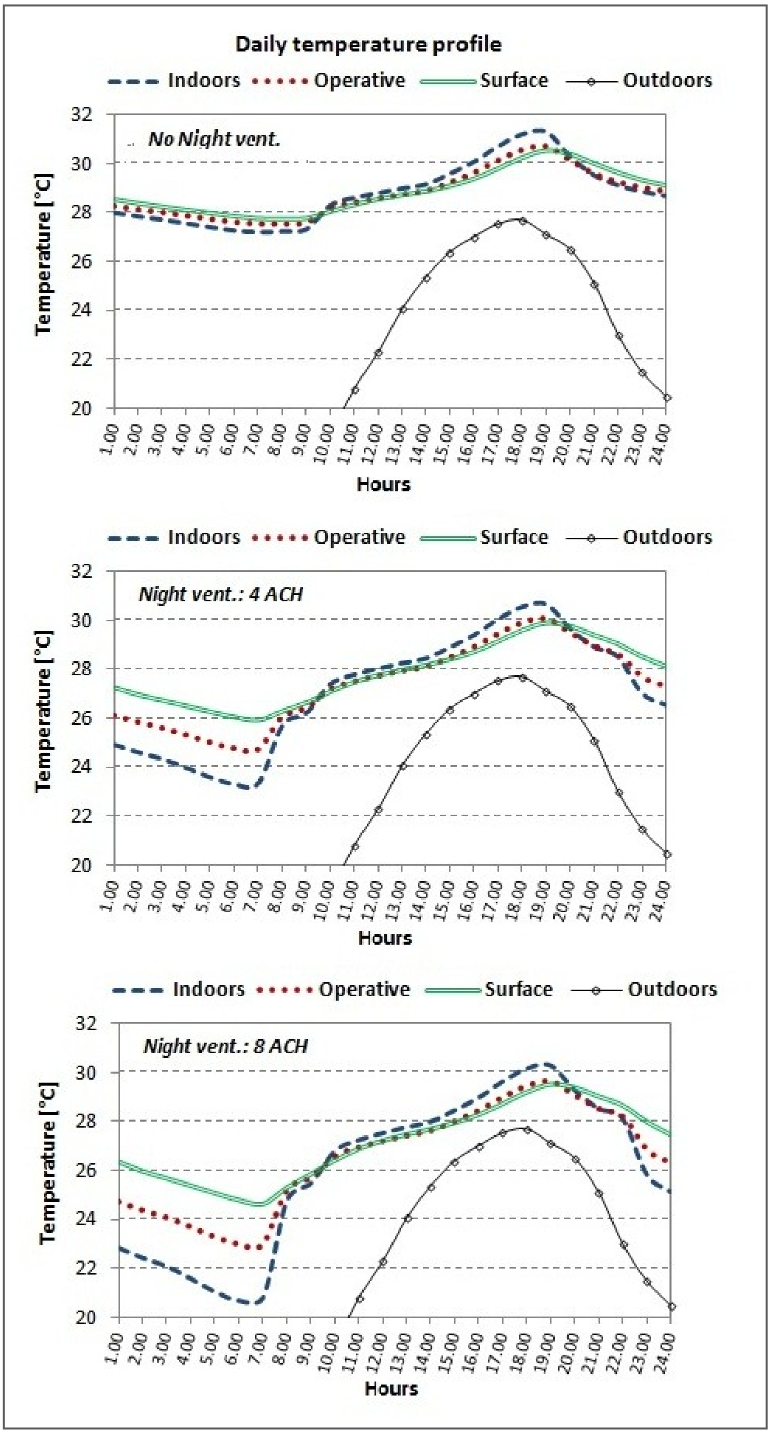

Fig. 29 Temperature profiles for a typical summer day (5th of July) in the case a.

The daily temperature's profiles show a quite similar trend in the case without activation of the night ventilation system; if the night ventilation occurs the temperatures start to decrease.

The higher the ventilation rate the higher the splitting of one curve from each other, especially during the nighttime when the indoor and the operative temperature are more affected by the activation of the ventilation system.

In fact, during the night period, the minimum values of temperature are reduced considerably: the indoor temperature is lowered by more than 4°C with the medium ventilation rate and even by about 7°C with the highest ventilation rate. Surface temperature is not much affected although it decreases by less than 3°C (next to the minimum).

However, considering the maximum values occurring during the daytime, there is no significant reduction but temperatures remain quite high; in fact peak values of the indoor, the operative and the surface temperature decrease similarly by 0.6°C and 1°C respectively for 4 ACH and 8 ACH .

Concerning the comfort indicators, as we state previously, we considered the adaptive comfort theory (see §2.1) and so we evaluated the comfort categories for the city of Lyon[5].

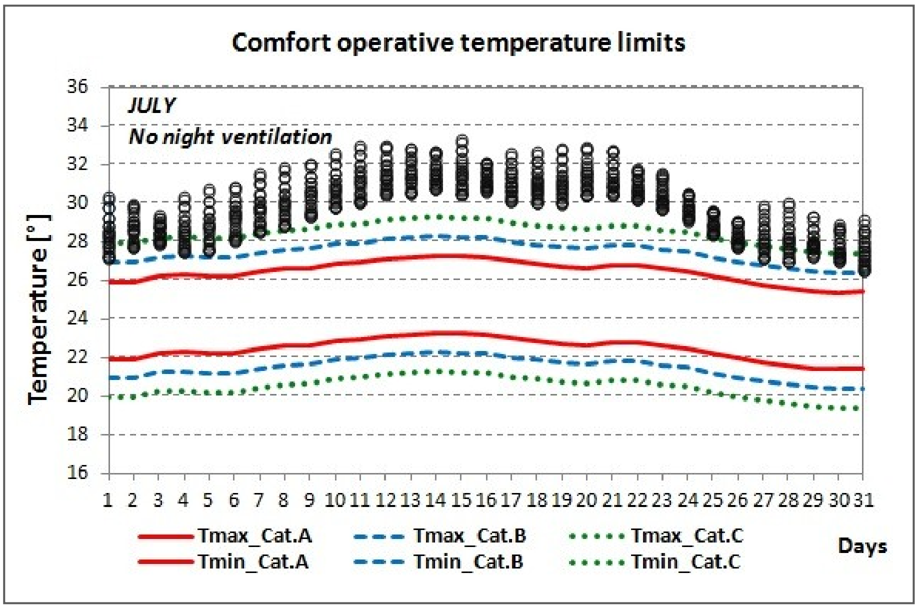

Fig. 30 Comfort categories of the city of Lyon and comfort temperatures in the time period from 8:00 a.m. to 8:00 p.m. without night ventilation.

[5] As we've already said previously the program EnergyPlus doesn't provide the weather data for the city of Grenoble; so we had to use the weather data of Lyon which is the nearest city with a similar climate conditions.

To the aim of determining the comfort categories, it is firstly necessary to evaluate the running mean outdoor air temperature (T_{mr}) by using the equation (1).

Then using the equations (2), we could calculate the maximum and minimum values for each category during each month of the summer period.

The results of the over mentioned calculations are showed in the graphs of *Fig. 30*-*Fig. 31*. -*Fig. 32*. The comfort categories A,B,C are delimited by three different lines.

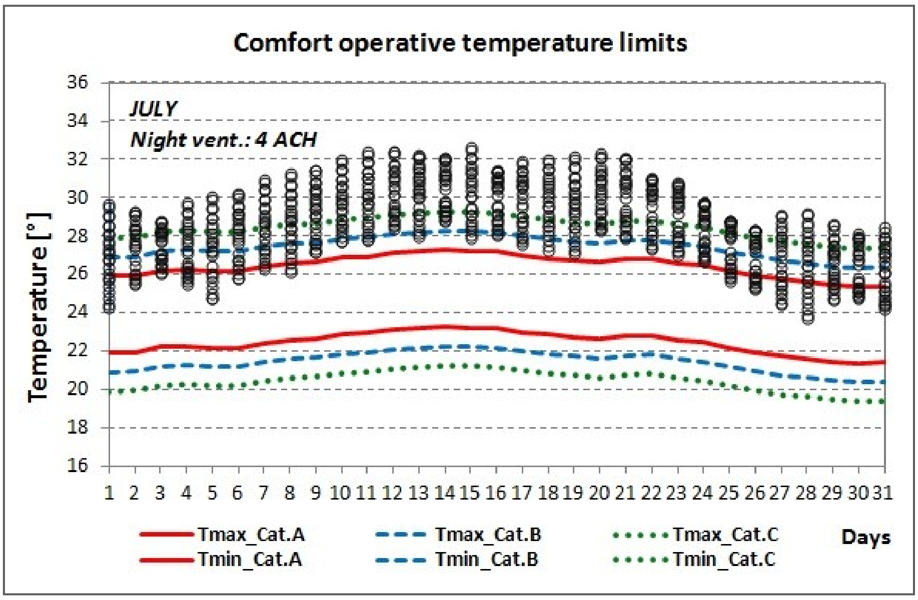

Fig. 31 Comfort categories of the city of Lyon and comfort temperatures in the time period from 8:00 a.m. to 8:00 p.m. with 4 ACH by night.

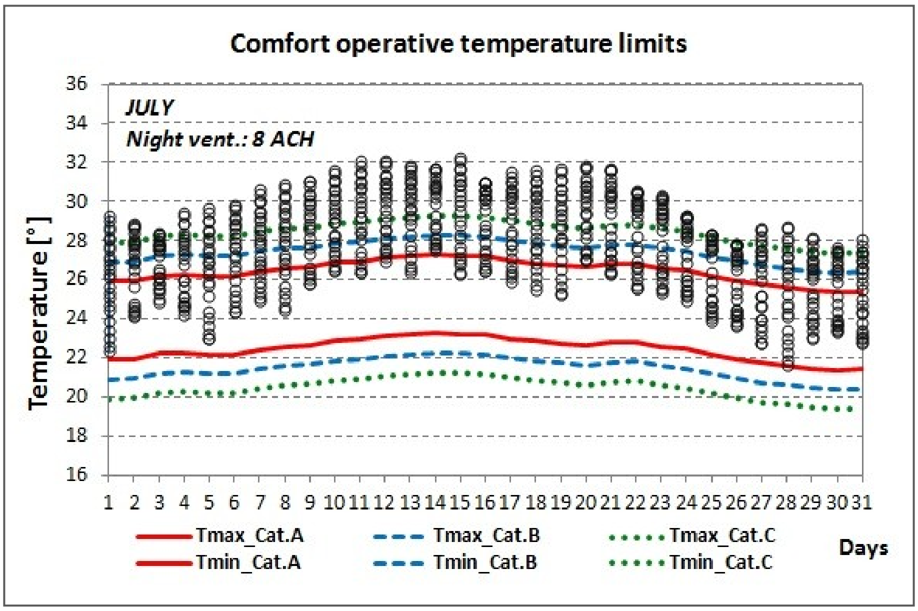

Fig. 32 Comfort categories of the city of Lyon and comfort temperatures in the time period from 8:00 a.m. to 8:00 p.m. with 8 ACH by night.

In particular each graph reports the frequency of the operative temperatures falling within the limits of the comfort categories during the working time (08:00 a.m. - 08:00 p.m.) and according to a different night ventilation rate. As we can see, the higher ventilation rate, the higher the lowering of the points cloud closer to the comfort temperature limits, although the attainment of the comfort conditions can't be fully satisfied.

The *Fig. 33* summarizes the main results. The increasing frequency of comfort corresponds to an increase of the air changes per hour provided by the ventilation system, but only the activation of the highest ventilation rate could ensure a quite satisfactory result in terms of comfort occurrence for the comfort category A.

Same considerations can be stated for the average of the maximum operative temperature, which can be reduced by about more than 1°C only next to 8 ACH.

So we can deduce that the only ventilation system is not sufficient to improve effectively the indoor thermal conditions and ensure the comfort requirements.

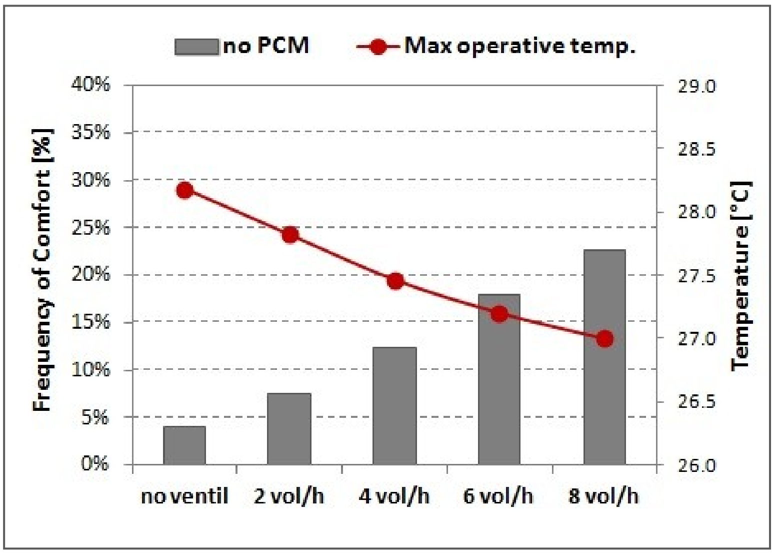

Fig. 33 Frequency of thermal comfort for the category A and reduction of the maximum operative temperature.

8.2. Results of case a.1.

As we already said, we considered two case studies. The first one called "*case a*" takes into account the simulations for the building already described (§ 7.1) which is located in Grenoble and which is subjected to the intervention of system 1, i.e. the application of the PCM on the inner side of the internal partition (§ 7.2.5).

Then, in order to assess the effectiveness of PCMs for improving the summer thermal comfort in the building, we compared the results of the base case with those obtained by the application of PCMs.

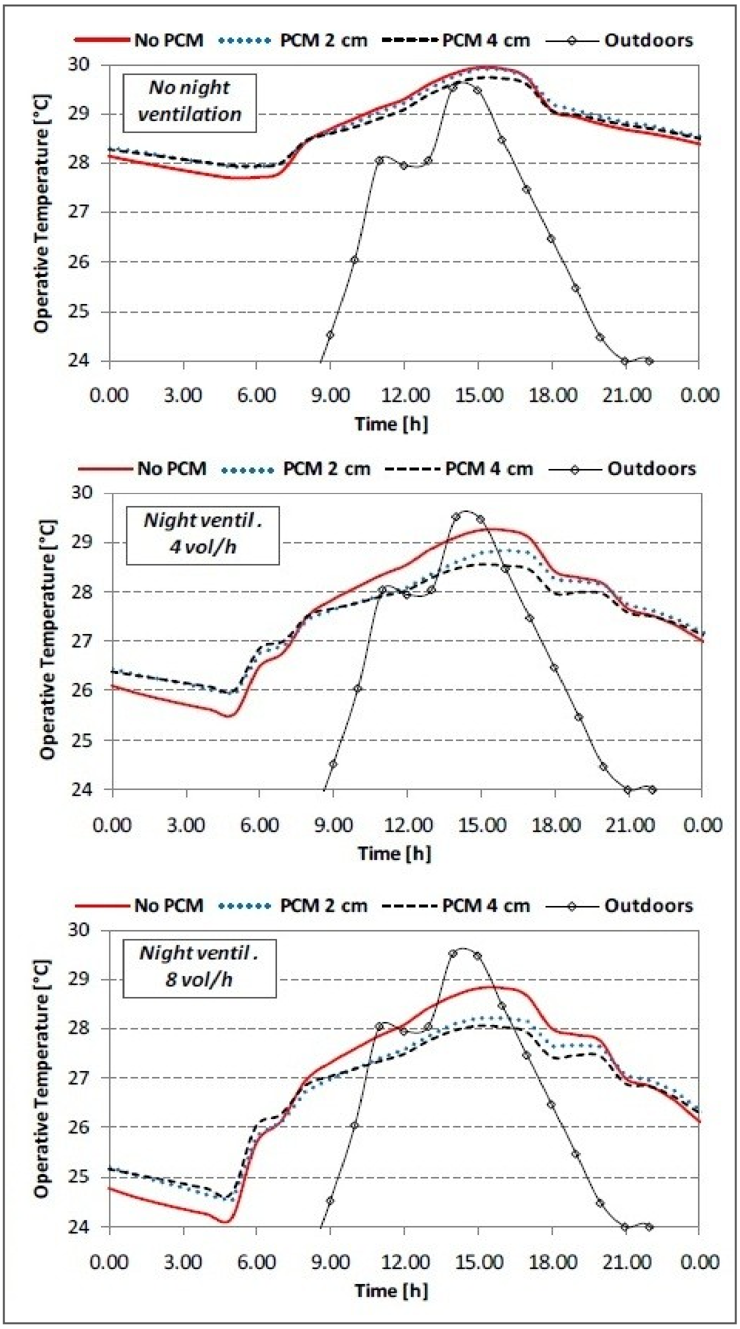

Fig. 34 Trend of the operative temperature of the case a.1.

Furthermore, for assessing the role played by the mechanical ventilation rate and the thickness of the PCM, the same simulations are performed varying the night ventilation rates and considering two thicknesses of the panel.

The *Fig. 34* reports the operative temperature during a typical summer day (4th of July). We can notice that the efficacy of the PCMs is highly connected to the night ventilation rate: if the ventilation system doesn't operate, there are no relevant differences between the temperature of case "No PCM" and the one of case "PCM 2 cm" or "PCM 4 cm". On the contrary, if the night ventilation is activated it is possible to observe a reduction of the peak operative temperature as high as 0.5 °C at 4 ACH and 0.8°C at 8 ACH.

The graph allows us to perceive the influence of the thickness of the PCM panel on the room behavior. The operative temperature profiles of the 2 cm thick panel is alike the profile of the 4 cm panel, even though the temperatures achieved by the thicker panel are slightly lower than the ones related to the half-thickness panel.

However the difference of the first curve from the second is not so meaningful. So we can deduce that using a 4 cm thick panel rather the 2 cm thick one does not imply a such significant improvement in the effectiveness of the PCM as to compensate the additional costs.

The behavior of the PCM should be evaluated over a longer time period; in fact, the PCMs could not work properly during particularly hot and sunny days, when solidification is not effectively performed, or it could be useless during fresh and cloudy day, when melting is not produced.

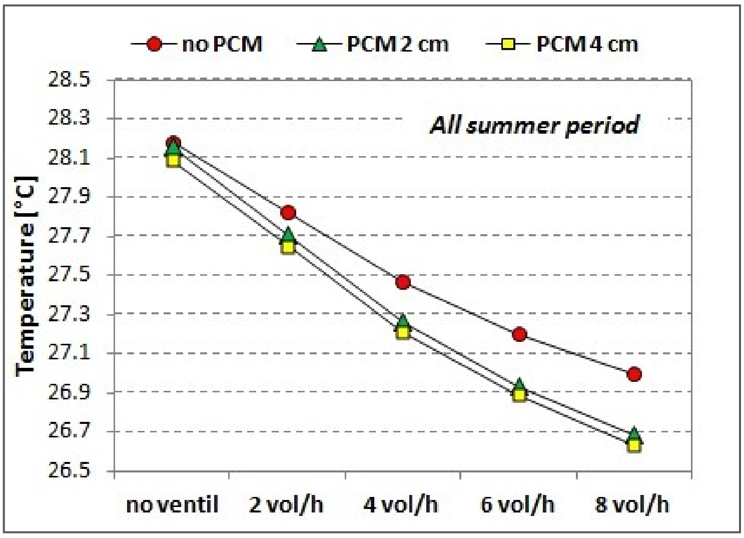

Fig. 35 Mean operative temperature during all summer period in the case a.1.

To this aim, it may be interesting to look at the mean operative temperature during all summer period (*Fig. 35)* and during the hottest months (*Fig. 36*).

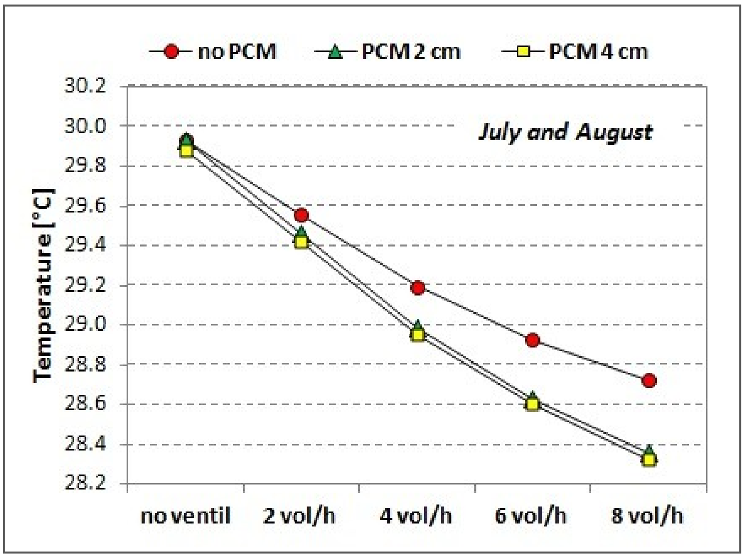

Fig. 36 Mean operative temperature during the months of July and August in the case a.1.

The graphs remark how the reduction of the operative temperature is strictly related to the night ventilation rate: as it is obvious, the highest improvement corresponds to the maximum ventilation rate (8 ACH) but a quite acceptable reduction is related to the medium ventilation level (4 ACH).

After the assessment of thermo-physical parameters we pointed the attention on the evaluation of the thermal comfort conditions by calculating the Frequency of Comfort and Intensity of Discomfort which help us to investigate the characteristics of the discomfort, such as the intensity, the fluctuation within a certain period and the frequency in the occurrence of the comfort conditions according the adaptive comfort theory.

Concerning the Frequency of Comfort we considered the same graph of the comfort categories already calculated for the preliminary simulations ; then we reported in it the occurring operative temperatures.

In order to estimate the percentage of comfort, we considered as a threshold value (T_{lim}) the one corresponding to the upper limit of category A which represents the most strict thermal comfort category (the cat. A is bounded by red lines).

The points cloud showed in the *Fig. 37* represents the operative temperatures occurring in the present case a.1.

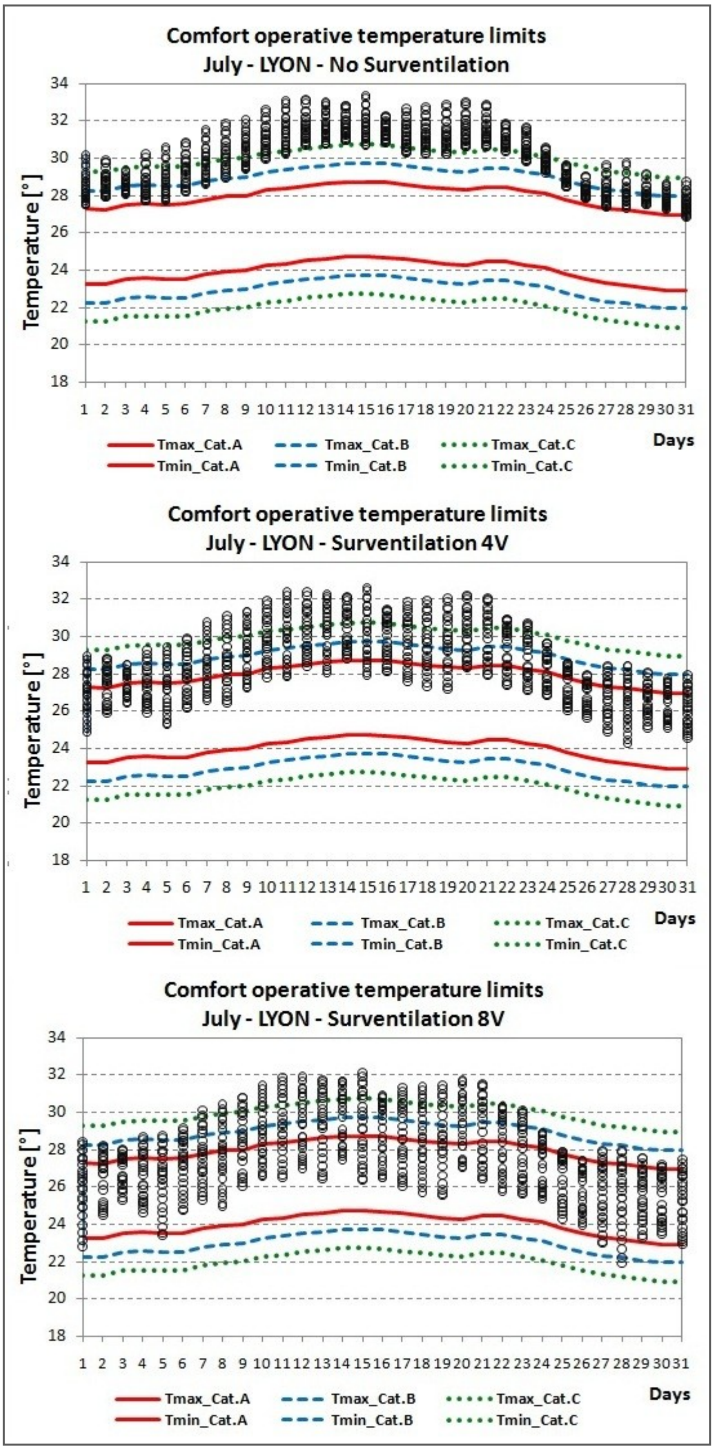

Fig. 37 Occurrence of the comfort temperatures in the case a.1. for different night ventilation rates.

As we can see the operative temperature falls mostly outside the comfort range of category A in the case without the night ventilation system; if the night ventilation

is activated the "points cloud" starts to fall down until is almost entirely included in all comfort categories specially with the highest ventilation rate 8 ACH.
The summary of the results for the Frequency of Thermal Comfort is reported in the *Fig. 38*. In particular the percentage is calculated considering the values which ensure compliance with the limits of the category A.

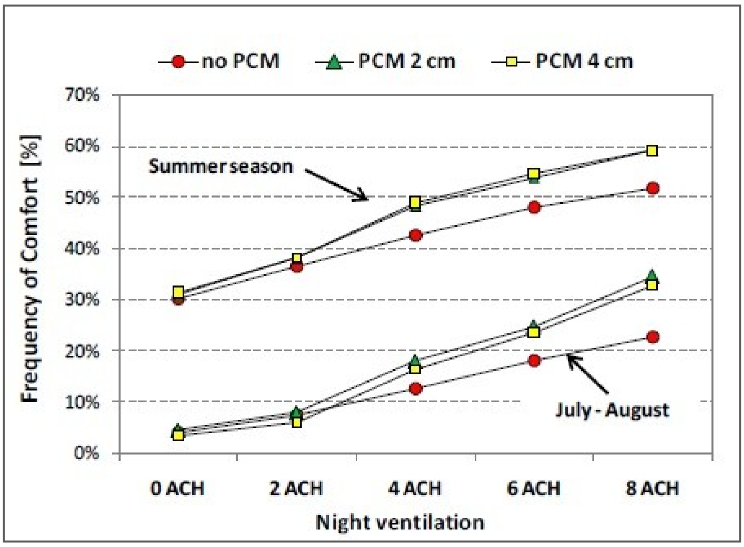

Fig. 38 Frequency of the thermal comfort during all summer period and during the hottest months.

One can notice that during the whole summer season (from June to September) the adaptive thermal comfort is assured for up to the 60% of the occupancy at 8 ACH (10% more than the case without PCMs), no matter the thickness of the installed PCM. Anyway, 4 ACH are sufficient to provide comfort for the 50% of the occupancy while under 2 ACH no significant increase of FTC occurs.
However, the FTC drastically reduces if looking only at the two hottest months (July and August): as an example the FTC is reduced at 18% at 4 ACH.
In both periods considered it is evident the major role of the mechanical ventilation to make the PCM panels more efficient.
The *Fig. 39* shows the results concerning the Intensity of Thermal Discomfort calculated during the summer period; the graph reports the comparison amongst the different rates of the night ventilation system.
First of all it is possible to notice that the effectiveness of PCMs on the ITD is significant only if combined with ventilation otherwise the ITD reduction is negligible. Specifically, the effectiveness of the PCM is strictly related to the rate of

the night mechanical ventilation, since the ITD decreases linearly by increasing it even if an asymptotic behavior seems to emerge at 8 ACH. At 8 ACH the seasonal ITD obtained with a 2 cm PCM panel is quite lower than the one in the case without PCM; also the 4 cm PCM panel guarantees a slightly lower ITD value than the previous case.

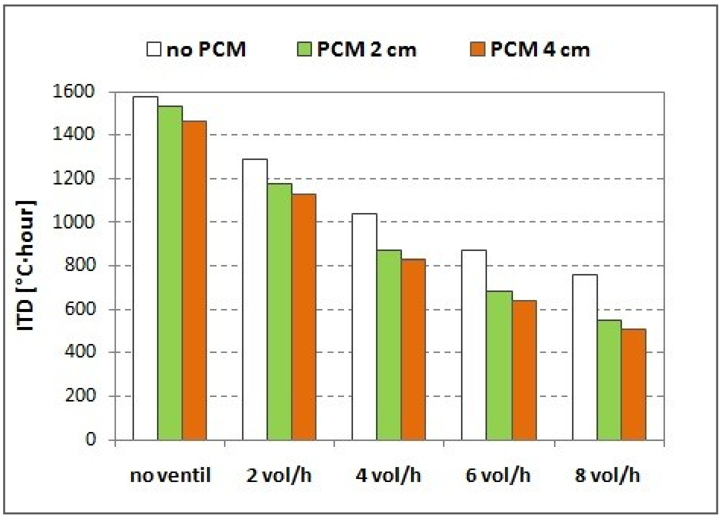

Fig. 39 Intensity of the Thermal Discomfort during all summer period.

The *Fig. 40* highlights the percentage reduction of the two PCM solutions (2 cm and 4 cm thick panel) according to the different night ventilation rate: without a night ventilation system the application of PCM doesn't make relevant results (about 2.4 % for the 2 cm PCM and 6.8% for the 4 cm PCM). While if we increase the night ventilation rate the lowering of the ITD undergoes a more significant

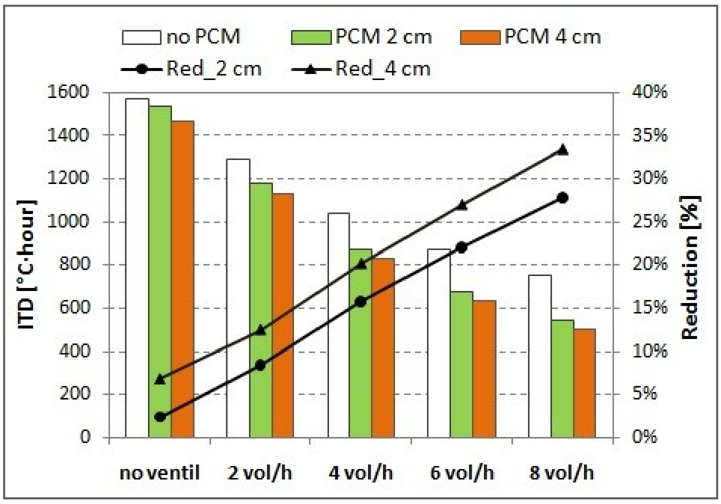

Fig. 40 Reduction of the ITD by using the PCM panels according to different night ventilation rate.

reduction up to 27.9 % (in the case of 2 cm PCM panel) and 33.4 % (in the case of 4 cm PCM panel) at 8 ACH.

However, considering a medium ventilation rate (4 ACH) it is possible to achieve good results, that is a reduction of 15.8 % and 20.2 % related respectively to the use of 2 cm panel and 4 cm panel.

Furthermore, as we noticed before, for a given ventilation intensity the use of the 4 cm thick panel is not so advantageous than the 2 cm panel because it further reduces the ITD of only the 5%, despite using more material.

As we've already said previously, in order to assess the effectiveness of the phase change materials we have to investigate the internal surface temperature. This parameter affects not only the evaluation of the mean radiant and operative temperature, but also it allows us to estimate the new parameter that we called Frequency of Activation (see § 7.3).

So, as shown in *Fig. 41* for the simulation of a typical hot summer day (4th of July), the installation of the PCM panels without a night ventilation system doesn't provide significant reduction of the surface temperature; the 2 cm PCM panel seems to have no effects, while the 4 cm panel provides a little reduction.

Looking at the second graph of *Fig. 41*, if a night ventilation rate is activated (4 ACH) the PCM can produce a reduction on the peak surface temperature of about 0.5°C for the 2 cm panel and 1°C for the 4 cm panel. Furthermore the daily fluctuation of the surface temperature is limited to around 2°C (with 2 cm panel) or even to 1°C (with 4 cm PCM panel).

Obviously the increase of the ventilation rate (8 ACH) is more effective in reducing the surface temperature because it reduces the surface temperature by 1°C - 1.4°C.

However, the only information on surface temperature are not sufficient to have a more comprehensive description of the PCMs effectiveness because they don't give information about the amount of the material activated and duration of the transition phase. To this aim we introduced in § 7.3 the new parameter that we called Frequency of Activation (FA) representing the percentage of time during which the PCM is “activated”, i.e. its surface temperature falls between its melting and solidification temperature. The phase change range for the PCM studied in this work is 22°C ÷28.5°C (see § 7.3, *Fig. 25*) .

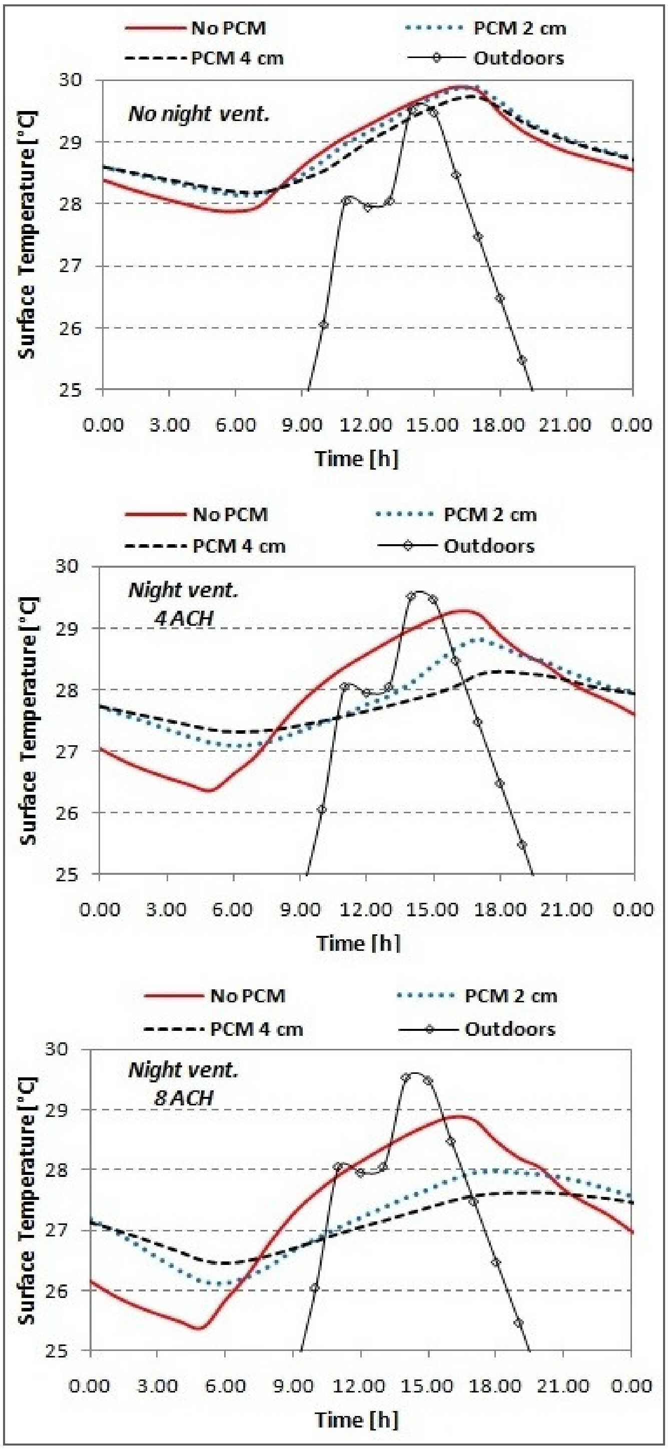

Fig. 41 Daily surface temperature in the case a.1.

For the calculation of this new parameter we firstly considered the surface temperature of all internal partitions on which the PCM panels are applied. Thus we evaluated how long the surface temperature falls within the phase change range (23°C-28.5°C) during all day or during the night when the ventilation system is on. Lastly we calculated the surface weighted mean frequency for all ventilation cases considered.

The *Fig. 42* shows the frequency of PCM activation for the 2 cm and 4 cm thick panel according to three different night ventilation cases (No ventilation, 4 ACH, 8 ACH). It is possible to notice that in the first case the material is activated for a little more than 50% of the time, but during the rest of the time, the PCM tends to remain molten probably because of the low regeneration process (solidification phase).

Fig. 42 Frequency of activation of 2 cm and 4 cm PCM panel.

When the night ventilation system is activated with 4 ACH or 8 ACH the frequency of activation increases respectively by 7.1% and 10.8% and consequently the percentage of time during which the material remains in the molten phase reduces. Moreover, as the frequency of activation doesn't increase linearly with the ventilation (the increase next to the highest rate of ventilation is almost 4%), it is possible to say that the PCM panel works quite well even with 4 ACH since it is activated on average for more than the 60% of the time.

Furthermore, by studying the graphs of FA we can observe a distinction between the three partition walls because the better behavior competes to the panel installed on the east wall (the one facing the window). This probably occurs because it is the farthest from the window and consequently less solicited by the incoming solar radiation which may cause a rapid melting.

The FA parameter is calculated for both thicknesses of the panel but we can note no significant differences between the 2 cm and 4 cm PCM panel. So the use of a thicker panel doesn't imply a greater efficiency of the PCM in terms of activation. The same considerations were already stated concerning the results about discomfort parameters.

In the graphs of *Fig***.** *43-Fig. 44* we reported the percentage of utilization of the PCM defined as the ratio between the average daily heat exchanged by the wall (depending on the real daily surface temperatures) and the maximum latent heat associated to the PCM panel. This index highlights that the average amount of stored and released heat by the phase change material according to the climatic condition is lower than the storage capacity of the material. In fact not all material is involved in the melting/solidification process, but a part of it doesn't change state and remains in the solid/liquid phase. This is due to some typical thermo-physical and chemical problems of the material, such as the low conductivity, the phase separation, the sub-cooling ,.... which affect the PCM performance (see § 4).

It is evident that percentage of utilization is strictly related to an adequate ventilation system which is necessary to ensure the discharging of the stored heat during the night and so enhancing the regeneration process.

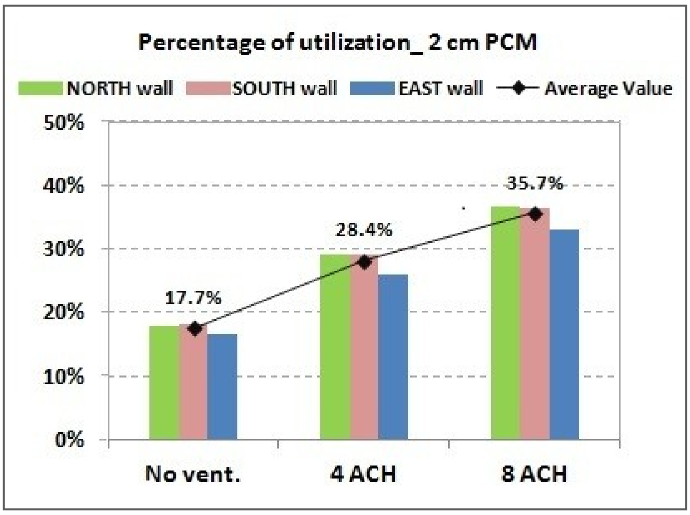

Fig. 43 Percentage of utilization of 2 cm panel.

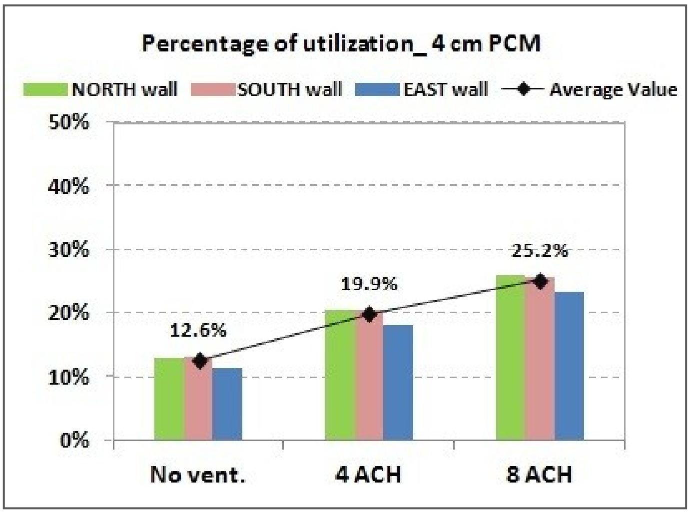

Fig. 44 Percentage of utilization of 4 cm panel.

However it also noticeable that the 2 cm panel ensures a greater percentage of utilization than the 4 cm panel. This is due to the stratification problems related to the larger thickness of the panel which implies a more difficult and inhomogeneous melting/solidification process.

So, summarizing the results it can be noticed that the installation of the PCM panels on the internal surfaces of a room produces very good results in order to achieve the thermal comfort purposes; but, as it is already said, their work efficacy is strictly related to a suitable ventilation system ensuring the discharge process during the night and the improvement of the new phase change cycle.

However even if the best results concern the highest level of ventilation (8 ACH), the PCM panels work quite well also with 4 ACH that we consider a more proper intensity of ventilation for building use.

For the purpose of improving the effectiveness of the PCM we took into account another solution for the building application as described in the follow.

8.3. Results of case a.2.

The second solution for the application of the PCM panels consists of a ventilated air gap between the honeycomb panel and the internal wall in order to enhance the cooling process during the night and so the regeneration of the PCM.

The air gap is made only in the east side of the test room, which is the partition opposite the window and adjacent to the corridor. This choice is due to practical issues of creating the system, in fact the air stream flowing in the gap is fed by the main ventilation air system installed in the ceiling of the corridor.

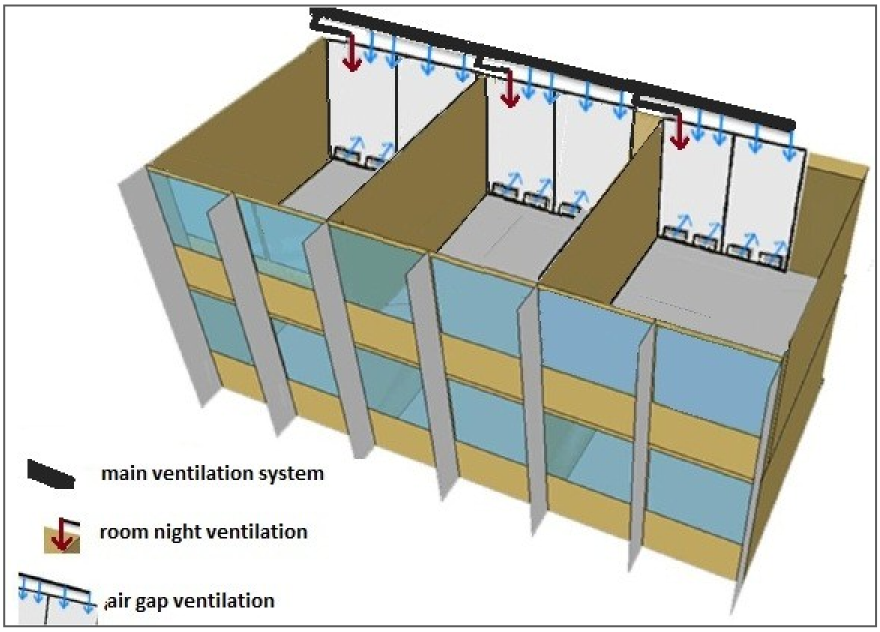

Fig. 45 Scheme of the connection of the air gap with the main ventilation plant.

For the present case we carried out the same simulations of the case a.1. but, unlike it, the night ventilation feeds two flows: the air stream flowing into the gap (4 ACH) and the air change into the room (4 ACH). Similarly to the foregoing case, the ventilation rate is activated within the time period from 21:00 p.m. to 6:00 a.m.

In this case a.2. we didn't carry out the simulations with the 4 cm thick panel because, as we already pointed out in the previous paragraph, the improvements related to it are not so significant as to compensate the increased spending that results by choosing a thicker panel.

The *Fig. 46* reports the comparison between the operative temperature profiles for the two application systems during a typical summer day (4th of July). We can immediately note the advantage achieved by the air gap system which allows a decrease of the operative temperature up half a degree than the case with simple application of PCM and 1°C than the case with no PCM.

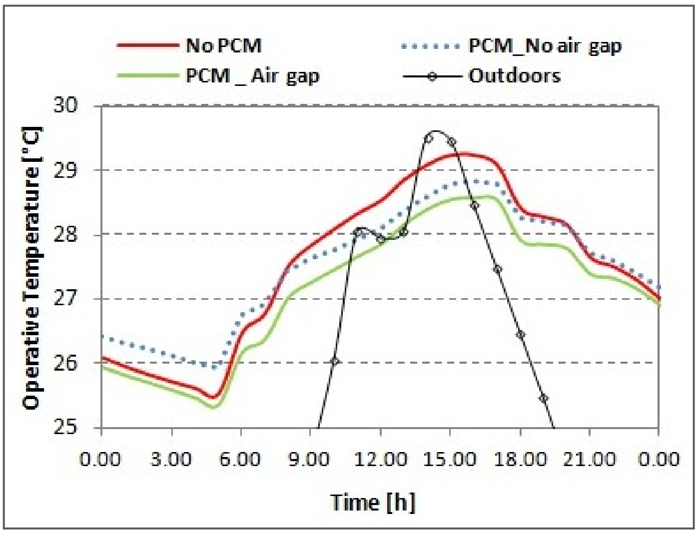

Fig. 46 Comparison of the operative temperature for the two application systems in a typical summer day.

Comparing the two cases with the base case "no PCM" it is also interesting to observe that the case without the air gap is characterized by a reduction of the temperature only during the period from 6:00 a.m. to 9:00 p.m. (that is when the night ventilation system is off). While in the case with air gap the operative temperature remains all the time below the two other temperature profiles.

This is due to the focused and limited action of the air stream on the PCM surfaces which guarantees a greater decrease of the material's temperature.

Consequently, the mean daily operative temperature undergoes a very significant reduction when the "air gap system" is applied both in all summer period and in the hottest months (July and August).

As shown in *Fig. 47* the first system (PCM without air gap) causes a temperature reduction of about 0.7%, while the second solution (PCM with air gap) produces a significant reduction of the mean daily operative temperature (about 2.7%).
These considerations apply equally to the two analyzed time periods, in fact both systems achieve the same result in terms of reduction considering a longer period (all summer) or only two months (July and August).

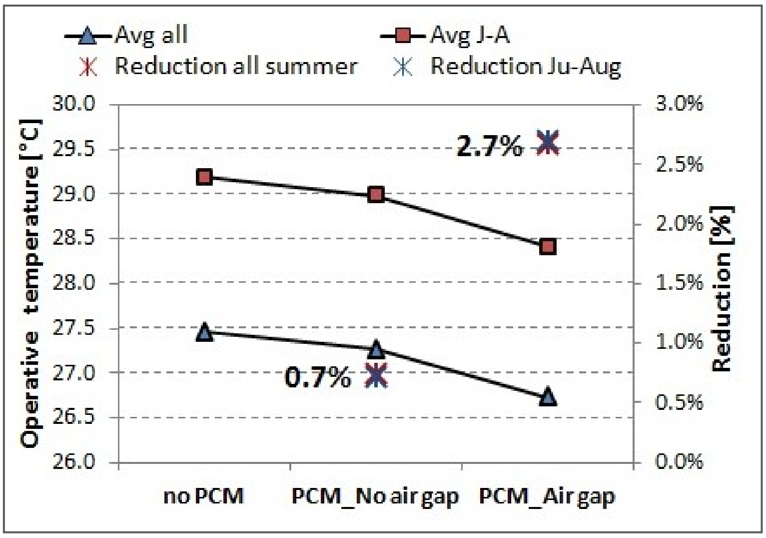

Fig. 47 Frequency of the mean operative temperature.

The lower operative temperatures correspond to the enhancement of the thermal comfort conditions, in fact a larger percentage of the operative temperature falls within the limits of the comfort categories.
The mere application of the PCM improves the thermal comfort conditions by only 5% both for all the summer season and for the hottest months; while the new system (air gap) leads to a considerable increase of the percentage of occurrence of thermal comfort conditions up to about 13.7% during all summer and 20.6% during the months of July and August.
The graphs of *Fig. 48* report the "points cloud" representing the hourly daily operative temperatures falling within the comfort limits.

As can be noticed the operative temperatures start to come down when we applied the first system (application of PCM), but better results are achieved considering the air gap system.

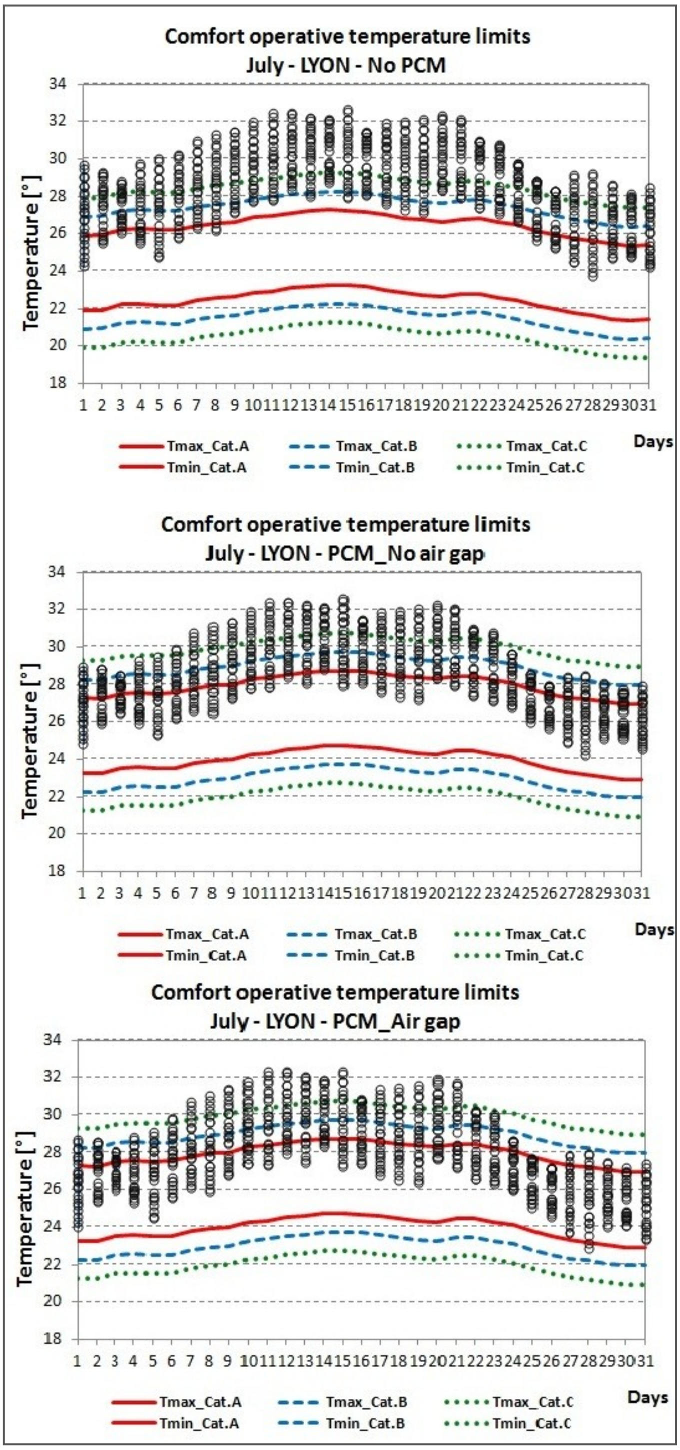

Fig. 48 Comparison of comfort operative temperature for the two application systems.

In order to evaluate and compare the total frequency of comfort we calculated the percentage of the operative temperatures falling in the most strict comfort category (cat. A) and the corresponding increase achieved by each PCM solution in the two time periods considered.

In particular, it is possible to observe that the simple application of the PCM leads to very similar results both in the entire summer season (5.7%) and in the months of July and August (5.5%). Contrariwise in the case of PCM with air gap the largest increase of the percentage of comfort occurs in the hottest months during which the increment rise up to 20.6%.

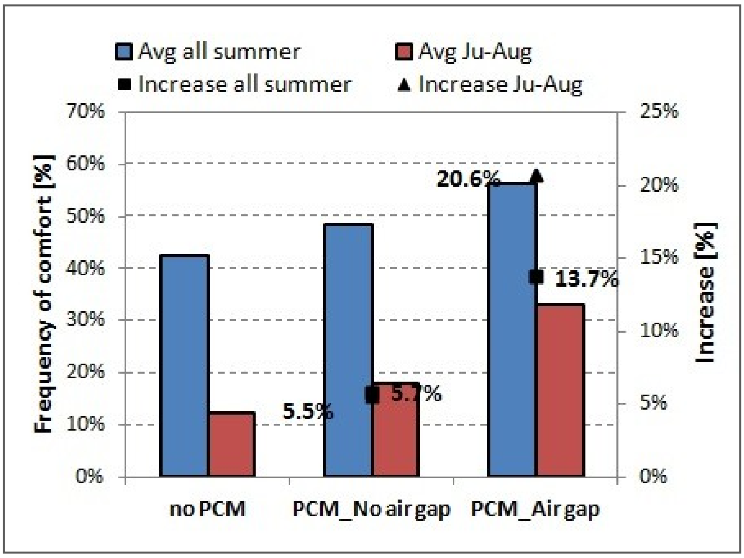

Fig. 49 Frequency and increase of thermal comfort for the two PCM solutions.

This trend could give some important information, as for instance for deciding the activation period of the air flows in the gap according to the climate conditions.

Considering the frequency of activation we can notice that the percentage of time during which the PCM is "activated" is almost equal to 60% while the PCM temperatures falling below or above the boundary temperatures are just over 20%.

The *Fig. 50* shows a different behavior of the east wall than the other internal partitions; this trend is due to the presence of the air system which causes a considerable reduction of the surface temperature of the wall.

The delimited ventilation process produces on the one hand a good improvement of the regeneration of the material increasing its effectiveness on the indoor thermal comfort, while on the other hand, it causes a larger frequency of surface temperatures below the melting temperature.

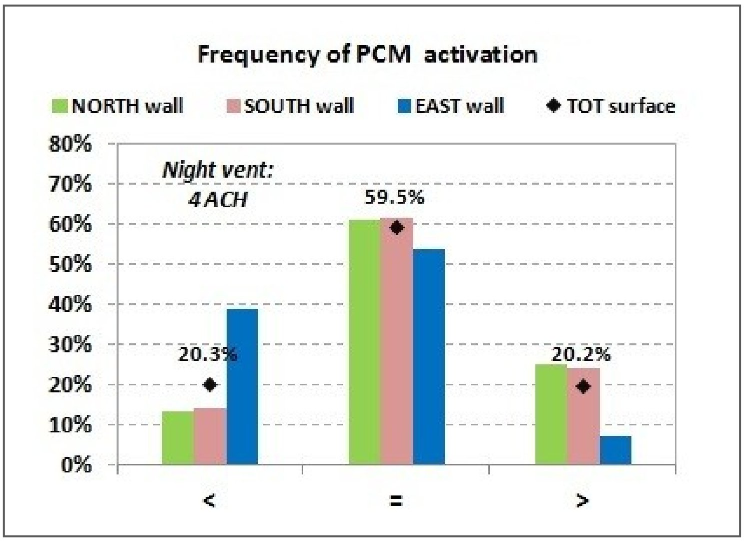

Fig. 50 Frequency of PCM activation in the case with air gap.

Comparing results of frequency of activation for both cases (PCM without/with air gap) it is interesting to observe that there is a very little difference between the two systems during the entire summer season but , considering the hottest months, the second system shows a widest gap than the first system (*Fig. 51*).

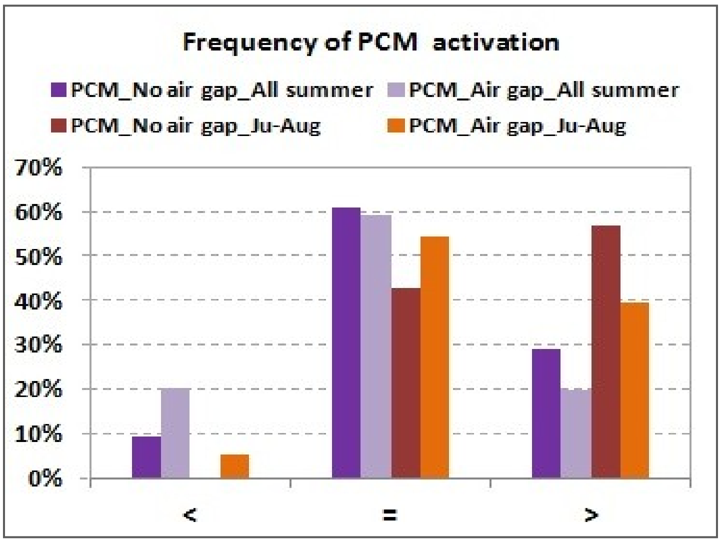

Fig. 51 Comparison of frequency of activation for the two cases and periods.

So we can deduce that, even though the two solutions achieve very similar results in terms of material's activation during all summer, the air gap system allows a better performance of the PCM during the most disadvantageous period.

The previous considerations are noticeable by looking at the graph in *Fig. 52*.

The PCM with the air gap system ensures better results than the first case and particularly the percentage mostly rises during the hottest period during which the increase is almost 18% more than the case without air gap.

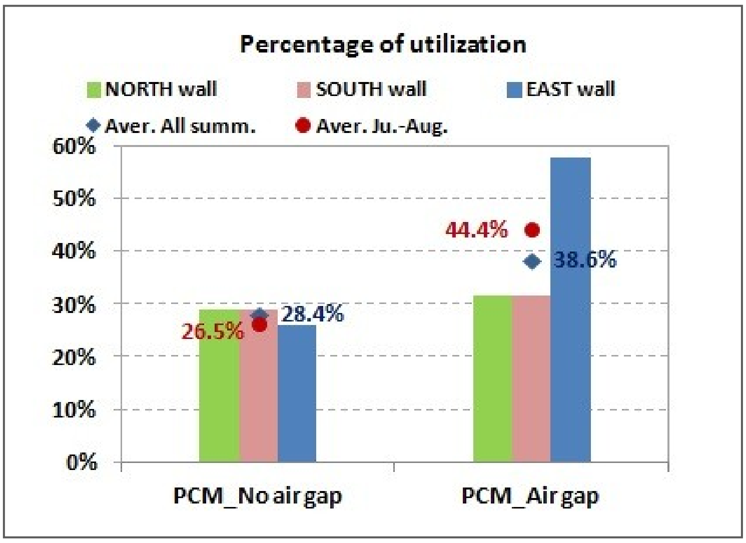

Fig. 52 Comparison of percentage of PCM utilization for the two cases.

9. Case b

9.1. Base case

In order to test the effectiveness of the PCMs we proposed to apply them in different climatic conditions. In particular we considered a city of the Mediterranean area such as Catania.

Before assessing the effect of phase change materials in these new climatic conditions we carried out some preliminary simulations in order to evaluate the thermal behavior of the building without applying any passive system but considering only the current state and varying the ventilation rate.

Thanks to these simulations we could assess the building performance according to the new weather conditions and specially determine the phase change material most proper for this different case.

Firstly we investigated the trend of temperatures during a brief summer period (from 2nd to 6th of July). As shown in the *Fig. 53* the temperature fluctuations are included within the range from about 30°C to 34°C. The external temperature reaches very high values affecting considerably the other kinds of indoor temperature.

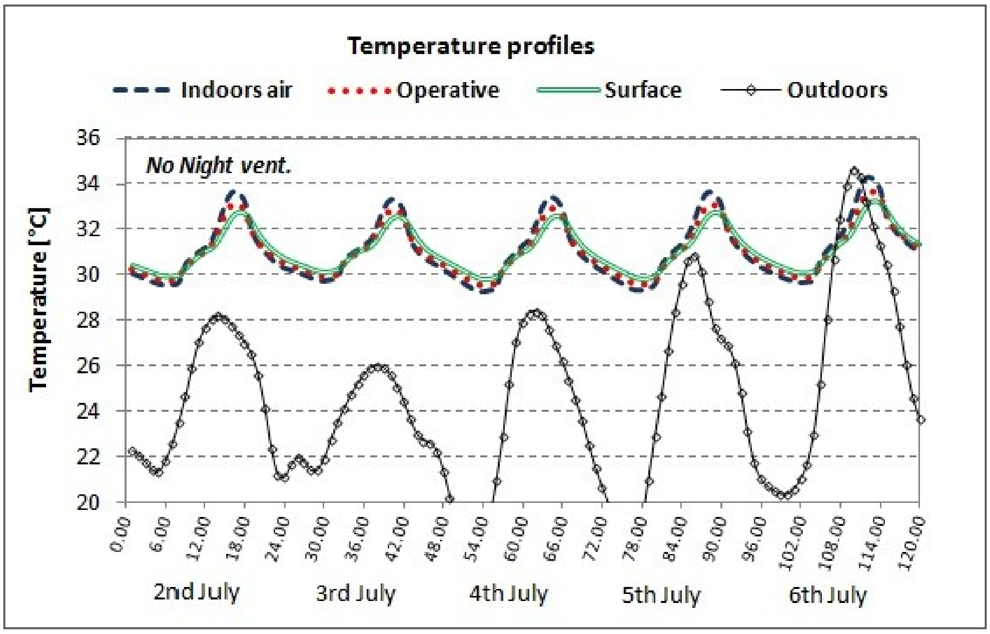

Fig. 53 Fluctuations of temperatures with no night ventilation during a summer period (2nd-6th of July) in the case b.

The same assessments are carried out increasing the night ventilation rate. The results show a small reduction of the temperature curves but it is not sufficient to ensure good indoor thermal conditions for the occupancy.

Nevertheless, the increment of the night ventilation rate causes a higher temperature swing as the reduction of the minimum and maximum values occurs differently. The reduction of temperature is more noticeable during the nighttime but it even occurs during the daytime increasing the possibility of discomfort sensation.

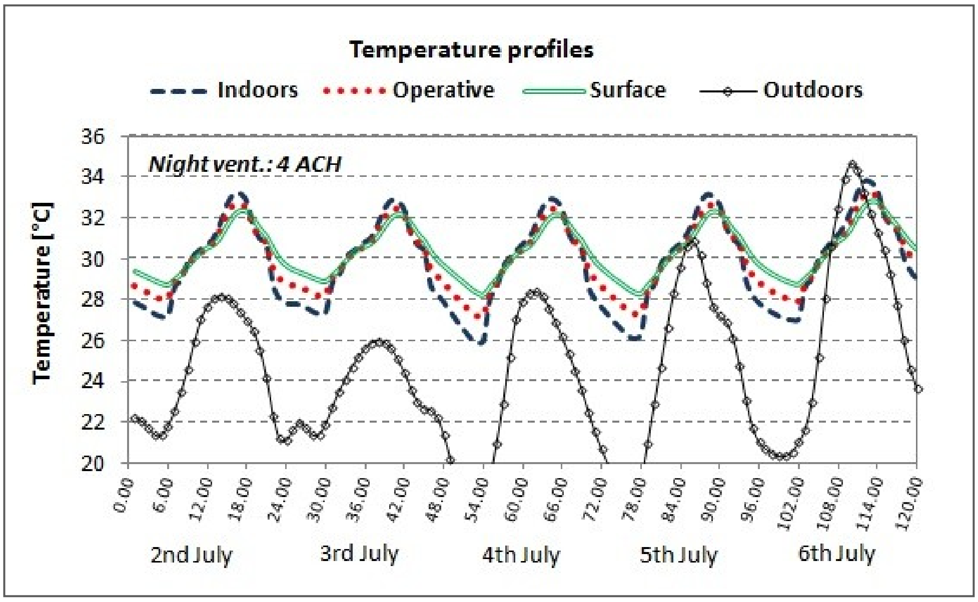

Fig. 54 Fluctuations of temperatures with 4 ACH by night during a summer period (2nd-6th of July) in the case b.

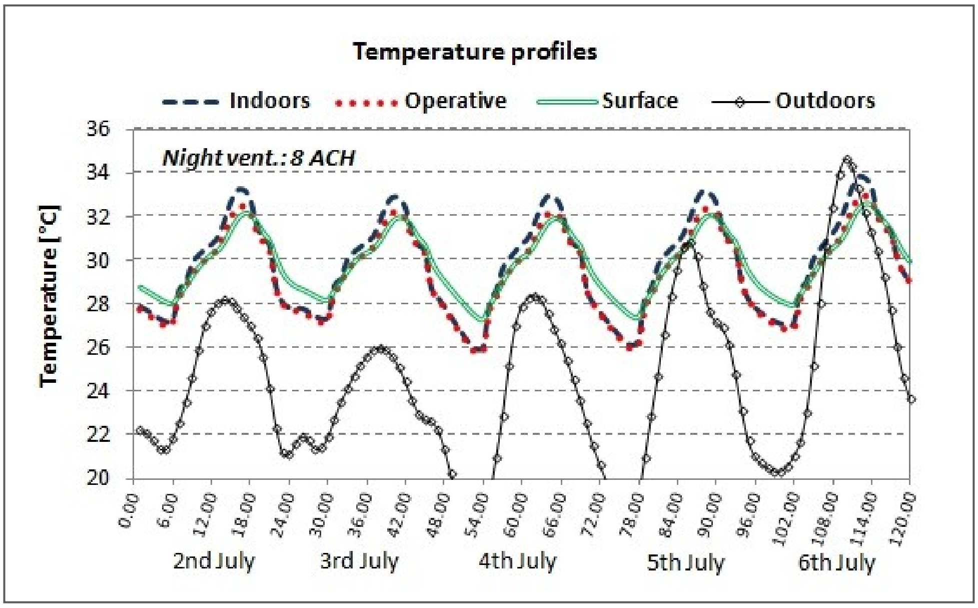

Fig. 55 Fluctuations of temperatures with 8 ACH by night during a summer period (2nd-6th of July) in the case b.

After assessing the temperature profiles in a longer period, we focused on the thermal behavior of the test room during a typical summer day (4th of July).

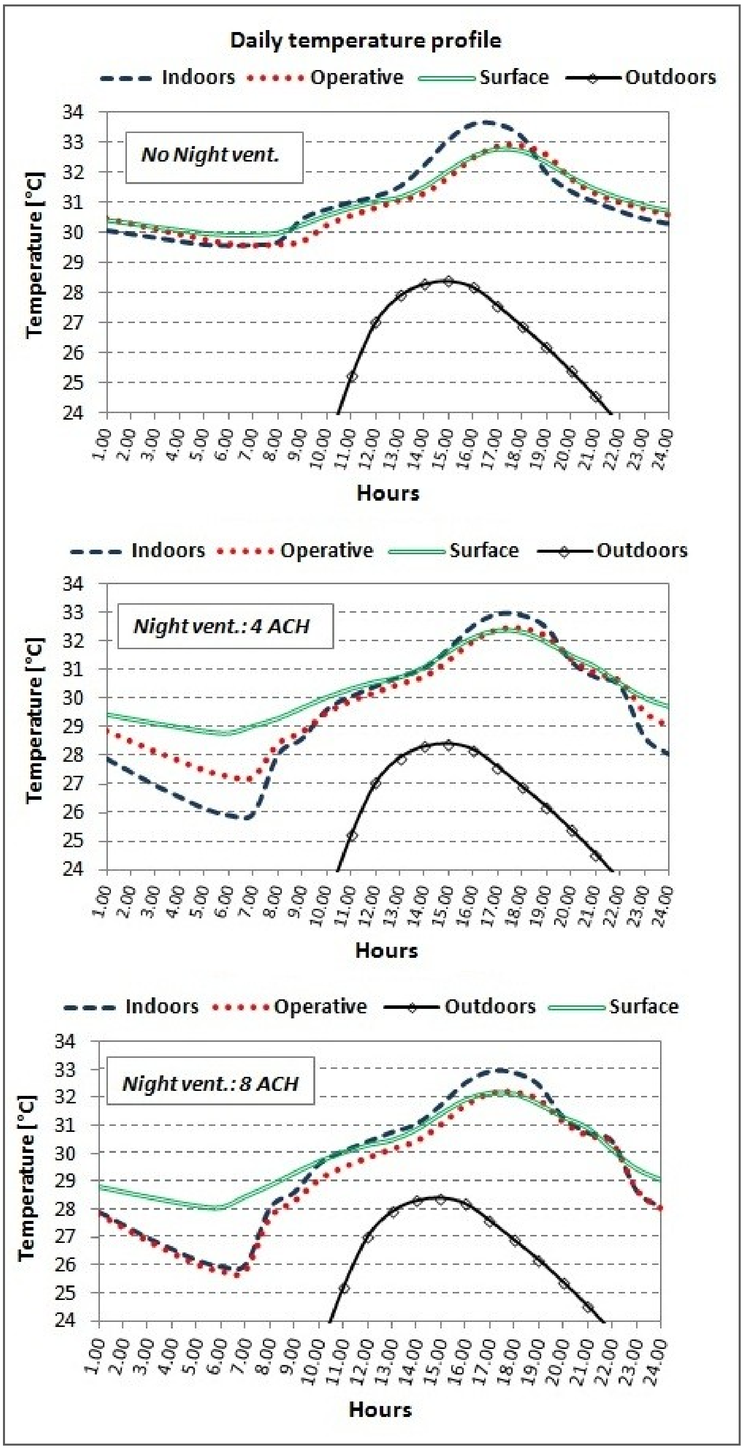

Fig. 56 Temperature profiles for a typical summer day (4th of July) in the case b.

The *Fig. 56* shows the influence of the night ventilation on the operative temperature which reduces considerably its values during the night period; but this effect doesn't last during the daytime when the temperature starts again to increase significantly until the ventilation is activated again (at 21:00).

Contrariwise the peak temperature, that occurs at about 18:00, reduces by less than 1°C.

As in the previous case, for the evaluation of the frequency of comfort we took into account the temperatures occurring in the time interval from 08:00 a.m. to 08:00 p.m. (time occupancy of the building) and then we calculated the percentage included in the comfort categories.

For instance, in the month of July the absence of the night ventilation system (*Fig. 57*) implies that all the operative temperatures fall above the maximum upper limit.

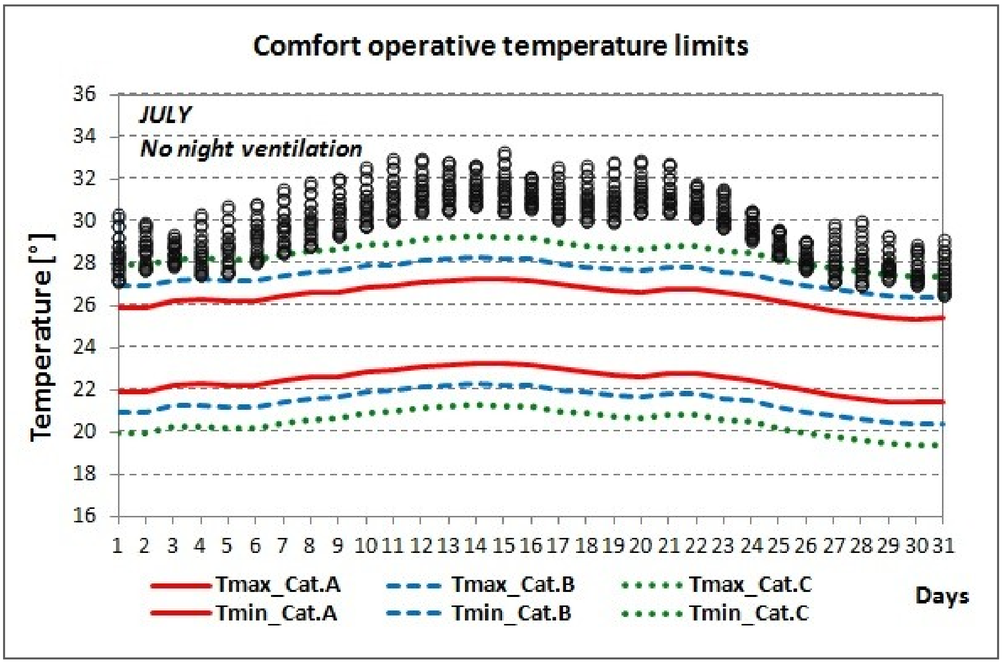

Fig. 57 Comfort temperatures falling within the comfort limits of Catania in the time interval from 8:00 a.m. to 8:00 p.m. and without night ventilation.

The activation of 4 air changes per hour leads to a reduction of the operative temperature closer to the comfort limits, but best results can be achieved only introducing the maximum ventilation rate (*Fig. 58-Fig. 59*).

So as we already observed, the increment of frequency of comfort is proportional to the increment of the ventilation rate.

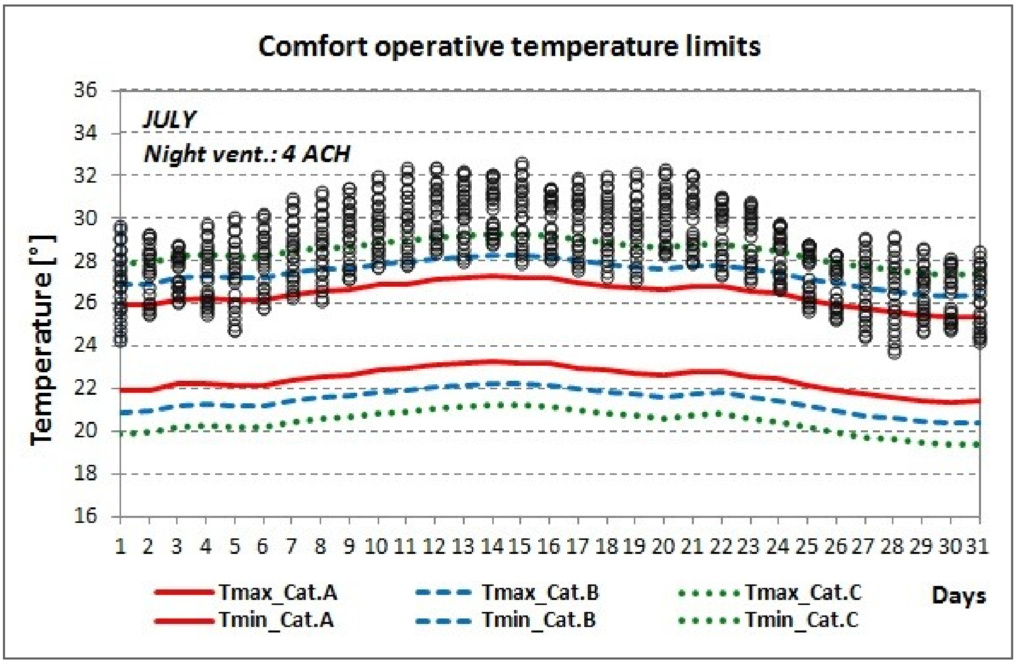

Fig. 58 Comfort temperatures falling within the comfort limits of Catania in the time interval from 8:00 a.m. to 8:00 p.m. and with 4 ACH by night.

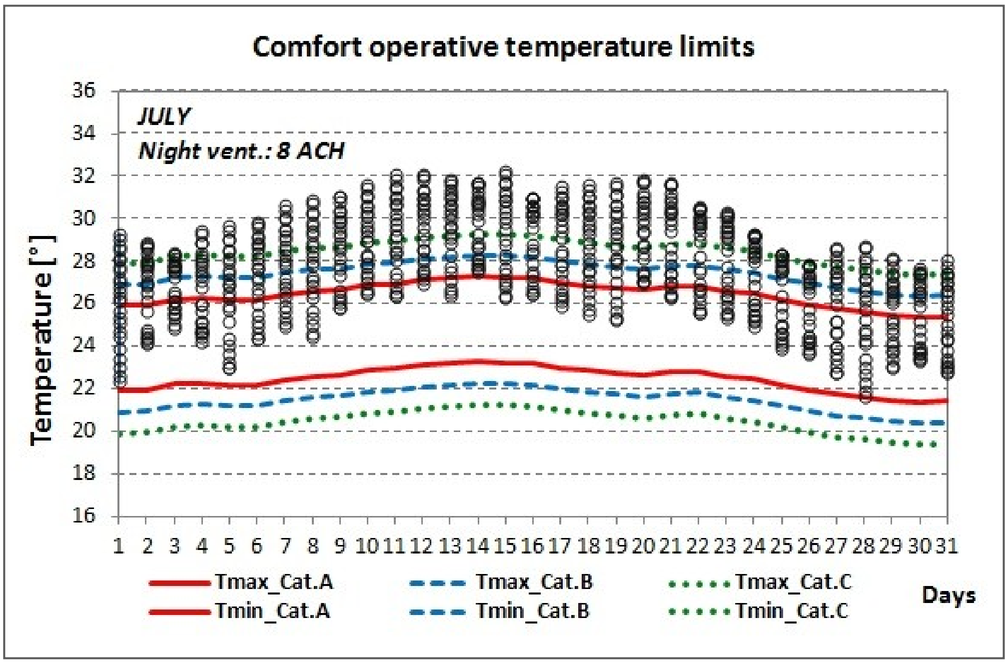

Fig. 59 Comfort temperatures falling within the comfort limits of Catania in the time interval from 8:00 a.m. to 8:00 p.m. and with 8 ACH by night.

Analyzing both the trend of the operative temperatures and the frequency of comfort for the whole summer period we can notice that, even though the temperature fluctuations vary considerably from the nighttime to the daytime, the intensity of discomfort decreases if a night ventilation system is activated.

The *Fig. 60* summarizes the increase of the frequency of comfort and the reduction of the average maximum operative temperature during all summer period according to the increase of the night air changes per hour.

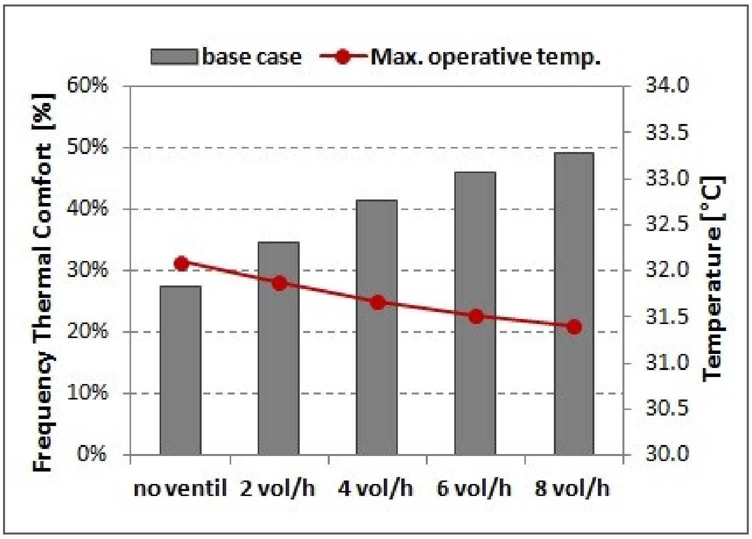

Fig. 60 Trend of frequency of thermal comfort and average maximum temperature in the base case b.

This previous assessment of the building model without the application of the phase change materials allows us to evaluate the thermal behavior of the building in its present condition but above of all it enables us to select the suitable PCM to be used for this case.

First of all we have to state that the selection of the proper phase change materials for a specific climate area is still a difficult issue. The choice of the adequate PCM properties, in particular the melting temperature, can be made only by measurements and experimental tests.

Anyway, as in the present case we hadn't the possibility of performing experimental studies such as the ones described in the § 6.1.1.-6.1.2., we decided to select the PCM melting temperature on the basis of simulations results. In specific we considered the occurrence of the surface temperatures during all summer period.

As shown in the graph of *Fig. 61* the months of July and August affect greatly the occurrence of the surface temperatures. Thus the seasonal average temperature falls within the ranges 31°-32°C and 32°-33°C and so T=32°C represents the most occurring temperature.

So we considered T=32°C as melting temperature even though a too high value could lead to problems in PCM regeneration process and so reduce its effectiveness. Anyhow, the investigation of the chemical properties and process within the phase change material is not included in the context of this work and so, for the evaluation of its thermal behaviour, we only considered the results provided by the simulation tool EnergyPlus.

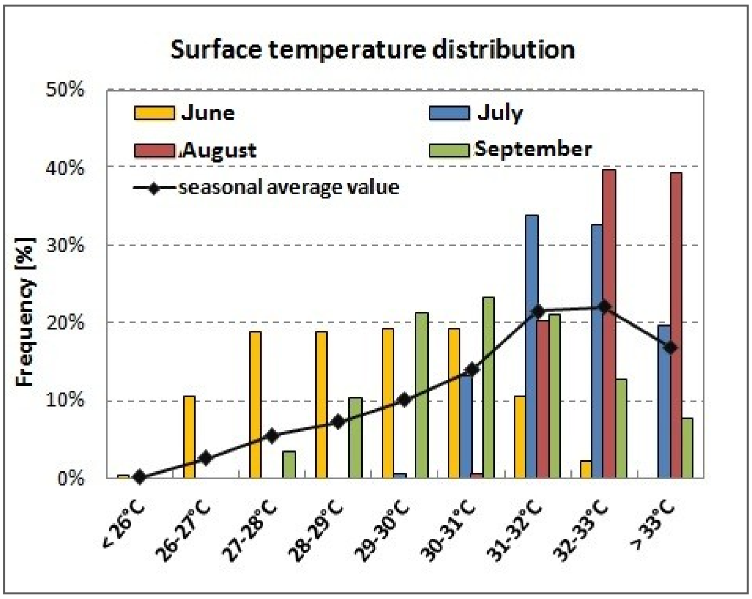

Fig. 61 Frequency of the surface temperature during the summer season.

Once chosen the melting temperature, we could define the behaviour of this "new" PCM by calculating the specific heat according the equations (19) and (20) developed in the context of the preliminary activities by using the inverse method.

The other parameters of the PCM panel such as the thickness, the thermal conductivity, the density and the roughness, are maintained constant as previously defined (see § 6.2, *Fig. 19*.).

As we expected, the heat specific curve of the new PCM (we defined it PCM_32) has a similar trend than the previous material (PCM with melting temperature 27.5°C) but, in these new operating conditions, the Cp profile is shifted to higher values of temperature (*Fig. 62*).

Consequently also the phase change range shifts towards higher values and it is included between the temperature of 27° C and 33° C. This interval also represents the temperature range that we considered for the calculation of the parametr "Frequency of Activation" in the present case.

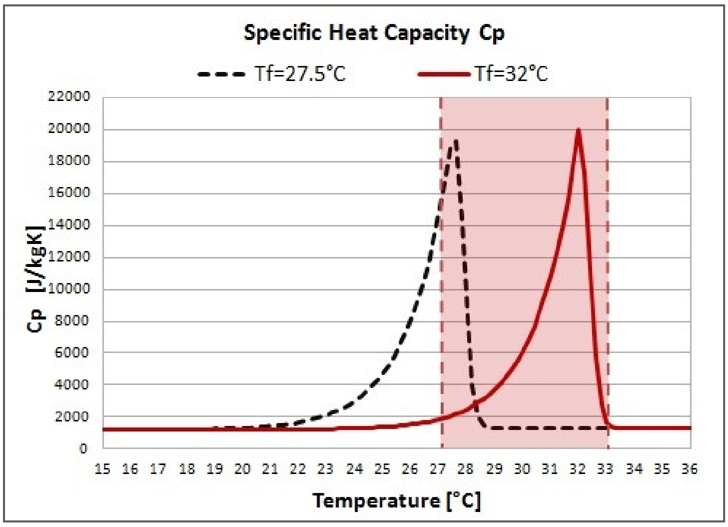

Fig. 62 Cp function of PCM_32.

After performing these first evaluations, we calculated again the values describing the h(T) function in order to introduce them as inputs in the specific schede of EnergyPlus (*Fig. 20*). Thus we started the simulations.

Similarly to the previous case we considered two cases:

- *case b.1.*
- *case b.2.*

The first deals with the solution 1 of PCM application, i.e. the apposition of the panels on the inner surface of all interior partitions of the test room; the second case considers the system consisting of a ventilated air gap between the interior partition (only the east wall) and the PCM panel.

In order to evaluate the results we followed the same steps of the previous cases (a.1. and a.2.) by calculating the same physical parameters and comfort indicators. At last we compared the results.

9.2. Results of case b.1

Looking at the physical parameters in a summer day, we can notice that a good reduction of the operative temperature begins to be evident with a 4 air changes per hour and it increases with a higher ventilation rate. At 8 ACH the maximum operative temperature drops from 32.5 °C to 31.7 °C and to 31.4 °C respectively in the case of 2 cm and 4 cm PCM panel (*Fig. 63*).

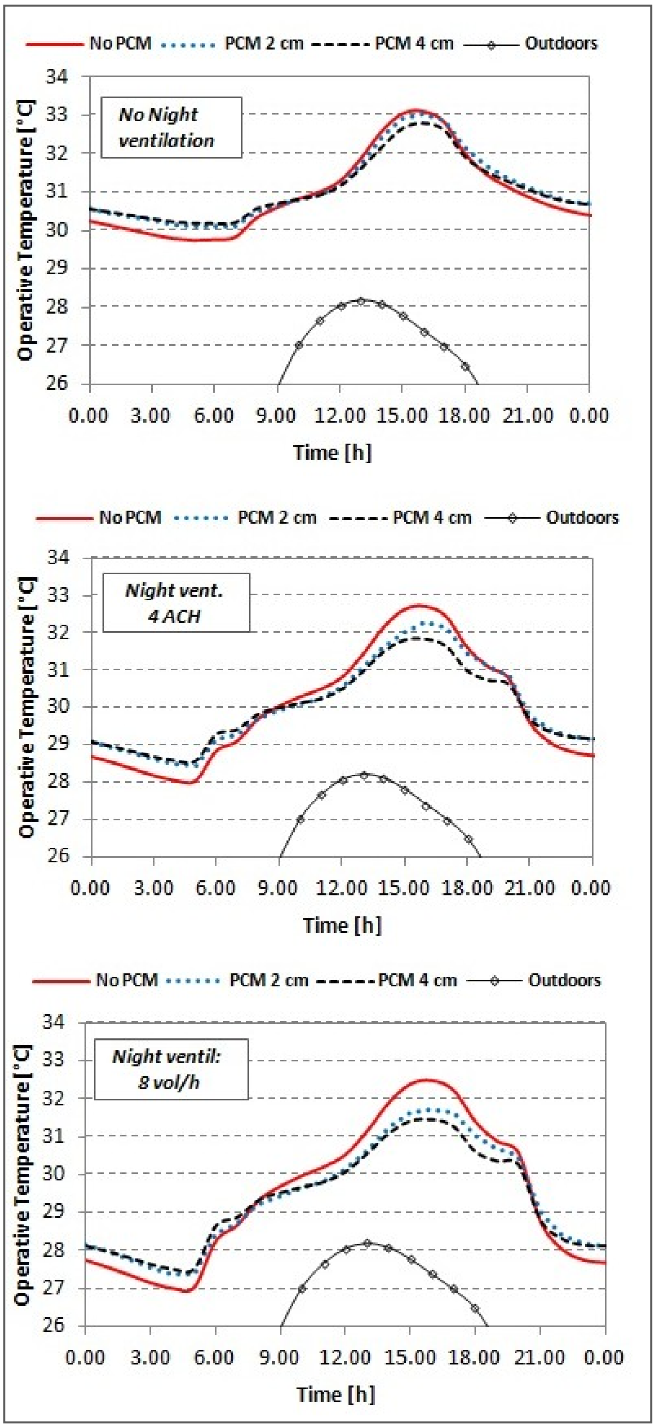

Fig. 63 Operative temperature's trends for a typical summer day.

The trend of temperature is very similar to the one shown in the case a but, as it is obvious, the functions stand at higher values of temperature because of the hottest climatic conditions of this locality (Catania).
Furthermore, the application of the PCM panels allows a considerable decrease of the temperature's fluctuation: in the case with a medium intensity of ventilation (4 ACH) the operative temperature's amplitude decreases by 1 °C (2 cm PCM) and by 1.5 °C (4 cm PCM), while in the case with the highest ventilation rate (8 ACH) it drops respectively by 1.2 °C and 1.8 °C.
The mean daily operative temperature is reduced considerably and the reduction of the maximum operative temperatures occurs largely.

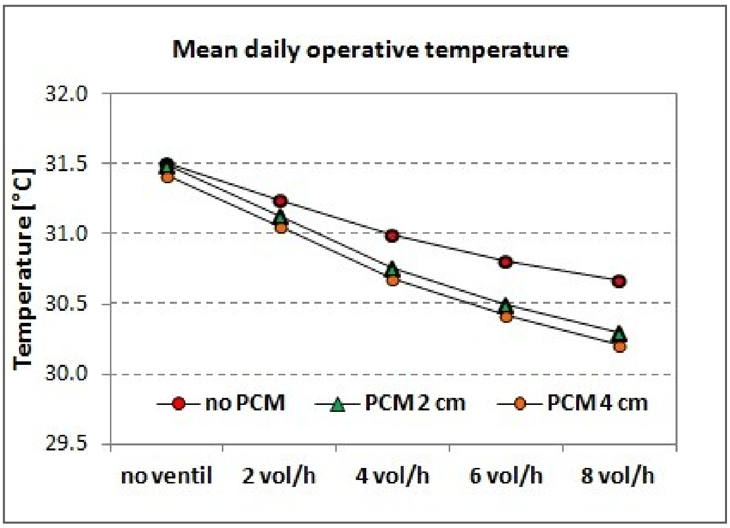

Fig. 64 Mean daily operative temperature of the summer season.

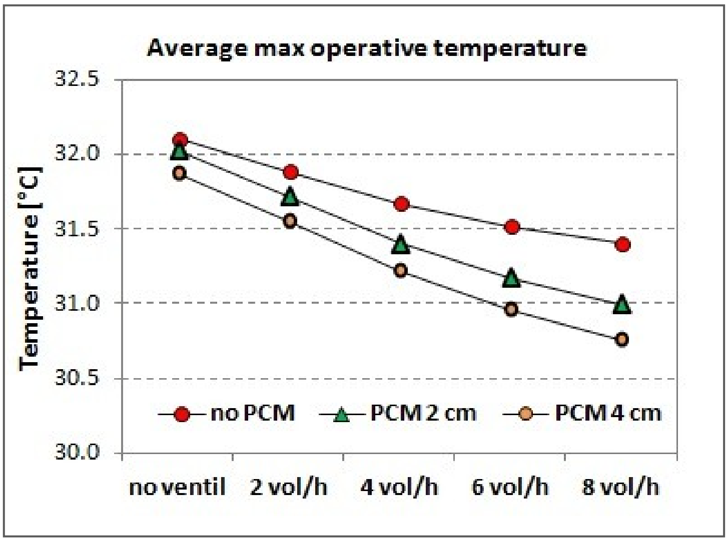

Fig. 65 Average maximum operative temperature of the summer season.

The graphs of *Fig. 64- Fig. 65* show a different influence on temperature of the two thicknesses of panel: in the first graph concerning the mean daily operative temperature there isn't any meaningful difference between the 2 cm or 4 cm panel, while in the second the gap is greater. However this difference is not so significant to affect differently the efficacy of the two typologies of panel.

Consequently an increase of the frequency of comfort happens.

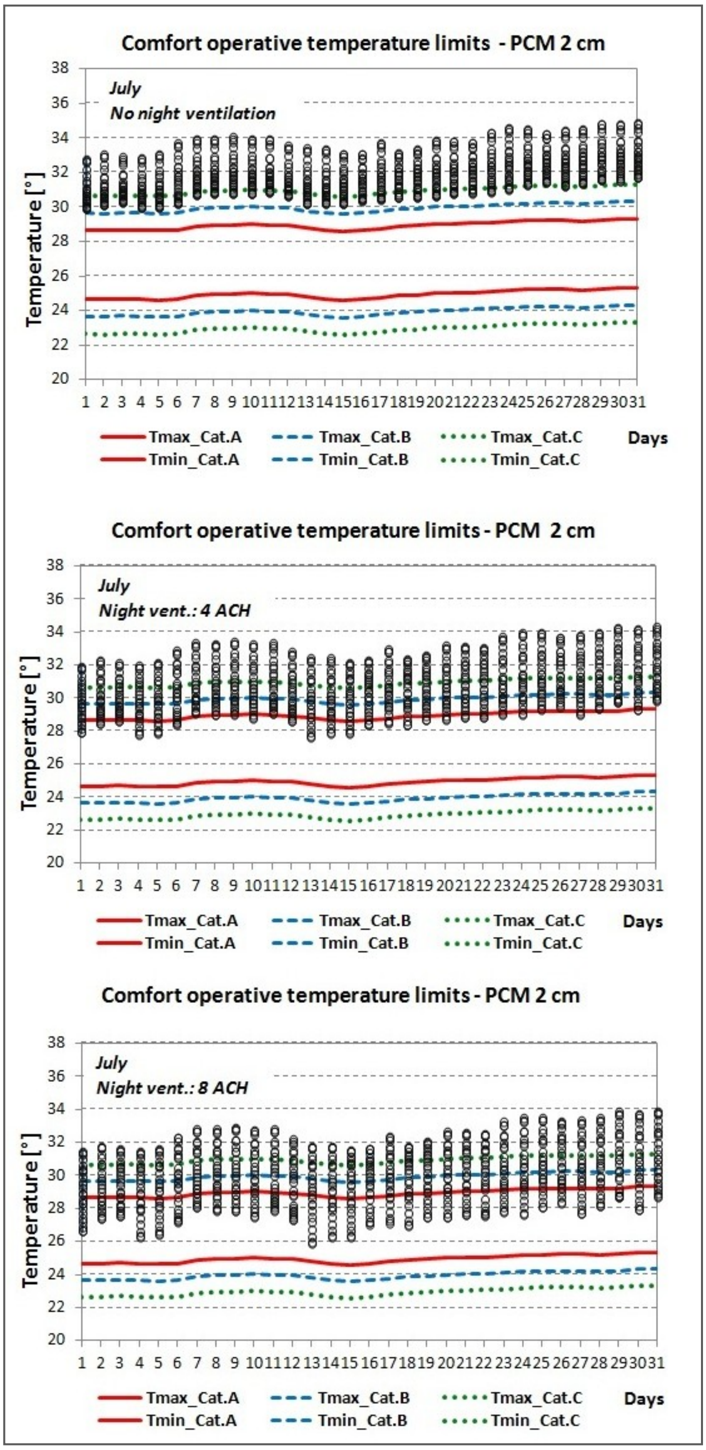

Fig. 66 Frequency of comfort operative temperatures by using 2 cm PCM panel in the case a.2.

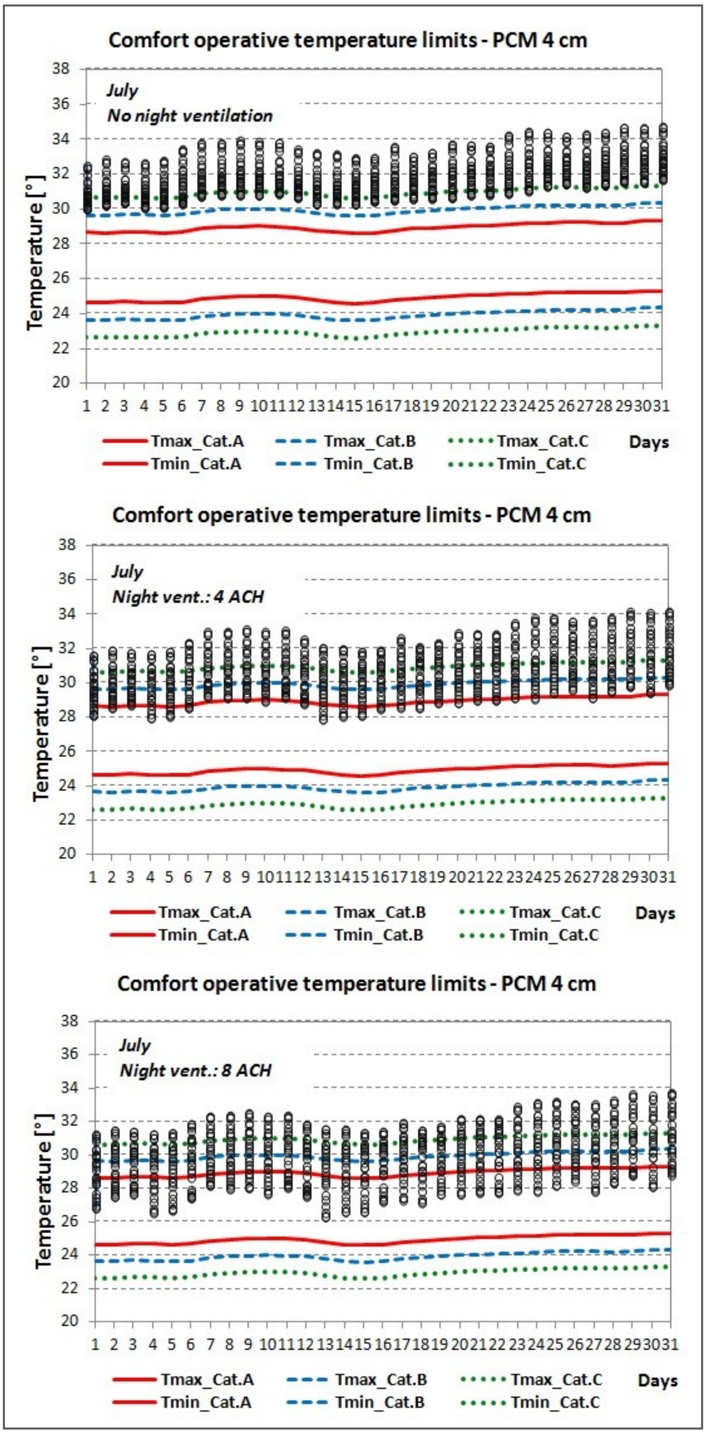

Fig. 67 Frequency of comfort operative temperatures by using 4 cm PCM panel in the case a.1.

The graphs included in *Fig. 67* show the lowering of the point clouds towards the comfort categories for the two typologies of PCM.

At first sight there are no evident differences on the frequency of comfort by using the 2 cm or 4 cm thick panel; only looking at the numerical values we can note a slight difference but it becomes more noticeable only for higher rates of ventilation.

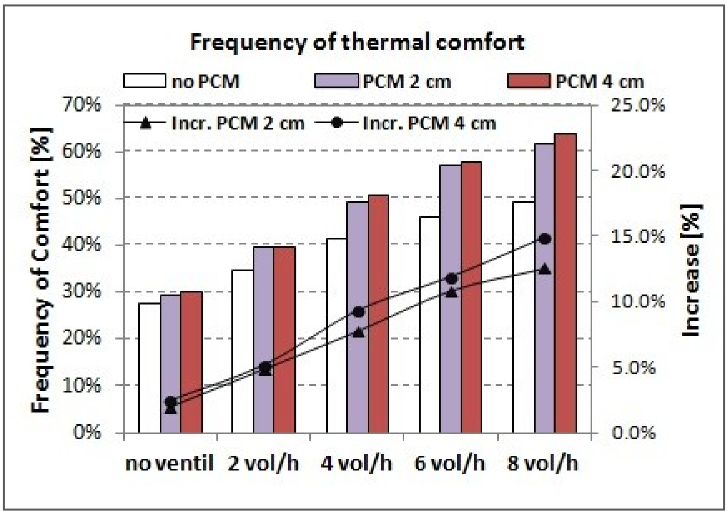

Fig. 68 Percentage of thermal comfort within the three categories (A,B,C).

Considering a largest comfort range the indoor thermal comfort is achieved in the 50% of time if a medium night ventilation rate is activated (4 ACH) and in more than 60% of time with the maximum ventilation level (8 ACH). As shown previously, the effect of the two different panels is very similar; the gap starts to be evident with the increasing of the ventilation rate, although the difference between the 2 cm and 4 cm panel is very low.

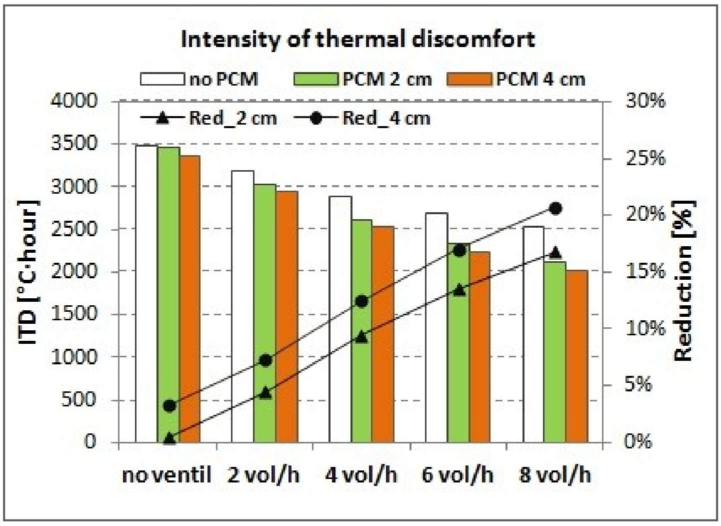

Fig. 69 Intensity of discomfort in the case b.1.

Consequently, the intensity of discomfort is reduced; in fact the discomfort intensity drops by about 12% with a medium ventilation rate and by more than 20% with 8 air changes per hour. (*Fig. 69*).
As we already remarked previously, the thermal behaviour of the PCM is not so dependent on the thickness of the panel; looking at the green and orange columns the gap between the two typologies is constant at about 5% according to each intensity of ventilation.

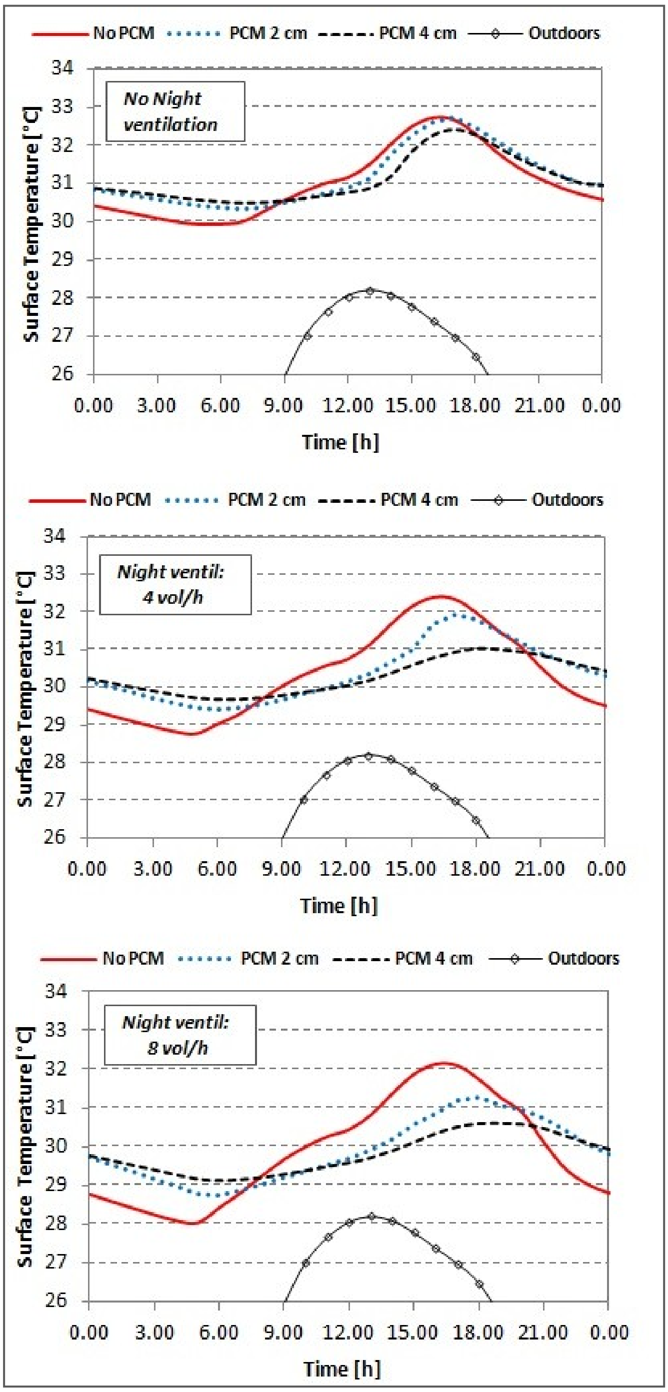

Fig. 70 Surface temperature for a typical summer day in the case b.1.

Similar results regard the trend of the surface temperature.

Considering a typical summer day, the application of the PCMs produces a decrease of the maximum temperature by 0.4 °C and 1°C by using respectively the 2 cm and 4 cm panel. Also the temperature swing is reduced considerably going from 4.1 °C (base case) to 2.7 °C (case with 2 cm panel) and 1.5 °C (case with 4 cm panel). As shown in the *Fig. 70* the higher the ventilation rate the higher the temperature's swing reduction.

In order to assess the efficacy of the phase change material in these new climate conditions we have to evaluated the "Frequency of Activation". This indicator highlights a too high percentage of material "activated" during all day both for 2 cm and 4 cm PCM; it means that almost the time the material is characterized by temperatures falling within the phase change range (*Fig. 71-Fig. 72*).

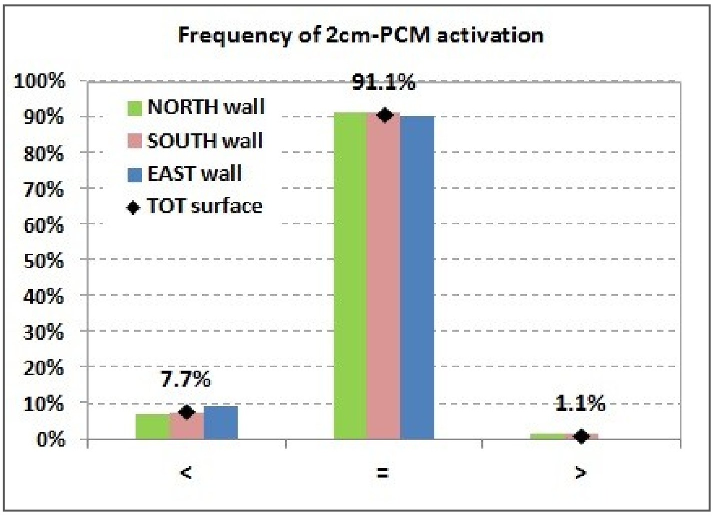

Fig. 71 Frequency of activation of the 2 cm PCM panel.

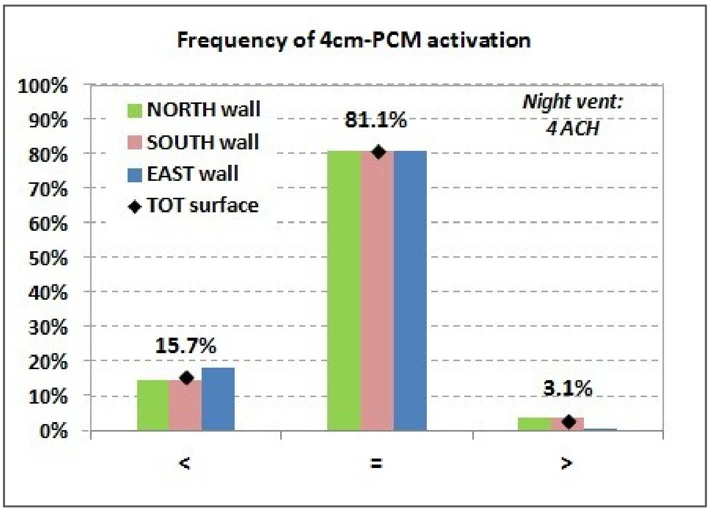

Fig. 72 Frequency of activation of the 4 cm PCM panel.

Besides, focusing the attention only on the night period, during which the material undergoes the cooling phase, the percentage of material remaining in the liquid phase drops to zero. It means that the night ventilation system is effective in order to reduce the material's temperature and enables a larger regeneration of material.

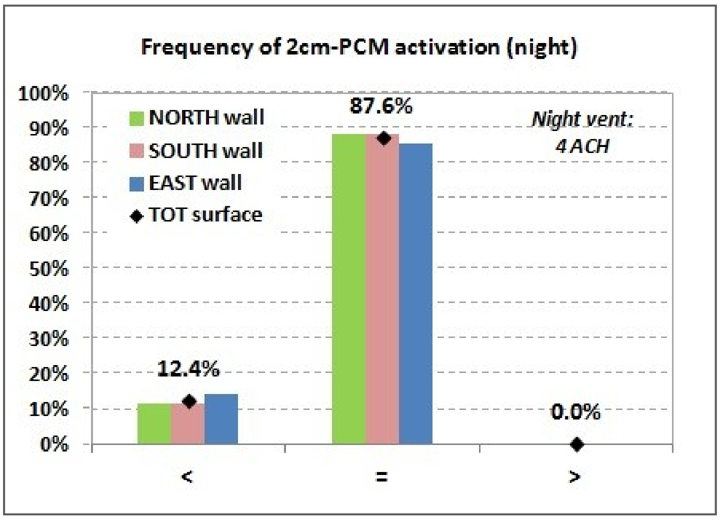

Fig. 73 Frequency of activation of the 2 cm panel during the night (9:00 p.m.-6:00 a.m.).

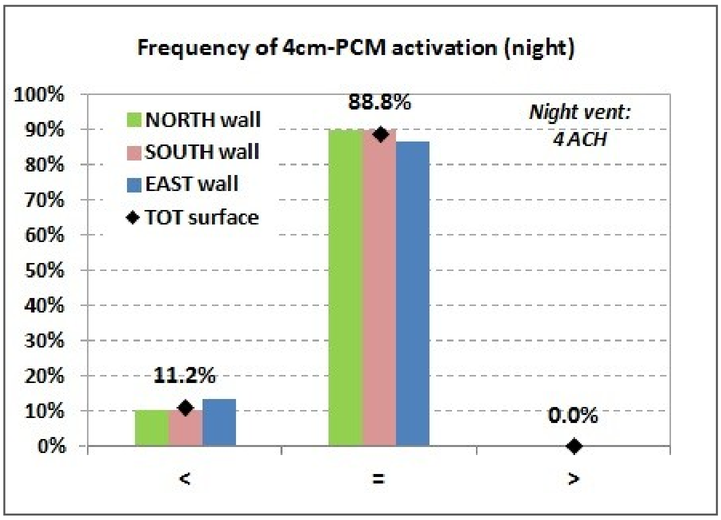

Fig. 74 Frequency of activation of the 4 cm PCM panel during the night (9:00 p.m.- 6:00 a.m.).

Further considerations have to be expressed concerning these results: if a more effective night cooling system is made, it can get better results on regeneration of the material. To this aim we also assessed the second PCM solution for building application , i.e. the "air gap system".

The results of simulations are reported in the follow paragraph.

9.3. Results of case b.2.

The case b.2. takes into account the realization of the air gap between the PCM panel and the east interior wall.

Looking at the graph of the operative temperature and comparing the trend of different cases the improvement achieved by applying this system is quite noticeable. The peak of operative temperature of the solution 2 (PCM_air gap) decreases by 1.4°C than the base case and about 1°C than the case with only PCM. Moreover the amplitude of fluctuation is significantly lower, going from 5.5°C (case No PCM) to 4.5°C (case with PCM but no air gap) and to 3.5°C in the last case (*Fig. 75*).

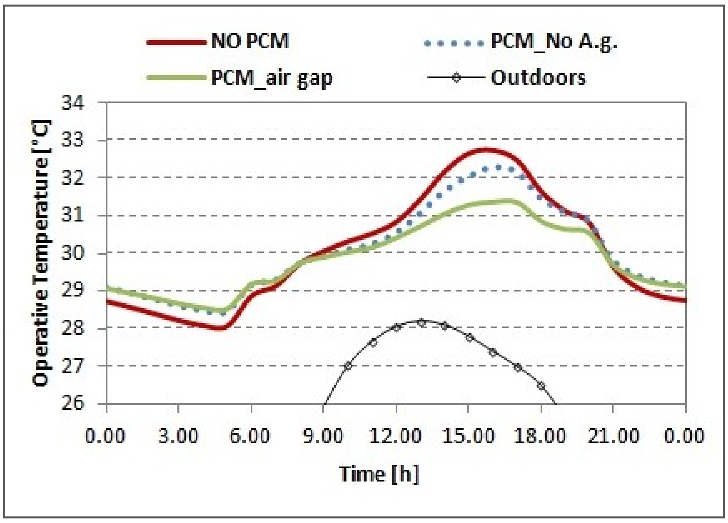

Fig. 75 Comparison of the operative temperature's profiles in the case b.2.

The curves of the operative temperature show in advance the improvement that the combined system "PCM-air gap" can bring to the thermal comfort inside the room. As it is obvious lowest operative temperatures, specially during the daytime, correspond to a lowering in sensation of thermal discomfort of a person placed in a room.

This noticeable consideration is confirmed by evaluating the specific comfort indicators. Comparing the intensity of discomfort of the case b.1. and b.2. we can notice a good reduction of the discomfort intensity thanks to the air gap system which allows a reduction two times more than the case with simple application of PCM (*Fig. 76*).

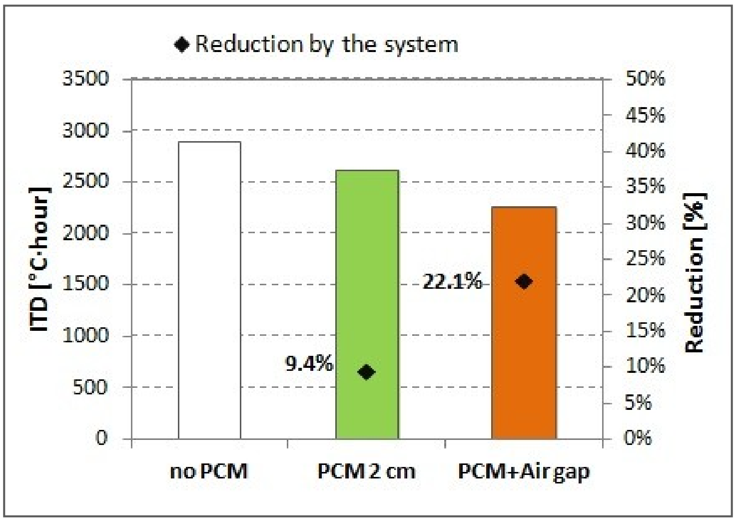

Fig. 76 Comparison of the operative temperature's profiles in the case b.2.

Similar results are shown in the *Fig. 77* concerning the Frequency of Comfort.

The use of the air gap system determines an increase in the occurrence of thermal comfort temperatures. The thermal comfort conditions are satisfied in more than 50% during the summer season. However the increase of the frequency of comfort is not so significant as the reduction of the intensity of discomfort previously assessed. This means that, even though we can reduce considerably the temperatures exceeding the upper comfort limit by applying the PCM system (with or without air gap), the operative temperatures remain quite higher.

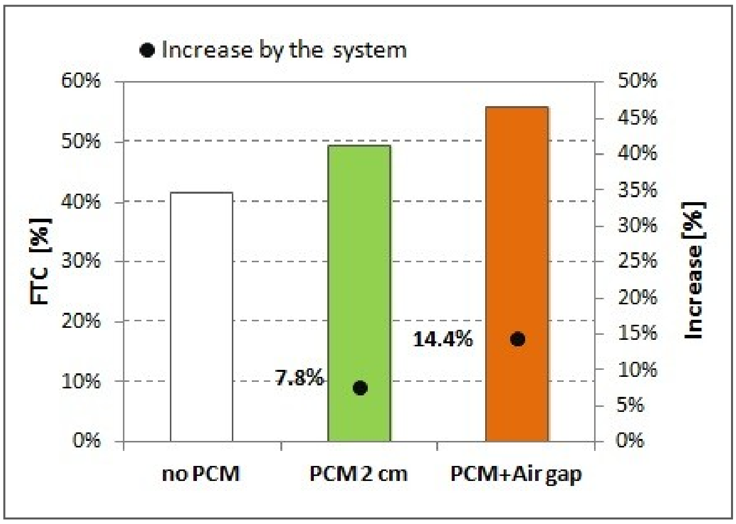

Fig. 77 Comparison of the Frequency of comfort and its increase of the cases b.1. and b.2.

Anyway the results achieved till now are quite satisfactory to state the efficacy of this system for the thermal comfort purpose.
As we expected concerning the frequency of activation the air gap system implies a greater cooling of the material during the night period due to the air stream concentrated on the PCM panel. The percentage of "activated" material is high both during all day and during the night ventilation period.

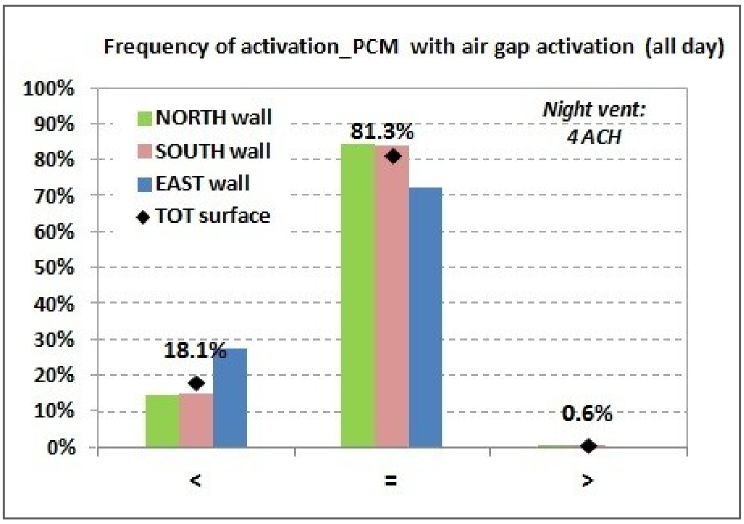

Fig. 78 Frequency of activation for the PCM with air gap during all day.

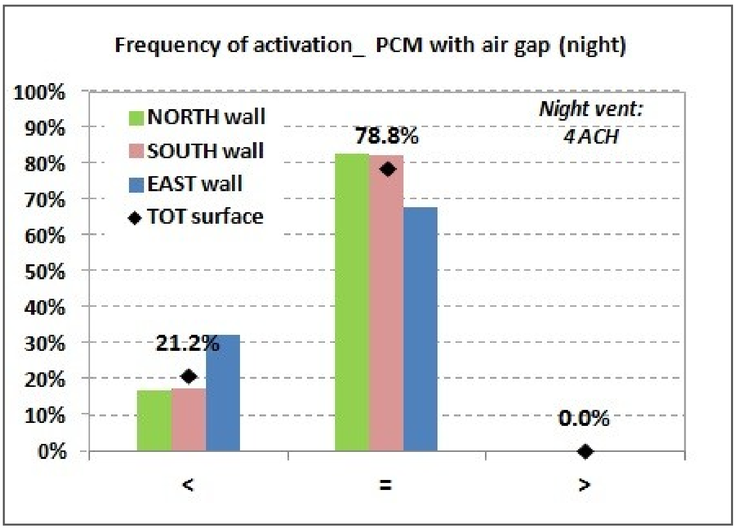

Fig. 79 Frequency of activation for the PCM with air gap during the night.

The results of the two cases b.1. and b.2. (*Fig. 80-Fig. 81*) are very similar in terms of "activation" of the material. Anyway looking more carefully at these results we can state that the air gap system represents the better solution because it further reduces the temperature of the material and allows both a greater discharge of the stored heat and so a larger quantity of regenerated material than the case b.1.

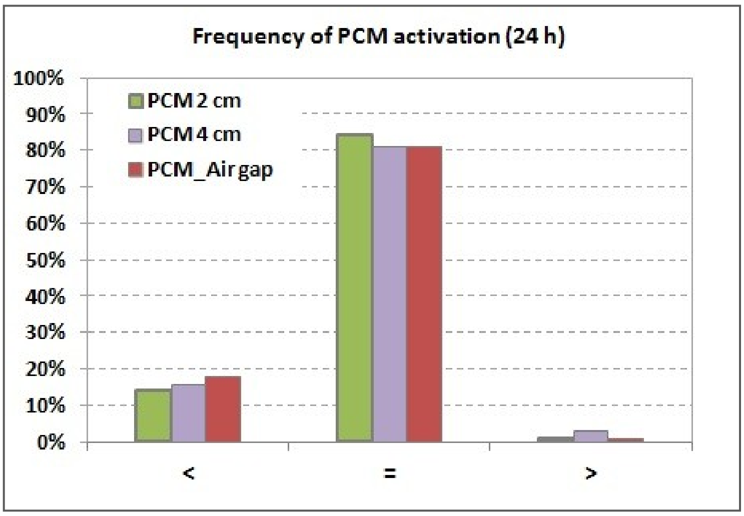

Fig. 80 Comparison of the frequency of activation for different solutions during all day.

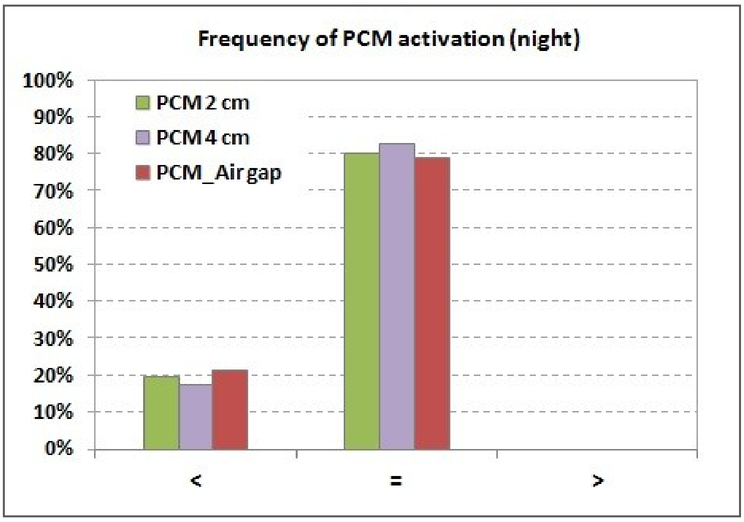

Fig. 81 Comparison of the frequency of activation for different solutions during the night.

Conclusions

The present research work allowed us to demonstrate the efficacy of the PCMs on thermal and energy performance of the building. In particular they are very helpful for enhancing the summer indoor thermal comfort in lightweight buildings and reducing the energy consumption for cooling demand.

In the case of refurbishment of existing buildings the application of the PCM panels is very advantageous because they allow little intervention inside a building without affecting structural components.

However, as they work according a cyclic process, it is necessary to assist their regeneration phase (from liquid to solid phase) by including a night ventilation system ensuring the discharge of the stored heat during the night.

The ventilation can be achieved by a main mechanical ventilation plant which introduces air flows in the overall room or in a particular constructional element such as a ventilated air gap between the PCM panel and the interior wall. Anyway, the ventilation support must be activated during the night in order to reduce the material's temperature and so improving the discharge of the stored heat by the material.

In particular, as we already demonstrated in this work for both cases *a* and *b,* the insertion of a specific device for ventilation such as the air stream on the PCM surface (air gap system) ensures better results concerning the frequency of activation and efficacy of the material.

However the application of PCMs is subjected to local climate conditions. The selection of PCMs is also essential for the successful application of free cooling techniques in buildings. The thermal improvement in a building due to the inclusion of PCMs depends firstly on the melting temperature of the PCM, the type of PCM and the climate of the building's location. In fact the selection of the PCM based on phase transition temperature for one climatic region will not be appropriate for another. So, more detailed surveys and experimental tests are necessary for the selection of the proper material in order to optimize the thermal storage in buildings in specific weather conditions.

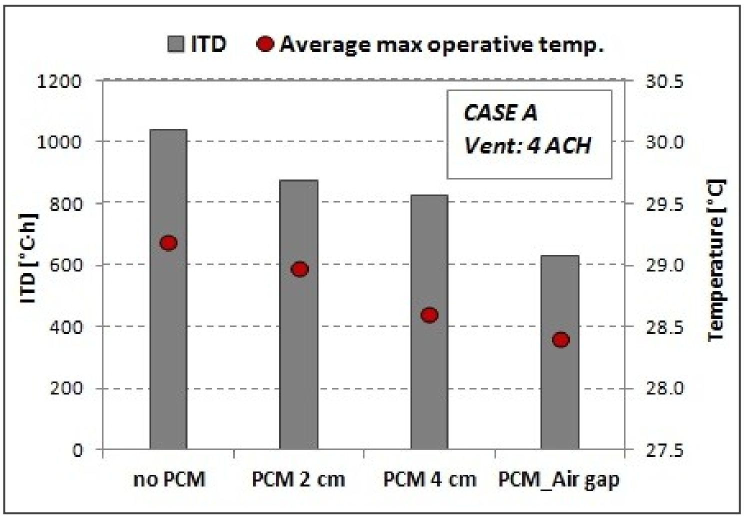

Fig. 82 Summary of the main results achieved in the case a.

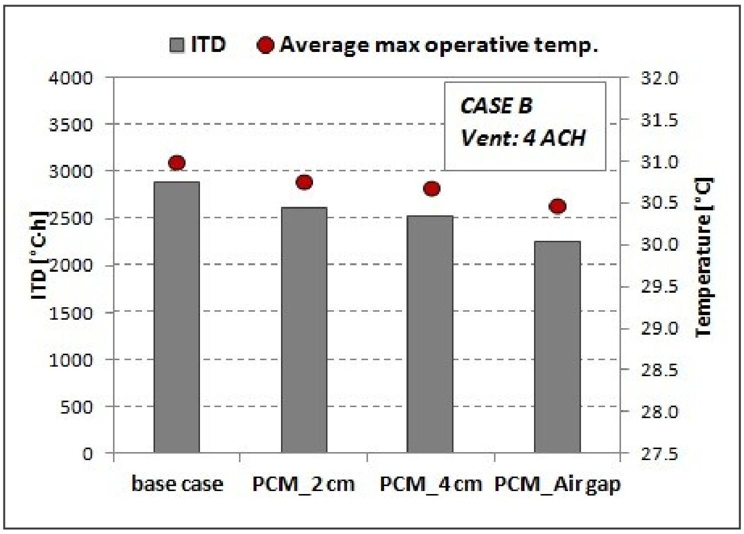

Fig. 83 Summary of the main results achieved in the case b.

This study also showed that the 2 cm thick panel works quite well. The use of a thicker PCM panel is not so effective in obtaining further improvements of the system.

In fact the improvements achieved by a panel with a larger thickness are not proportional to the increase of the amount of material used and also they are not so meaningful to compensate the additional costs.

Rather, the use of a thicker panel can easily produce an internal stratification of the material and reduce its thermal efficacy.

The optimization of all parameters above mentioned is fundamental to allow the better exploitation of the PCMs as thermal storage materials and demonstrate the possibilities of success of these means in enhancing the energy performance of the building .

Summarizing we can state that the application of the PCMs as thermal energy storage materials in buildings has several advantages:

- the increase of the indoor thermal stability by reducing the fluctuations of the indoor air temperature and wall surface temperature;
- the increase of thermal inertia of the building envelope without adding larger or voluminous building components;
- the improvement of indoor thermal comfort enhancing the frequency of temperatures occurring within the indoor thermal comfort categories;
- the realization of a flexible and simple-integrated solutions for improving the energy performance of existing buildings in the case of refurbishment ;
- the decrease of building energy consumption during the summer season by reducing the use of cooling systems;
- the integration with mechanical or electrical devices in order to improve the PCM efficacy both for cooling and for heating.

In conclusion we can state that PCMs represent very effective means to make the maximize the overall building performance and reduce the global energy consumptions.

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