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Application of passive thermal energy storage in buildings using PCM and awnings

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…to Dad, Mom, and Grannie…

for your love and support…

for everything you have done and given to me to help me get this far…

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1 Introduction and Objectives

1.1 Overview

The storage of thermal energy, or thermal energy storage (TES), is nowadays among the most studied energy saving methods and it is beginning to be applied on several fields as its scope broadens gradually thanks to R&D activities, particularly during the last decade. However, the benefits of thermal energy storage may not be so evident directly since their effects are not immediate in some cases or they are only appreciable under specific circumstances.

This is why a continental overview of the potential saved energy by means of using different TES systems in specific cases and its correspondent environmental effect in Europe has been carried out. It is desired to provide "a numerical proof" of the energy savings, the possible reduction of waste heat as well as the associated CO_2 emissions cut-down, instead of generating accurate calculations data. The results and data management have been based on a previous calculation initiative performed in Germany and following their data processing methodology.

The emphasis of this work, however, is on the use of PCM in buildings, as one of the main fields of TES application, which has been already addressed both in literature and in works similar to this one. Based on information found in those works, the use and effects of awnings in passive buildings which incorporate PCM has been analyzed experimentally, aiming to highlight the potential improvement of the energy savings and related CO_2 emissions reduction. On the other hand, the effect of adding awnings over the PCM activation is desired to be studied.

This PhD thesis consists of four chapters. Chapter one is divided in three sections. The first section is an overview of the research focus of this thesis and its structure and contents. The second section is a literature review about the potential of thermal energy storage, and about phase change materials, their generalities and application in buildings. The third section includes the objectives of the thesis.

Chapter two shows the results of the numerical potential of TES in Spain and Europe, presenting the formal model which was employed, and summarizing the main criteria, required data, and consulted data sources. Main results are expressed in terms of load reductions, energy savings, and CO_2 emissions reduction. A short parametrical study of these results, as a function of the storage implementation, is also included.

Chapter three is focussed on the analysis of experimental data which was obtained from cubicles with and without PCM, with and without awnings. The effect of the PCM/awnings combination over the wall temperature, PCM activation, inner temperature, and inner comfort of the cubicle is discussed and compared to the same values at cubicles that did not have whether PCM, awnings or both. As experiments were also performed within a partially controlled temperature environment (by means of heating the cubicle inside so temperatures could stay close to the PCM theoretical melting temperature), the effect over the mentioned variables, the energy consumption, and CO_2 emissions is analyzed.

Chapter four presents a summary of conclusions and future work.

1.2 Introduction to the potential of Thermal Energy Storage

1.2.1 Energy sector in the EU-25

The energetic model employed by society is not sustainable, as 85% of energy needs are currently supplied by coal, gas, and oil, which generate CO_2 [1]. In addition to this, energy systems are complex and their behaviour may be uncertain, not always well understood, and information on them is often incomplete. However, based on available generic information it is known that there exists a mismatch between the energetic supply and demand, low yield and high cost.

In the EU-25, about 50% of total primary energy supply is delivered to the different sectors of energy industry (38% of the primary energy is consumed by power plants). Some primary types of energies (e.g. lignite, nuclear, as well as hydro and wind) are almost completely consumed by energy industries [2]. Other sectors like district heating, refineries, etc. represent a share of about 11% of energy consumption.

However, it is the final energy demand and/or consumption the one related more directly to this work. It is to be clarified that the concept of final energy refers to true end-use energy, i.e. the energy derived after the final conversion taking place at the end-user for supplying some demanded energy service [3], some details about the energy-consumer sectors in the EU are overviewed next.

1.2.1.1 Housing buildings

The term "buildings" refers both to housing buildings (often referred to as "households" and intended for people to dwell in) and non-housing buildings (employed by the services sector, such as offices, hospitals, etc.).

In the case of households, most residential energy in developed countries is consumed for space heating (60%, although not as important in some countries with a warm climate, but in this case energy may be used for cooling purposes) with this application followed in order by water heating (18%) and domestic appliances (6% for refrigeration and cooking, 3% for lighting) with other uses accounting for 13% [2,4].

The consumption pattern of the residential sector in the EU-25 is dominated by heating, cooling and cooking applications, which represent about 85% of the total final energy consumption [5]. Final energy consumed for space conditioning (heating and cooling) accounts for 66% of total energy used in the sector. Cooling accounts for a small fraction (less than 1%) of energy needs of households. Energy consumed for other heat uses (water heating and cooking) account for 22% of total energy consumption in the sector [2]. Electric appliances and lighting only represent a share of less than 15% of total final energy consumption in private households. It is worth mentioning that about half of electricity consumption in the EU-25 is used for different heating purposes and cooling at present [5].

Natural gas is the predominant energy source for households, accounting for 40% of total energy consumption. Gas ranks first both in space heating and in other heat uses, which includes water heating and cooking. Regarding other energy sources, taking year 2005 as a reference, the use of coal and lignite in heat applications by households had a 3% share, while consumption of oil products attained 23%. Currently, liquid fuels have been replaced mainly by gas, a trend that is expected to continue for the following 20 years. Electricity ranks second in the EU structure of residential energy consumption and, for example, it had a share of 23% in total energy consumption in 2005 [2].

1.2.1.2 Non-housing buildings

The services sector accounts for 12% of total final energy demand. During the last fifteen years, services were the fastest growing activity in the EU. New services have emerged, such as leisure services, information technology and telecommunications, driving further the development of the services sector. These trends are likely to prevail also in the future growth pattern of the EU and are assumed to continue. To name one case, the construction of new office buildings offering high quality working conditions is among the fastest growing sectors in the EU economy. This trend has consequences for energy consumption, both regarding the level of energy needs per employee and the structure of energy uses and the fuel mix [2].
Similar trends are experienced in other market services and trade supporting services: their infrastructure became larger and more energy demanding, new energy uses have emerged which were generally facilitated by proliferation of electricity applications [2].

The share of energy consumption for heating and cooling is about 20% less than in the residential sector. Final energy demand of services is dominated by space heating and other heat uses, which taken together accounted for 73% of energy consumption in 2005 for example. Distributed heat from district heating or combined heat and power (CHP) supply around 7% of total energy needs of the sector and this share is projected to remain rather constant. Renewable energies are emerging in the sector, displaying an average growth rate of 4.4%. The use of electricity and some other specific energy uses (e.g. agriculture) amount to about 30% of the total final energy consumption [2].

1.2.1.3 Industry and Transport

From an energy consumption point of view, the industrial sector may be sub-divided in smaller sectors: steam generation, iron and steel, non ferrous metals, chemical, non metallic minerals, pulp and paper, and others (these ones are not energy intensive and energy has a part of less than 2% in their overall cost structure and consume 35% of industrial energy consumption, not including feedstock to chemical industry). Energy consumption in industry, taken as a whole and excluding use of energy products as feedstock in petrochemicals, accounted for 27.8% of total final energy demand in 2005 [2].

Industry is still the largest consumer of electricity among the final energy sectors. More than 40% of the total electricity consumed in the final energy sectors came from industrial consumers. Industry also makes up the majority of fuel consumption in terms of final energy for solid fuels and for natural gas [5].

The transport sector is the fastest-growing sector in terms of energy use. The nearly complete dependence of the sector on oil products generates two sorts of concerns: security of oil supply with rising needs for transportation; and worries about climate change. The transport sector is the largest consumer of oil products in the EU energy system, consuming almost 60% of total oil product deliveries to final consumers. As inferred, the fuel mix for the transport sector (taken as a whole) is basically dominated by oil products, which accounted 97% in 2005. Energy consumption in the transport sector accounted for 31% of total final energy consumption in 2005 [2].

1.2.2 Climate change

1.2.2.1 CO_2

Climate change is a phenomenon currently affecting the whole planet, exerting local effects according to the considered geographical zone one may consider for analysis. It is a problem that basically requires fast and significant reductions in greenhouse gas emissions to stabilise the concentrations of these gases at a level which is sufficient to limit the increase of the global mean temperature to a level not exceeding 2 °C above the pre-industrial levels [5].

However, the effects of climate change go beyond the increase of global mean temperature as other collateral effects appear as a consequence of this increase, for instance, the increase of precipitation and flooding, the increase of global mean sea levels, the Arctic sea ice thinning and decreasing, or the retreat of glaciers and snow cover in area [6,7].

The most related effect to energy matters is however, the increase of CO_2 levels at the atmosphere, which is briefly addressed next.

In December 1997, representatives of 160 countries gathered in Kyoto at the United Nations Framework Convention on climate change to discuss targets for reductions in greenhouse gas emissions. The resulting 'Kyoto protocol' has called for the industrialized nations (so-called 'Annex I countries') to reduce the average of their individual emissions by at least 5% below 1990 levels in the period 2008–2012. The specific targets proposed for the key industrial powers of the European Union, Japan and USA were 7, 6, and 8%, respectively [8].

It was established that way because more than 80% of the energy comes from the combustion of fossil fuels, and continued use of fossil fuel as the major source of world energy strongly affects the environment. In fact, current consumption of fossil fuel releases more than 25 billion tonnes of carbon dioxide into the atmosphere each year [9].

More specifically, emissions come from energy systems and are driven by energy demand in three main components (buildings, industry, and transport), supplied increasingly through three main systems (electricity, refined fuels, plus direct fuel delivery) [10].

So, if current trends continue, atmospheric carbon dioxide will triple by the end of the century, bringing Earth atmosphere to a composition not seen for more than 40 million years. At this point, it must be taken into account that approximately 60% of the CO_2 emitted to the air stays in the atmosphere, while 20% is taken up by the ocean and 20% by terrestrial ecosystems. This distribution had been remarkably constant over the last two decades. However, the capacity of the ocean and the terrestrial biosphere to partially compensate for carbon emissions may change as future climate change slows down ocean circulation and as accumulation of organic carbon in soils with subsequent CO_2 emissions begins to balance the enhanced uptake in areas of reforestation [9].

Emissions would have to drop to about half of their current value by the end of this century to stabilize atmospheric concentration at 550 ppm. On the other hand it should also be remembered that the lifetime of CO_2 in the atmosphere is of about 1,000 years, which implicates the following [11]:

- The atmosphere will accumulate emissions during the 21st century.
- Near-term emissions growth can be offset by greater long-term reductions.
- Modest emission reductions only delay the growth of concentration (20% emissions reduction buys 15 years).
- If emissions were to be reduced to zero immediately, it would take more than 200 years for terrestrial and oceanic uptake of carbon to restore the atmosphere to its pre-industrial condition [9].

Based on this background, the European Union has proposed that the global average temperature rise compared with the average temperature of the preindustrial era has to be limited to 2 ºC. This would require stabilisation of carbon dioxide equivalent concentrations at a 450 ppm (CO_{2eq}) level if the assumed climate sensitivity is about 3 ºC. The contribution of other Kyoto Protocol gases is about 50 ppm in carbon dioxide equivalents. The targeted stabilisation level of CO_2 concentrations might require that global greenhouse gas emissions should be reduced roughly by 50% from today emission levels by mid of the Century [12].

As a reference, and again using 2005 numbers, the emissions were only 2.5% below their 1990 level. Emissions originating from transportation have increased continuously since 1990 and accounted for 26.6% of total emissions in 2005. This increase cancelled out the reduction of emissions in all other end-use sectors, especially in industry during the period 1990-2005. The part of emissions from power generation remained constant at roughly one third of the total by 2005. The accelerated penetration of renewable energies, mainly wind, the natural gas penetration and the further improvement of energy efficiency contributed to the moderate increase in CO_2 emissions over the past few years [2].

1.2.2.2 Buildings and CO_2

The current and/or potential effects of climate change present a number of primary challenges in particular for the building sector. In responding to these challenges, changes in building design may be considered, meaning low running costs in carbon terms while comfort is maintained. Design principles include super insulation, high-performance windows, ventilation heat recovery systems, and thermal storage using building mass [13].

However, not only is the position of the building sector regarding climate change remarkable because of the mentioned challenges, but also because the building sector has the largest potential for delivering long-term, significant and cost-effective greenhouse gas emissions compared to other major emitting sectors and since buildings have a relatively long lifespan, actions taken now will continue to affect their greenhouse gas emissions over the medium-term [4].

Despite so, at the same time, buildings are responsible for one third of global greenhouse gas emissions, both in developed and developing countries. The sector rate of growth of CO_2 emissions between 1971 and 2004, including through the use of electricity in buildings, is estimated to have grown at a rate of 2.5% per year for commercial buildings and at 1.7% per year for residential buildings. Though figures vary from building to building, studies suggest that over 80% of greenhouse gas emissions take place in order to meet various energy needs such as heating, ventilation, and air conditioning (HVAC), water heating, lighting, entertainment and telecommunications. So far, most developed countries and many developing countries have already taken steps towards reducing greenhouse gas emissions from the building sector, but these steps have had a limited impact on actual emission levels [4].

All previous facts regarding energy and climate change lead to the necessity of a better energetic model, and may be at least partially overcome with the use of thermal energy storage (TES). Indeed, there is a considerable amount of waste heat and cold generated each year in all types of applications, which can be used not only for the application itself but also for other purposes if recovered but more importantly, if properly stored, so it may be used at a later time or other location when required, with the correspondent benefits derived from it. TES is then a key element within an effective thermal management at the heating, cooling, and electricity generation sectors [14], and it is essential for a greater increase of the use of renewable energies. TES is among the most studied energy saving methods and it is beginning to be applied on several fields as its scope broadens gradually thanks to R&D activities, particularly during the last decade.

1.2.3 Definition and generic types of Thermal Energy Storage

In general terms, TES refers to a number of technologies that store energy in a thermal reservoir for later reuse. They can be employed to balance energy demand between day time and night time. The thermal reservoir may be maintained at a hotter or colder temperature than that of the environment. The majority of TES technologies store heat for later use in typical applications such as space heating, domestic or process hot water, or to generate electricity, though thermal energy may also be stored in the way of "cold" and be used whenever needed. Conventional heat and cold storage systems simply use a large tank using the working medium at the temperature required for later use. Virtually every cooling and heating system has such storage tanks; the heat and cold are produced at times of low demand and low generation cost and from intermittent energy sources such as wind and solar power. Thanks to the storage they are released at times of high demand and high generation cost or when there is no more generation capacity available [15].

There are diverse TES system types according to the temperature, power level and involved heat transfer fluids as each application has got its own specific operation parameters (Figure 1).

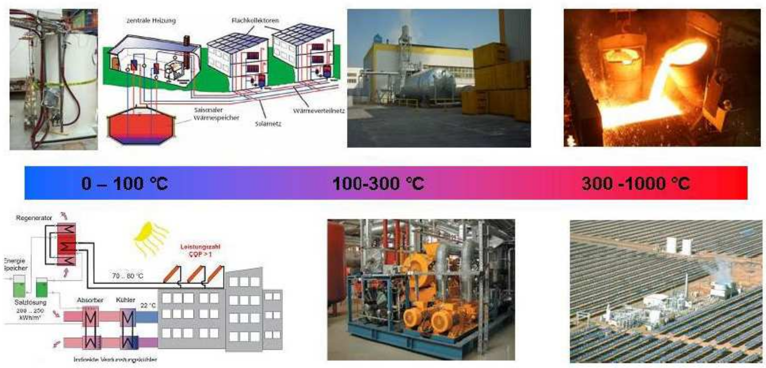


Figure 1. Thermal energy storage applications according to operation temperature range. Adapted from [16].

Due to the diverse demand profiles (regarding energy type, amount, and required power) each energy storage type requires a specific and optimum solution regarding efficiency and economy. Indeed, there is more than one TES technology type capable of fulfilling these requirements, however, the main and final goals of a TES system are always the cost reduction, and efficiency and reliability improvement, for which the involved materials, design, and integration into the system are to be considered [16].

According to the way heat is transferred at the process and the employed materials, the different types of TES are [17,18]:

- Sensible (water, rocks) where the temperature increase or reduction of the material is used.
- Latent (ice, paraffins, salt hydrates), taking advantage of using the high enthalpy of the phase change
- Chemical, where heat is absorbed and released by means of chemical reactions.

TES by sensible heat has been studied extensively and it has good results with substances of high density, high heat capacity, and the possibility to bear high temperature changes. TES by latent heat allows storing high amounts of energy working in narrow margins of temperature. Chemical TES is a technique in development with biochemical complexity [17,18]. As for the candidate materials for use at TES, back in 1983 Abhat [19] had already provided a classification of these substances, which is shown in Figure 2.

1.2.4 Benefits of Thermal Energy Storage

Some of the main advantages that TES features are listed below [14,15]:

- It conserves energy derived from many sources which would otherwise be wasted: solar energy, waste heat from equipment and processes, heat provided by warm air, infiltration and occupants. The principle applies to both heating and cooling over a wide range of applications.
- It enables portions of the energy demand to be shifted so that a more constant relationship is established between energy demand and supply. As a result, capital and operating costs for generation, transmission and distribution facilities can be reduced and the performance of the system improved. This principle applies to any form of energy distribution but principally to power and gas systems whereby the savings so realized can benefit both supplier and consumer.
- The application of autothermal exchange is possible in buildings where heat can be stored during the day for later use at night or whereby thermal storage capacity which is cooled by cold night air can subsequently absorb excess heat during the day.
- Appropriate thermal storage can be used to effect a significant reduction in equipment cycling frequency in burners, chillers and heat pumps and thus achieve a significant increase in operating efficiency. Equipment can also be downsized to reflect the improved operating conditions, thus reducing the investment required for new facilities.
- Excess electricity can always be stored cheaply in the form of heat and for a long time; however, the value of heat energy is much lower than that of electricity.
- It allows a better integration of renewable energies into the energetic system. Actually, reliable and affordable energy storage is a prerequisite for using renewable energy in remote locations, for integration into the energy system and the development in a future decentralised energy supply system.

- In solar thermal systems for heating and cooling, it is necessary because heat generation depends on solar radiation for energy production.
- For both stationary and transport applications, energy storage is of growing importance as it enables the smoothing of transient and/or intermittent loads, and downsizing of baseload capacity.TES is expected to reduce fuel consumption in the transport sector.

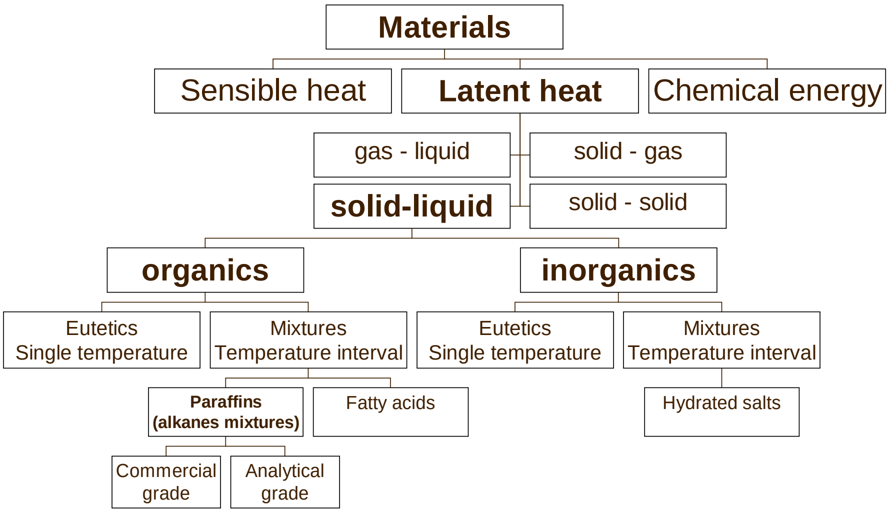


Figure 2. Classification of energy storage materials [19].

1.3 Phase Change Materials

1.3.1 Definition

The substances used for the thermal energy storage by means of phase of change are internationally denominate PCM (Phase Change Materials). When the ambient temperature rises the chemical bonds of the material will break up, therefore the material will change from solid to liquid, or from liquid to vapour, and so on. This phase change is an endothermic process and as a result will absorb heat. As the ambient temperature drops again, the PCM will return to the solid state and give off the absorbed heat [20]. Within possible phase changes in materials, the ones with vapour phase imply great variations of volume with a lot of problems of viability for their application. The phase change solid-solid does not show enough enthalpy variation. Finally, the phase change solid-liquid is the best and the most suitable option, and the one that more interest has attracted in the past years.

The latent heat is the energy necessary for the phase change of a material and presents higher energy density than sensible heat. The phase change liquid-gas is the one with higher energy density, but the volume expansion of the process presents serious problems in pressure control. On the other hand, the phase change solid-solid presents the lowest energy density. Solid-liquid phase change presents high energy density and no volume expansion problems, being the most suitable one [21,22].

An energy storage system incorporating phase change materials will reduce significantly its volume compared to sensible heat systems [23]. A further advantage of latent heat storage is that the process occurs in a narrow temperature range, achieving a good temperature control [24]. When coupled with solar energy it can provide continuous solar use, especially with space heating in winter [25]. A similar effect can be used in summer, storing the natural ventilation cooling at night and releasing it during the day.

The use of phase change materials for the latent heat storage has been studied in different applications and it has been commercialized in containers to transport blood and/or products sensible to temperature, to decrease the applications energy demand, in solar collectors and in other similar applications. Among the main references related with phase change materials, one may cite Abhat [19], Lane [26,27], Kenisarin [28], Dincer and Rosen [21], Zalba et al. [25], Hadorn [29], Paksoy [30], Mehling and Cabeza [22], Baetens et al. [20], and Cabeza et al. [31]. These works contain a complete review of the types of material which have been used, their classification, characteristics, advantages and disadvantages and the various experimental techniques used to evaluate the behaviour of these materials in melting and solidification process.

1.3.2 Classification

PCM are classified as organic and inorganic materials [18]:

- Organic PCM: Organic materials are classified as paraffin and non-paraffins. Their main characteristics are congruent melting, self-nucleation and usually non-corrosiveness to the container material. They are in general chemically stable, do not suffer from subcooling, are non-toxic, and have a high latent heat of fusion.
- Inorganic PCM: Inorganic materials are classified as salt hydrates and metals. They have got a high latent heat per unit mass. They are cheaper than organic compounds and are non-flammable. Decomposition and subcooling are some issues which may affect their phase change properties. In general they have a high heat of fusion, good thermal conductivity, are cheap and non-flammable. However, most of them are corrosive to most metals. Most common inorganic PCMs are hydrated salts.

Sometimes a third category is added (eutectics), which is a mixture of multiple solids in such proportions that the melting point is as low as possible, however, limited data are available on their thermal and physical properties [20].

Inorganic PCM, such as salt hydrates, remain at a constant temperature during the entire melting or freezing process. Organic PCM such as paraffins present a wider melting range according to purity, with an increased rise in thermal capacity within this range. Hysteresis, as a measure of the divergence of melting and freezing curves, is a further characteristic feature, particularly marked in the case of inorganic PCM. Wax paraffins exhibit high cycle stability, low reactivity, low hysteresis and are classed as non-toxic, properties that make them ideal for building applications.

Moreover, their thermal properties, specifically the melting point range, may be substantially adjusted by blending pure materials. The main drawback of paraffins is their combustibility. A comparison of the advantages and disadvantages of organic and inorganic materials is shown in Table 1.

Figure 3 presents their general behaviour in terms of melting point and range, specific heat and enthalpy.

Organic	**Inorganic**
Advantages	
Non-corrosives	Greater phase change enthalpy
Low or none under cooling	
Chemical and thermal stability	
Disadvantages	
Lower phase change enthalpy	Under cooling
Low thermal conductivity	Corrosion
Flammability	Phase separation
	Phase segregation, lack of thermal stability

Table 1. Comparison of organic and inorganic materials for heat storage [17].

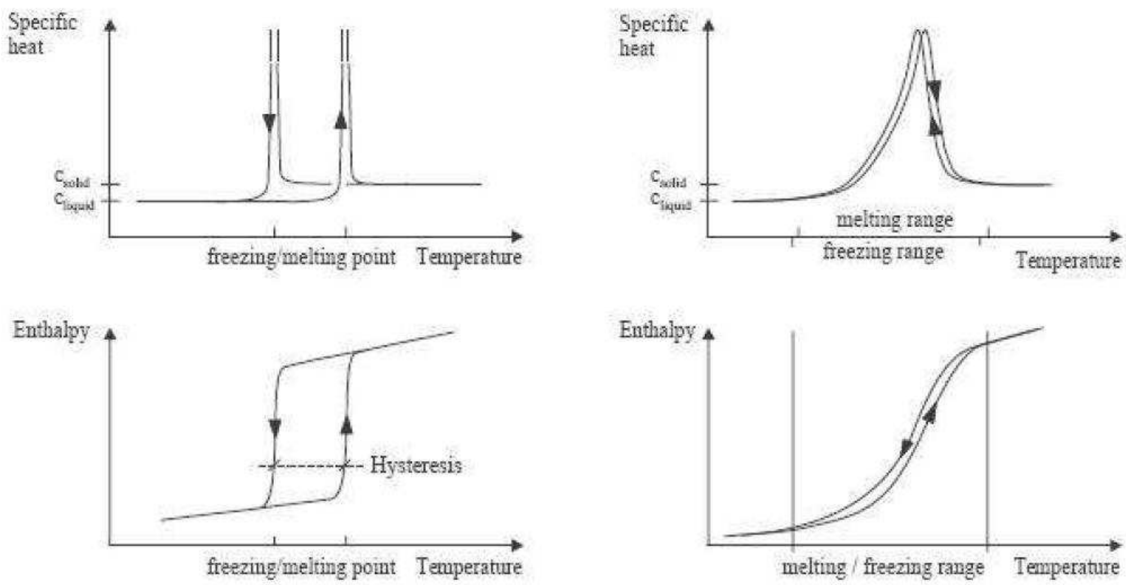


Figure 3. General behaviour of inorganic (left) and organic (right) phase change materials in terms of specific heat and enthalpy [32]

1.3.3 Available materials to be used as PCM

Many substances have been studied as potential PCM, but only a few of them are commercialised as so. A classification of available materials according to the phase change type is summarized in Figure 4.

Commercial phase change materials are available, however, thermo-physical properties must be characterized and verified since sometimes, laboratory results differ from the ones provided by manufacturers [33]. Several PCM used in buildings, commercial products and a compilation of materials with potential application as PCM (both organic and inorganic) with their most important properties, are presented by Castell [18] and Castellón [17]. Recently, Bhatt et al. [34] reviewed over 60 PCM including organic, inorganic, eutectic, and ionic liquids with respect to their thermal energy storage capacity. Zhu et al. [35] also reviews the development and investigations of PCM in thermal energy storage systems of various engineering applications, introducing various categories of PCM suitable for thermal energy storage, and discussing the investigations on their enhancement techniques.

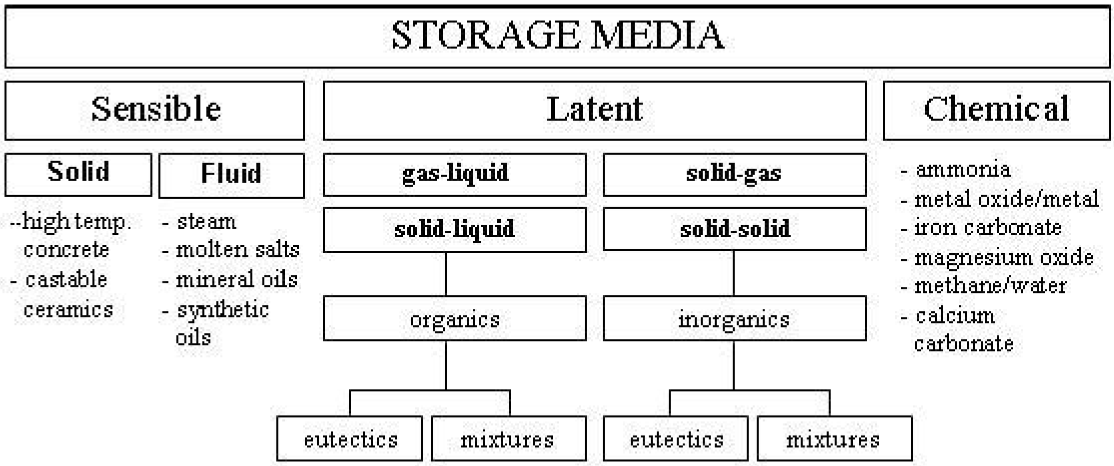


Figure 4. Material classification according to phase change type. Adapted from [25,36,37].

A significant number of authors have based their work on organic materials such as alkanes, waxes or paraffins [38,39]. Within organic materials, there is a group called MCPAM (Phase change materials made up of molecular alloys), formed by alkane-based alloys which have the advantage of being thermoadjustable [40], which means there may be alterations to the phase change temperature through their composition. Additional information on this topic can be found in the literature [40,41].

As far as concerns the storage temperature or phase change, the heat transfer in accumulators can be improved choosing the PCM in such a way that its phase change temperature optimises the thermal gradient with respect to the substance with which the heat is being exchanged [38,42,43]. For example, with paraffins and alkanes it is possible to vary the number of carbon atoms or form a different molecular alloy which allows a practically continuous variation of the phase change temperature within certain ranges. Notable among inorganic materials are hydrated salts and their multiple applications in the field of solar energy storage [21,27].

Authors have also worked on new materials, with potential commercial use in the future. Bayés-García et al. [44] worked over the preparation, characterization and thermal stability of PCM Rubitherm® RT 27, focussing on two different methods of preparing the PCM by changing the shell composition of the microcapsules. Prepared PCM were totally capable of developing their role in thermal energy storage.

Karaipekli and Sari [45] studied the preparation, characterization, thermal properties and thermal reliability of novel form-stable composite PCM composed of eutectic mixtures of fatty acids and expanded vermiculite for thermal energy storage application, concluding that the prepared form-stable composites can be considered as promising PCM for low temperature thermal energy storage applications due to their satisfactory thermal properties, good thermal reliability, chemical stability and thermal conductivities. Sari et al. [46] worked on the preparation of a novel form-stable composite PCM by incorporation of lauric acid within expanded perlite, characterization of the composite, and determination of thermal properties and thermal reliability of the composite PCM using DSC analysis. They concluded that this composite PCM could be considered to have good potential for thermal energy storage because of its good thermal energy storage properties, thermal and chemical reliability and thermal conductivity.

Darkwa [47] has developed and tested a laminated composite aluminium/hexadecane PCM material with a faster thermal response regarding the rate of heat flux and about 40% and 15% heat transfer enhancements during the charging and discharging periods respectively, though with about 5% less total cumulative thermal energy, which is attributed to the presence of the aluminium particles.

Kaizawa et al. [48] studied the thermophysical properties of various sugars and sodium acetate trihydrate aiming for their use in waste heat transportation systems, concluding that the erythritol sugar was the best PCM for such application. Alkan et al. [49] studied the preparation, characterization, and determination of thermal properties and thermal reliability of paraffin/polypropylene composite as a novel form-stable PCM for thermal energy storage applications. They found that the material has got good thermal reliability and chemical stability, and that the material thermal properties make it suitable for latent heat thermal energy storage purposes such as solar space heating applications.

Other studies which should be mentioned are those by Sari et al. [50], Li et al. [51], Sari and Karaikepli [52,53], Alkan et al. [54,55], Qiu et al. [56], Zhang [57], Pincemin et al. [58,59], Fang et al. [60], Aoyagi et al. [61], and Chen and Xiao [62].

1.3.4 Thermophysical properties

1.3.4.1 Temperature and heat of fusion

The most important properties of PCM are the temperature and the heat of fusion. For building applications the employed PCM should have a phase transition close to human comfort temperature (22-26 ºC). In general, it is imperative to have the temperature of fusion within the temperature range of application, though the temperature of fusion as such does not affect the energy storage capacity of a material. However, as a phase change is involved in melting, the inclusion of the temperature of fusion in the temperature range of application can permit the use of phase change as an on-off switch [34].

The heat of fusion, also known as enthalpy of fusion or latent heat of fusion, refers to the amount of thermal energy that a material must absorb or evolve in order to change its phase from solid to liquid or viceversa. Storage capacity of the PCM is directly dependent on the heat of fusion, as large values of heat of fusion lead to more efficient systems [34]. Passive heating/cooling applications for buildings require high heat of fusion to increase the energy stored, reducing the peaks of heating/cooling demand.

1.3.4.2 Long-term stability

PCM are usually used many times over, and often have an operational lifespan of many years in which they will be subjected to thousands of freeze/melt cycles. It is very important that the PCM is not prone to chemical or physical degradation over time which will affect the energy storage capability of the PCM. Long term stability can be a problem in some salt hydrate PCM, unless they are modified to prevent separation of the component materials over successive freeze/melt cycles [63]. Insufficient long term stability of the storage materials and containers and the number of cycles they can withstand without any property degrading is a problem that has limited the widespread use of latent heat storage. This poor stability is due to two factors: poor stability of the materials properties due to thermal cycling, and/or corrosion between the PCM and the container.

On the other hand, buildings are normally intended to have a long lifespan [4]. The construction materials should then have long-term stability to ensure their correct performance during the building lifetime. When studying PCM for building applications, some basic requirements may be raised.

PCM must be non-corrosive to avoid structural damages in the building or leaks of material. Several kinds of phase change materials have been tested in contact with both metals and plastics [64-73]. Table 2 presents different combinations of PCM and materials to determine their corrosion problems.

Most references on corrosion tests were performed with diluted salt hydrates, as common processes in the chemical industry, usually based on observation over experimental set-ups [74,75]. Porisini [76] tested the corrosion of four commercially available salt hydrates used as PCM in 1988. Cabeza et al. [77-79] studied corrosion resistance of five common metals (aluminium, brass, copper, steel and stainless steel) in contact with molten salt hydrates (zinc nitrate hexahydrate, sodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate, sodium carbonate, potassium hydrogen carbonate, potassium chloride, water, sodium acetate trihydrate, and sodium tiosulphate pentahydrate) in an immersion corrosion test.

PCM	Metal	Plastic
Salt eutectic	Possible corrosion	Compatible
Salt hydrate	Possible corrosion	Compatible
Fatty acids	Possible corrosion	Compatible
Organic PCM	Compatible	Possible corrosion

Table 2. Possible corrosion problems with different combination of PCM-materials [18].

Some investigations have been concerned with corrosion of molten salts at high temperature. Already in 1980, Heine et al. [72] studied the corrosion performance of six molten salts melting between 235 and 857 °C versus four metals used at these temperatures. Recently, Kenisarin [80] reviewed available high-temperature phase change materials (mostly salts but also including PCM metal alloys) for thermal storage and solar energy usage in the range of 120 to 1000 ºC [80], pointing out the materials main advantages and drawbacks from a theoretical and practical stand in views of their possible commercialization.

During 2005 and for ten months, Lázaro et al. [81] studied the compatibility of some PCM typically used for thermal energy storage with a melting temperature around 22 °C and some plastic materials used as encapsulate materials. The tested PCM were molecular alloy C16-C18, RT20, RT25, RT26, and TH24, and the tested plastic materials were PP, LDPE, HDPE, and PET. Two effects were detected: organic PCM migration in plastics and moisture sorption. It was also found that:

- LDPE had the highest mass variation and big deformations, for which it was discarded as encapsulate material.
- When a molecular alloy is used as PCM in plastic encapsulate as thermal energy storage, or in any other application used as molten paraffin, the best encapsulate material is PET.
- When RT20, RT25, and RT26 are used, the recommended plastic encapsulate material is also PET.
- If moisture sorption is taken into account, PP could also be recommended.
- When TH24 is used as molten salt and water sorption is not desired, PEHD should be chosen.
- PP, PET, and PELD showed big mass increase, therefore, they were not recommended as encapsulate material when moisture sorption can entail problems.

Castellón et al. [82] performed experimental studies on the organic PCM migration in plastics, and its effects on plastic properties, with emphasis on the environmental stress cracking, which is considered one of the most common causes of plastic failure. They found that, for encapsulating organic PCM, low-density polyethylene and polypropylene showed worse behaviour than high-density polyethylene.

Segregation is an important problem for salt hydrates since it affects the thermal behaviour of the material. The addition of gellants and thickeners can avoid segregation problems. Bentonite, starch and cellulose have been successfully tested as thickening materials [83]. The mixtures showed a similar thermal behaviour as the salt hydrate, with the same melting point and an enthalpy decrease between 20% and 35%, depending on the type and amount of thickening material used. Carlsson [84] studied the phase change behaviour of pure and some chemically modified calcium chloride hexahydrate materials suggested in the literature as suitable heat storage media in order to evaluate their long-term reversibility. Phase segregation effects were also analyzed. It was concluded that with those materials, reversible phase change cycling can be performed and therefore there is no need for thickeners to be added to avoid irreversible tetrahydrate formation, successively reducing heat storage capability.

There are also the effects of thermal cycling on the melting temperature, latent heat of fusion and the specific heat of commercial grade PCM. Sharma et al. conducted accelerated thermal cycle tests for stearic acid, acetamide and paraffin wax [85-87]. No regular degradation in their melting points during repeated 1,500 thermal cycles was observed. Other studies were carried out for salt hydrates with melting temperatures between 15 and 32 °C by measuring latent heat of fusion and melting temperature after repeated cycles [88]. Hadjieva et al. [89] tested three paraffin mixtures and verified that thermal cycles do not affect their properties. It was also demonstrated that neither the cycles nor contact with metals degrade the thermal behaviour of paraffin [90]. Shukla et al. [91] studied the effect of thermal cycling over paraffin waxes, di-sodium tetraborate, ferric nitrate, sodium hydroxide, barium hydroxide and erythritol and concluded that none of the selected inorganic PCM is useful for latent heat thermal energy storage purposes, however, paraffin waxes showed reasonable good thermal reliability with respect to thermal cycling and it was stated that further studies are needed on the subject.

Tyagi and Budhi [92] studied calcium chloride hexahydrate as a potential latent heat storage material and performed 1,000 accelerated thermal cycle tests, after which it was observed that the material melts between a stable range of temperatures and has small variations in the latent heat of fusion during the thermal cycling process, thus, being a promising phase change material for heating and cooling applications for various building storage systems.

El-Sebaii et al. [93] studied the influence of the melting/solidification fast cycling over commercial PCM grade acetanilide and magnesium chloride hexahydrate for usage as storage media inside solar cookers. They concluded that acetanilide is a promising PCM for cooking indoors, showing good compatibility with aluminium, while the magnesium chloride hexahydrate did not exhibit the same feature (also with stainless steel) and was not stable during its thermal cycling due to the phase segregation problem; for which it was not recommended as a storage material inside solar cookers for cooking indoors.

Another important problem, particularly for salt hydrates is the subcooling effect, pointed out by Lane [26]. Fortunately, when an effective nucleator can be found, this problem is solved. A PCM is selected with a melting temperature of 5 to 10 ºC above the system operating temperature. This minimizes heat losses while providing enough temperature difference to maintain good heat transfer. Subcooling of more than a few degrees will interfere with proper heat extraction from the store, and 5 to 10 ºC of subcooling can prevent it completely. Even if there is no subcooling, an inherently slow crystal growth rate can limit the rate of heat withdrawal to an unacceptable low value.

In an effort to overcome these problems, many investigations [94-98] were carried out using salt hydrates in direct contact between an immiscible heat transfer fluid and the salt hydrate solution. The agitation caused by the heat transfer fluid has minimized the subcooling and prevented phase segregation [99]. Ryu et al. [100] performed extensive studies on suitable thickening and nucleating agents, which can be used for a number of salt hydrates, showing a significant reduction in the degree of subcooling. Zhang and Niu [101] studied the effects of subcooling over microencapsulated n-hexadecane intended for cooling storage media for building cooling applications, finding that, because of the subcooling phenomena, subcooling is necessary to utilize the latent storage capacity, or only the partial storage capacity can be used at a limited cooling temperature, with electric-driven cooling storage, this subcooling will lower the COP of the cooling storage process, and that for passive cooling schemes, this would mean reduced utilization hours of natural cooling sources.

1.3.4.3 Fire characteristics

Flammability of building materials is a key point for their implementation in real applications. Both flame spread and smoke composition must be evaluated to meet all the requirements from standards for health and structural safety. Salyer et al. [102] studied the reaction of PCM to fire and the possible fire-retardant additives (organic halogenated compounds) that improve the response to fire of the material. Their work covers an important number of applications in the field of heating and cooling, and sets out a review of materials, advantages, disadvantages and characteristics of a series of PCM substances applicable to thermal storage in buildings. Of the four possible types of PCM analyzed, those with the greatest advantages were the paraffins (hydrocarbons; -60 to 80 ºC) that are obtained from the polymerization of ethylene or as a by-product of petroleum. Among the cited suppliers are Shell, Exxon, Gulf, Sun Oil, and Witco.

Some flammability tests conducted by Banu et al. [103] on gypsum wallboard with about 24% organic PCM indicated that the material did not meet all requirements to be used in buildings. The incorporation of a flame retardant can reduce the flammability of energystoring wallboard. Other approaches can also be considered:

- Adding alternate non-flammable surface to the plasterboard.
- Sequential treatment of plasterboard, first in PCM and then in an insoluble liquid fire retardant. The insoluble fire retardant displaces part of the PCM and some remains on the surface, thus imparting self extinguishing characterization to the plasterboard.
- Using brominated hexadecane and octadecane as PCM. When these halogenated compounds are combined with antimony oxide in plasterboard, the product will be self extinguishing.

Koschenz and Lehmann [32] developed a thermally activated ceiling panel incorporating paraffin and indicated that the micro-encapsulation of the PCM, its bedding in gypsum and encasement in a sheet steel tray ensure a certain level of fire resistance. The system was to be incorporated in the new-building administrative facility of BASF AG housing company "Ludwigshafener Wohnungsunternehmen LOWOGE/GEWOGE". Due to the envisaged use of the space and the provision of a sprinkler system, the PCM ceiling meets the German fire regulations with a B1 fireresistance rating. Further improvements are needed to broaden its applicability.

Zhang et al. [104] determined that adding expanded graphite on paraffin/high density polyethylene PCM based material improved its flame retardant efficiency. The effects of adding expanded graphite to high-density polyethylene/paraffin composite have also been analyzed, concluding that its flame retardant efficiency was improved [105].

Cai et al. [106] prepared a flame retardant system which consisted of magnesium hydroxide and microencapsulated red phosphorus and that was based on form stable PCM (polyethylene/ethylene-vinyl acetate/organophilic montmorillonite nanocomposites) and paraffin compounds. After characterizing the system by several methods, they found that there were improvements in the thermal and flammability performances of the system.

Cardoso and Gomes [107] tested ways of inserting microencapsulated PCM as flame retardants into the fibres of fire fighter protective clothes, and concluded that only a conjugation of both microcapsule protection and non-woven flame retardant finishing was appropriate, and that the resulting clothes material could pass the EN532, which states that the material has to resist washing and still be flame retardant. The resultant material though, was unacceptably stiff.

It can be concluded from the information compiled thus far, that the main characteristics required of phase change materials are those indicated in Table 3.

1.3.4.4 Thermophysical properties determination

Speyer [108] provided a good overview of the thermal analysis methods in general, but also Eckert et al. [109] should be mentioned. Naumann and Emons [110] and others [69,111] focussed their studies on thermal analysis methods for PCM.

Analysis techniques used to study phase change are mainly conventional calorimetry, differential scanning calorimetry (DSC) and differential thermal analysis (DTA). Among studies relating to DSC, it is worth citing Flaherty [112] for characterisation of hydrocarbons and natural waxes, Giavarini [113] for characterisation of petroleum products, Salyer [114], Bayés-García et al. [44] for characterisation of microencapsulated PCM with different shell compositions, Kenar [115] for characterisation of oleochemical carbonates, and Ukrainczyk et al. [116] for characterisation of paraffins.

Thermal properties	**Physical properties**	**Chemical properties**	**Economic properties**
Phase change temperature fitted to application	Low density variation	Stability	Cheap and abundant
High change of enthalpy near the temperature of use	High density	No phase separation	
High thermal conductivity in both liquid and solid phases (although not always)	Small or no subcooling during freezing	Compatibility with container materials	
		Non-toxic, non-flammable, non-polluting	

Table 3. Important characteristics of energy storage materials [117].

As mentioned by Gibbs [90], there is considerable uncertainty about the property values provided by manufacturers (who give values of pure substances) and it is therefore advisable to use DSC to obtain more accurate values.

Albright et al. [118] addressed possible inconsistent results obtained with the DSC method, for paraffin PCM, claiming that it is due to the samples low thermal diffusivity as well as improper data analysis methods. The authors concluded that the errors are actually due to undesired thermal gradients within the sample that result in misrepresentative data, and suggested that if the process is continued to be used, these errors must be corrected by inserting the results into a model (developed by them) that closely resembles the DSC process (as it is complicated to interfere with the hardware or process of DSC), so the model will determine the true effective specific heat capacity and latent heat of the sample by matching the model simulation results to the actual DSC results.

Yinping [119] reviewed the above-mentioned conventional methods of PCM property analysis and pointed out their limitations, of which the following stand out:

- Small quantities of sample are analysed (1-10 mg), although some behaviour of the PCM depends on their quantity.
- The analysis instrumentation is complex and expensive.
- Phase change cannot be visually observed.

Yinping proposed the T-history method for determining phase change temperature, subcooling, enthalpy, specific heat, and thermal conductivity in solid and liquid phases. Temperature–time graphs and properties are evaluated for comparison with other reference materials (usually pure water). This method does not take a small amount of sample, but it also has restrictions on accuracy of thermo-physical properties.

The main advantages of T-history method are [120]:

- Simple experimental system.
- Able to measure lots of samples and obtain several thermo-physical properties.
- Enough precision of measurement for engineering applications.
- The phase-change process can be observed clearly.

Hong et al. [121] tried to improve the accuracy of the T-history method to measure heat of fusion. Marín et al. [122] developed a further evaluation procedure to determine specific heat and enthalpy as temperature dependent values and an experimental improvement is proposed.

A proper methodology to verify the correct setup and data analysis method of a T-history installation using standard materials with known properties was described and tested [123]. The proposed steps were:

- Calibration of the sensors.
- Verification of the correct measurement of the temperature using pure substances with a fixed phase change temperature.
- Verification of the correct evaluation of the enthalpy by using different substances with known phase change enthalpy.

The obtained results confirmed that the T-history installation can be used to analyze different PCM.

Krawaritis et al. [124] reviewed the proposed improvements so far to the T-history method and proposed some of their own regarding the following:

- The experimental arrangement, the experiment should be performed inside a test chamber of controlled indoor environment.
- The way of measurement processing, by using the thermal delay (i.e. temperature difference) between the PCM and the reference fluid at any specified time and not in the use of their time delay at any specified temperature, as in the original method.
- The kind and presentation format of the final results, are related to the effective thermal capacity function, a function that contains much more information than the final results given by the original method, and provides the possibility to compare different PCM and is more useful in most applications and especially in numerical calculations.

Castellón et al. [125] investigated the dynamic method and the step method for hf-DSC analysis, and tested their accuracy in the determination of enthalpy–temperature relationship of PCM. Commercial PCM RT27 was chosen as sample material to avoid subcooling and kinetic effects in the test measurements. For the dynamic method, a strong influence of heating/cooling rate was observed. For the step method, the resulting enthalpy–temperature relationship proved to be independent of the heating/cooling rate.

Del Barrio et al. [126] developed a new method for characterization of shape-stabilized phase change materials based on one single sample and proposed one single experimental device which consisted of a cylinder of PCM heated/cooled in a furnace following specific temperature patterns (steps, isotherms, and ramps). In order to retrieve the whole set of parameters/functions characterizing the PCM from temperature measurements at one single point within the PCM, a numerical heat transfer model was proposed. Parameters are retrieved by solving a problem of time-dependent source estimation by inversion of a linear heat conduction model. An experimental test for characterization of graphite/salt composites was carried out to illustrate the appropriateness of their developments.

Günther et al. [127] reviewed main details of the DSC, T-history and a method presented by them to deal with PCM objects. According to them, the enthalpy vs temperature values must be known with an uncertainty lower than 1 K. The authors affirm that the precision of a measurement can be quantified by comparing results from heating and cooling measurements. Among their main observations regarding the mentioned methods are:

- Measurements using DSC in the dynamic mode are not in general suitable to determine the enthalpy of PCM due to their characteristic properties.
- Using the same method with the isothermal step mode, offers sufficient precision.
- DSC in general is not suitable for heterogeneous materials due to its small sample size; the T-history provides results precise enough for these ones instead.

The method presented by them consists of an air flowchamber for calorimetric measurements of PCM objects; results tests performed with this method were compared to T-history measurements. It was demonstrated that there was good agreement between results obtained.

A method for determining thermal conductivity in PCM at temperatures around phase change temperature is established in Delaunay [128]. This method is based on analysing one-dimensional conduction in a cylinder. Various alternatives are proposed in the literature for the enhancement of thermal conductivity such as increasing the heat transfer surface, inserting metallic fins [129] or adding metallic additives [130]. Manoo [131] presented some interesting charts relating to variations in conductivity, density and enthalpy against temperature for some paraffins. Cabeza et al. [77-79] experimented with different heat enhancement materials, finding out that the use of graphite composites gives best results.

1.3.5 PCM integration methods

1.3.5.1 Direct

Successful integration of PCM in building envelopes requires a good means of encapsulation to avoid leakage and guarantee structural stability. The heat transfer area and coefficient also result in key factors for the charging and discharging of the PCM. Different techniques have been studied depending on the application. When using the direct technique, liquid or powdered PCM is added to building materials during its production, resulting into an economical integration method. A laboratory scale energy storage gypsum wallboard was produced by the direct incorporation of 21–22% commercial grade butyl stearate (BS) [132].

The same technique was used to integrate 5% of microencapsulated PCM into concrete. The new material was used to build an experimental set-up consisting of two identical cubicles, one made with conventional concrete and the other one done with the new PCM concrete. The thermal behaviour of the improved concrete was studied [17,133].

Immersion of PCM in building envelopes was presented as an alternative to the addition of filled pellets. A higher potential of storage capacity was demonstrated when this technique was used [134,135]. The porous building material is dipped into hot molten PCM, which is absorbed into the pores by capillary action. The porous material is removed from the liquid PCM and allowed to cool and the PCM remains in the pores of the building material [136]. The immersion process for filling the wallboards with wax was successfully scaled up from small samples to full size sheets. Other processes to incorporate the PCM into the plasterboard were successfully demonstrated: post manufacture imbibing of liquid PCM into the pore space of the plasterboard and addition in the wet stage of plasterboard manufacture.

Hawes and Feldman [137] examined the mechanisms of absorption and established a way of developing and using absorption constants for PCM in concrete to achieve diffusion of the desired amount of PCM. However, as Schossig et al. [138] pointed out, leakage may be a problem over a period of many years for this method.

1.3.5.2 Encapsulation of the phase change materials

The encapsulation of PCM presents interesting advantages for its integration in different applications and has developed interest in several researchers. The advantages and disadvantages of different geometries of PCM encapsulation with different materials and their compatibility were discussed by Lane [26]. Due to the geometry simplicity of a sphere (one dimension), it has been widely considered and analyzed as an example, and the freezing and melting processes of water contained in spherical elements have been studied experimentally [139], proposing semi empirical equations that allow the mass of ice within a sphere to be predicted at any time during the freezing or melting processes.

Generally speaking, PCM containment requirements and functions should be the following [117]:

- Meet the requirements of strength, flexibility, corrosion resistance and thermal stability.
- Act as barrier to protect the PCM from harmful interaction with the environment.
- Provide sufficient surface for heat transfer.
- Provide structural stability and easy handling.

Eames [139], Bédécarrats et al. [140,141] and Alloncle [142], studied the crystallization process of an organic eutectic in a spherical encapsulation. Kalaiselvam et al. [143] analyzed the solidification and melting processes of PCM inside cylindrical enclosures. The encapsulation of PCM (50-80%) with unsaturated polyester matrix (45-10%), and water (5-10%), intended for the use of PCM in buildings, was studied by Morikama et al. [144]. Several authors have presented extensive reviews on encapsulation techniques for PCM [120,145,146].

Macroencapsulation

Macroencapsulation comprises the inclusion of PCM in some form of package such as tubes, pouches, spheres, panels or other receptacle (Figure 5 and Figure 6). These can serve directly as heat exchangers or they can be incorporated in buildings products [147]. Some commercial products are available in the market [18,148]. The main problem is the large surface to volume ratio required to meet the heat transfer demand.

Wang et al. [149] have prepared a macro-capsule through in situ polymerization by using silica gel as the shell material and shape-stabilized phase change materials containing 50 wt% of n-octadecane of high density polyethylene as the core. The capsules surface and construction, the permeability of the capsule wall and the release kinetics parameters were experimentally investigated. The results showed that the wall thickness of the macro-capsules was about 20-50 μm under the experimental conditions. The shape-stabilized PCM surface, modified with chromic acid, is rough, and there are many tiny holes about 3 μm in diameter in it. For these reasons, either the hydrophilicity of the shape-stabilized PCM surface or the cohesion between the core and the wall have been greatly improved, and then, the weight loss percentage of the macro-capsules is decreased by about 1.5 and 2.5 times relative to that of un-modified and modified shape-stabilized PCM, respectively.

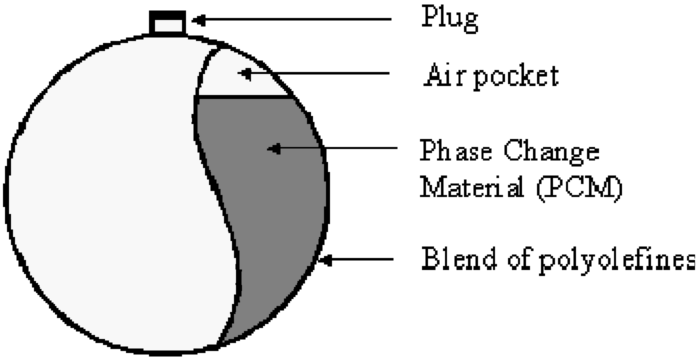


Figure 5. Spherical nodule filled of PCM developed by Cristopia.

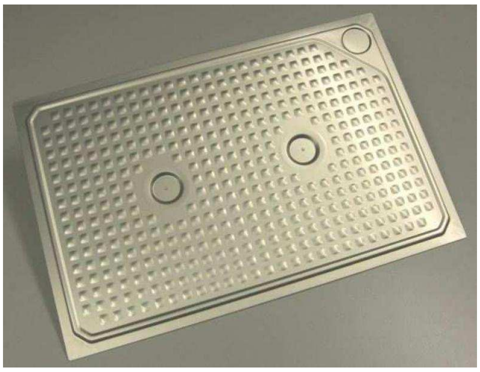


Figure 6. CSM panel developed by Rubitherm.

Microencapsulation

Microencapsulation is a process where small, spherical or rod-shaped particles are enclosed in a thin, high molecular weight polymeric film (Figure 7). The coated particles can then be incorporated in any matrix that is compatible with the encapsulating film. Unless the matrix encapsulating the PCM has high thermal conductivity, the microencapsulation system suffers from low heat transfer rate. The rigidity of the matrix prevents convective currents and forces all heat transfer to occur by conduction. This can reduce seriously the heat transfer rates, especially in the charging mode [117].

For many applications, PCM are microencapsulated, and this has been studied by several researchers [150-154,154-166], and developed by companies like BASF [167,168] and CIBA [17], which was acquired by BASF on 2009. Nevertheless, the potential use of microencapsulated PCM in various thermal control applications is limited to some extent by their cost and high ratio of encapsulating medium to PCM. However, because the performance of thermal control for space applications is so important and because costs are less important, several authors believe that the development of such PCM could be a milestone for space technology [169].

Figure 7. Microencapsulated PCM commercialized by BASF.

Bulk systems

In this case bulk systems refer to the encapsulation at tank heat exchangers for PCM, which are similar in design to existing tanks used for energy storage, but with some significant differences. The key unique characteristic of PCM bulk systems is the need for a more extensive heat transfer than that found in non-PCM tanks because the heat storage density of the PCM is higher compared to other storage media. The heat transfer area is smaller but it still requires a high rate of heat release or gain. The different approaches extensively used are inserting fins or using high conductivity particles, metal structures, fibers in the PCM side, direct contact heat exchangers or rolling cylinder method [117].

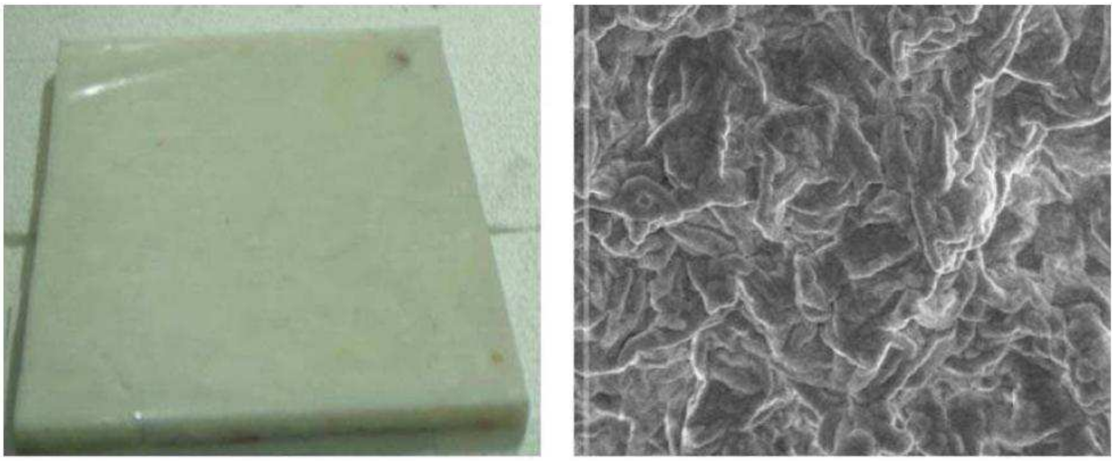
Shape-stabilized

In recent years, a novel compound PCM, the so-called shape-stabilized PCM has attracted the interests of the researchers [111,170-173] to overcome the main problems of encapsulation such as the increase of price. It consists of paraffin as dispersed PCM and (high density polyethylene) HDPE or other material as supporting material. Since the mass percentage of paraffin can be as much as 80% or so, the total stored energy is comparable with that of traditional PCM.

Inaba and Tu [111] studied the thermal performance of shape-stabilized PCM composed of paraffin and HDPE. The material contained 74 wt.% paraffin. Hong and Xin-shi [170] investigated several types of high density polyethylene (HDPE) with different melting index (MI) for use as supporting material and screened the optimal one. Py et al. [171] prepared paraffin-expandable graphite shape-stabilized PCM with high thermal conductivity. Xiao et al. [172,173] selected styrene– butadiene–styrene copolymer (SBS) as supporting material to form shape-stabilized PCM. This material contained up to 80 wt.% paraffin.

Zhang et al. carried out a lot of research in this field, both in the development of materials [174] and its application [175-178]. They developed and thermally characterized many shape-stabilized PCM using paraffin and HDPE (high density polyethylene) as a supporting material. Different shapes were produced by extrusion (Figure 8).

The application of these new materials to floor [175,176] and under-floor electric heating system [177,178] was studied both numerically and experimentally. Results showed the potential of the new technique and gave some guidelines for the design of such systems. Finally, the numerical models were validated achieving a relatively good agreement.



(a) (b)

Figure 8. Shape-stabilized PCM plate. (a) Plate; (b) electronic microscopic picture by scanning electric microscope (SEM) [174].

Cheng et al. [179] studied the potential improvement of the thermal conductivity of shape-stabilized paraffin/high density polyethylene composite phase change material by the addition of graphite powder and expanded graphite, finding that the latent heat of the heat conduction enhanced PCM decreased little due to small amount of the graphite, and that PCM structure exhibited good uniformity. Li et al. [180] synthesized shape-stabilized paraffin/silicon dioxide (SiO_2) composite PCM by using sol-gel methods, silicon dioxide was used as the supporting material. They found that the paraffin was well dispersed into the porous network of silicon dioxide, and that the paraffin/silicon dioxide composites had a solidifying temperature of 57.07 °C, solidifying latent heat of 59.66 kJ/kg, melting temperature of 58.10 °C, and melting latent heat of 139.59 kJ/kg.

Chen et al. [181] developed a novel shape-stabilized polymer-matrix phase change material via electrospinning technique. The results indicated that the electrospun fibers showed smooth surfaces and cylindrical shape with diameters ranging from several tens to several hundreds nanometer, and the latent heat of fusion of the fibers was of about 70.76 J/g. Although the tensile properties of the electrospun composite fibers were lower than that of the electrospun pure fibers, they showed suitable and competent tensile strength for the potential applications in solar energy storage and thermo-regulating textile.

Yan et al. [182] prepared and studied shape-stabilized paraffins with phase change temperatures between 20 and 30 ºC, and high phase change latent heat. The results showed that the prepared shape-stabilized PCM are ideal thermal storage materials to be used in walls, that they have good stability, no leakage, and that the phase change latent heat increases with the increasing of the mass content of paraffin mixture.

Ma et al. [183] have prepared a shape-stabilized composite phase change building material for latent heat storage by a vacuum infiltration method using the eutectic mixture of palmitic acid and hexadecanol as phase change material, expanded perlite as skeleton. The phase change temperature and the phase transition enthalpy of melting for the composite were found to be 41.49 °C and 122.9 J/g, the thermal conductivity of the composite was increased by adding 10% graphite. It was determined that the composite can integrate with normal building materials well, so that the building material which has thermal adjustment function can be prepared further.

Wang and Meng [184] prepared and analyzed the properties of a composite shape-stabilized phase change material based on lauric acid-myristic acid eutectic as core material, polymethyl methacrylate as polymer matrix and azobisisobutyronitrile as initiator; the composite was prepared by self-polymerization method. The results indicate that fatty acid and the composite have no chemical reaction and exhibit good compatibility with each other. The prepared composite keep the excellent thermal energy storage performances with proper phase change temperature and high latent heat, and has better resistance to the high temperature than the pure fatty acid. It was concluded that this kind of fatty acid/composite has the advantages of no seakage of liquid, low cost and simple process has potential values in solar application for building energy conservation.

Recently, Son et al. [185] reviewed recent studies on the preparation methods of shape stabilized phase change materials (melting and absorption methods), and also studied PCM based on polypropylene blended with n-eicosane.

Liang et al. [186] prepared and studied shape-stabilized phase change paraffin with high-density polyethylene as the support materials in walls. Both the two prepared mixtures have low melting point and are suitable for the wall. Their phase change temperatures were 26.6 and 25.5 °C, respectively, and they have higher phase change latent heats. After analyzing the materials by the DSC method, it was concluded that the shape-stabilized phase change paraffin is the ideal energy storage materials used in the wall.

Zhou et al. [187] investigated numerically the thermal characteristics of shape-stabilized PCM wallboard with sinusoidal temperature wave on the outer, and compared them with traditional building materials such as brick, foam concrete and expanded polystyrene. Phase transition keeping time of inner surface and decrement factor were applied to analyze the effects of PCM thermophysical properties (melting temperature, heat of fusion, phase transition zone and thermal conductivity), inner surface convective heat transfer coefficient and thickness of the wallboard They concluded that thermal conductivity of the PCM and inner surface convective coefficient almost have no effects on the phase transition keeping time, and that the outer surface convective coefficient slightly affects the decrement factor within the normal range of outdoor air velocity; and phase transition zone leads to small fluctuations of the original flat segment of inner surface temperature line. The results aim to be useful for the selection of shape-stabilized PCM wallboards and their applications in passive solar buildings and related areas.

A thermal analysis of the south-facing direct-gain room with a shape-stabilized PCM has been performed [188], finding that:

- The effect of PCM plates located at the inner surface of an interior wall is superior to that of an exterior wall (the south wall).
- The external thermal insulation of the outer wall obviously influences the operating effect and period of the plates and the indoor temperature in winter.
- The plates create a heavyweight response to lightweight constructions with an increase of the minimum room temperature at night by up to 3 °C for the case studied.
- The plates really absorb and store the solar energy during the daytime and discharge it later and improve the indoor thermal comfort degree at nighttime.

1.4 Building applications of Phase Change Materials

1.4.1 Introduction to building applications of PCM

The use of PCM in buildings provides the potential for a better indoor thermal comfort for occupants due to the reduced indoor temperature fluctuations, and lower global energy consumption due to the load reduction/shifting [189], furthermore, the ability to store thermal energy is important for effective use of solar energy in buildings [190].

Indeed, the use of PCM for thermal storage in buildings was one of the first applications studied, together with typical storage tanks. The first application of PCM described in the literature was their use for heating and cooling in buildings [26]. The use of building structural components for thermal storage was pointed out already in 1975 by Barkmann and Wessling [191], and Telkes [192], and later by other authors [21,193]. However, in general terms, the selection of PCM to meet residential building specifications has received minor attention, although it is one of the most foreseeable applications of PCM.

Phase change materials can be used in building envelopes to provide both latent and sensible heat storage. Castellón et al. [194] demonstrated experimentally that it is possible to improve the thermal comfort and reduce the energy consumption of a building without substantial increase in the weight of the construction materials with the inclusion of phase change materials. Their work was based on an experimental setup with various typical insulation and construction materials in real conditions in Puigverd de Lleida (Lleida, Spain). Nine small house-sized cubicles were constructed: two with concrete, five with conventional brick, and two with alveolar brick. PCM was added in one cubicle of each typology. For each type of construction specific experiments were done. In all cubicles, free-floating temperature experiments were performed to determine the benefits of using PCM. A Trombe wall was added in both concrete cubicles and its influence was investigated. All brick cubicles were equipped with domestic heat pumps as Heating, Ventilation, and Air Conditioning (HVAC) system; therefore, the energy consumption was registered, providing real information about the energy savings. Results were very good for the concrete cubicles, since temperature oscillation were reduced by up to 4 °C through the use of PCM and also peak temperatures in the PCM cubicle were shifted in later hours. In the brick cubicles, the energy consumption of the HVAC system in summer was reduced by using PCM for set points higher than 20 °C. During winter an insulation effect of the PCM was observed, keeping the temperatures of the cubicles warmer, especially during the cold hours of the day.

A second work performed at this same experimental setup was that of Castell et al. [195], who worked specifically with the cubicles constructed with brick (conventional and alveolar). For each construction material, macroencapsulated PCM was added in one cubicle (RT-27 and SP-25 A8). The cubicles had a domestic heat pump as a cooling system and the energy consumption was registered to determine the energy savings achieved. The free-floating experiments show that the PCM can reduce the peak temperatures up to 1 ºC and smooth out the daily fluctuations. Moreover, in summer the electrical energy consumption was reduced at the PCM cubicles in about 15%, which resulted in a reduction of the CO_2 emissions of about 1–1.5 kg/year/m^2.

Another work performed at the mentioned setup is that by Castellón et al. [196], who worked on the effect of microencapsulated PCM over sandwich panels. More details about this work are given in section 1.4.4, where the sandwich panels topic is discussed.

In 2008, Voelker et al. [197] elaborated a mathematical model based on an energy balance equation applied to a PCM-conditioned room in order to be able to reproduce the PCM effects over buildings and the influence of boundary conditions such as, for instance, the air change rate. The model was experimentally validated by means of measurements using paraffin as well as a salt mixture. A reduction of the peak temperature of up to 4 K could be ascertained. Furthermore it could be proven that the PCM forfeit their characteristic heat storage capacity after a few consecutive hot days, if they cannot be discharged over night, however, efficient night ventilation can counteract such effects.

As seen, the thermal storage efficiency of the building is improved and energy savings can be achieved. Different approaches have been studied for energy saving and thermal comfort improvement, depending on the building material and location in the building (envelope, heating/cooling system, etc.). Some reviews on the use of PCM in buildings summarize these techniques [33,120,198].

During the last 25 years, several forms of bulk encapsulated PCM have been marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial products was inadequate to deliver heat to the building after the PCM was molten by direct solar radiation. In contrast, the walls and ceilings of a building offer large areas for passive heat transfer within every zone of the building [199]. Several researchers have investigated methods for impregnating gypsum wallboard and other architectural materials with PCM [102,103,200,201]. Different types of PCM and their characteristics are described. The manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which have been impregnated with PCM, are discussed in several references [25,145][202].

The temperature inside a building depends, among other things, on the outdoor temperature and on the heat capacity of the construction material and other components in the building (Figure 9).

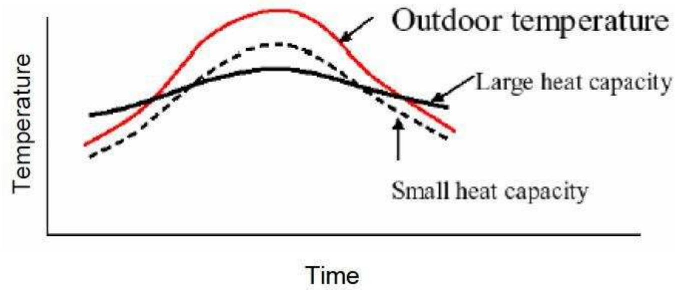


Figure 9. Temperature stabilizing effect by heat capacity of a building [202].

However in order to keep the weight of the building low, most building materials exhibit a low heat capacity. Introduction of phase change materials into the buildings materials will considerably increase the thermal mass of the building. Figure 10 shows the amount of different buildings materials required to achieve the same thermal mass as that of 1 cm of PCM. By mixing of conventional construction materials with phase change materials the thermal mass of the building will increase without substantial increase of the weight of the material. Simulations have shown that peak temperatures during hot days can be reduced by 2 ºC to 3 ºC by introduction of PCM into the building materials. However night time ventilation is crucial to release the stored heat and regenerate the PCM [202].

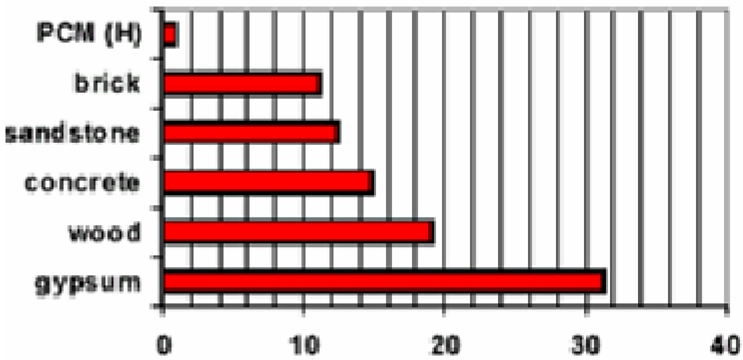


Figure 10. Amount of material required for equivalent thermal mass [202].

Several studies determined that between 15 to 20% of energy savings could be achieved by using thermal energy storage in buildings [145,203,204].

One important limitation of PCM application in building envelopes is its seasonal working period. Since the PCM is melting at a narrow range of temperatures, the latent heat can only we useful for certain weather conditions. Therefore, the PCM used must be selected for cooling or heating applications, but it can not be used for both. The PCM that reduces the internal air temperature swing during the winter season is not suitable for the summer season as the PCM remains in the liquid state at all the times during these months and hence the system cannot exploit the latent heat effect. This limitation implies the PCM is not working during a significant part of the year, reducing the thermal benefits achieved, the energy savings and its economical viability. Pasupathy and Velraj [205] studied numerically a double layer PCM concept to achieve year round PCM effect and passive thermal management.

1.4.2 PCM for peak load shifting

A big problem regarding energy consumption these days is the increase of the peak demands. At many countries important overloads of the electrical grid are detected during peak hours in summer. This extremely high energy consumption focused in few hours results in serious problems for both the grid and the power plants.

Using PCM as an energy storage system could solve the problem of electricity supply and demand mismatch. Thermal storage can shift cooling load from peak to off peak hours [206-208]. As a result, power generation capacity can be reduced and, when low rates for electricity are available at off peak hours, shifting the energy consumption will be cost effective. In 2008 Qureshi et al. [209] examined the application of price based demand side management in built environment using PCM. Two potential advantages were detected; reduced price of electricity consumption for consumer and price responsive peak load shifting during periods of high electricity demand for the distribution network companies. Using efficient thermal management for PCM home heating application it has been demonstrated that peak load shifting and consumption during low wholesale price can be achieved without compromising on comfort level. The results have also shown that PCM can provide energy efficiency gains and could possibly result in saving energy cost.

The peak demand for electricity during summer increases because of the air conditioning at commercial buildings. This increase results in high daytime demands and low night time loads. Nagano et al. [210] studied a new floor supply air conditioning system, using phase change material (melting at 20 ºC) to increase the building thermal storage. Results from measurements simulating an air conditioning schedule in office buildings indicate that 89% of daily cooling load could be stored each night in a system with 30 mm thick packed bed of granular PCM. However, the use of PCM deteriorated the control of the room temperature. The authors say this can be improved by varying the air flow rate as a function of the cooling load.

Following a similar trend, Halford and Boehm [211] studied the potential peak air conditioning load shifting by using encapsulated PCM within the ceiling or wall insulation (RCR – resistive, capacitive, resistive). They developed a simplified numerical model based on explicit numerical solution and finite difference method.

When the PCM was in one-phase the system was governed by the one-dimensional diffusion equation, and when it was in two-phase by the Stefan condition. Results showed that a significant load shifting is at least theoretically possible. Depending on the inner wall temperature range, the maximum reduction of the peak load is about 11-25% when compared to the same system but without phase change, and about 19-57% compared to the system with no PCM. The simulation demonstrated that the effectiveness of the material is freezing limited. The authors remark that the simulation is a merely first approach at modelling an extremely complex problem. Many simplifications were done and must be validated (such as the one stating that the variation of temperatures is steady-periodic).

Zhang et al. [212] developed a thermally enhanced frame wall using phase change materials to reduce peak air conditioning demand in residential buildings and did experimental tests. The macrocapsule containment method reduced the flammability of the wall and eliminated the moisture transfer problem across the envelope. Results showed that peak heat fluxes were substantially reduced (up to 38% of reduction) as well as the space-cooling load (from 8.6% to 10.8%). The load shifting was spread over many hours and the relative humidity of indoor air did not increase.

Yamaha and Misaki [213] proposed an air distribution system with PCM in air ducts for peak load shaving. The simulation study based on a part of one floor of an office building in Japan showed that the use of 400 kg of PCM in the proposed system for a room with 73.8 m^2 surface could maintain a constant indoor temperature without using any cold source in a hot summer day. The melting temperature suitable for the system was around 19 ºC, which can be achieved by using MT19.

The effects of the peak shaving control of air-conditioning systems using the PCM ceiling board in an office building in Tokyo, Japan were examined by Kondo and Ibamoto [214]. The results from numerical simulations showed that the maximum thermal load using the PCM ceiling board was reduced by 9.4% as compared to the conventional rock wool ceiling board. The overall running cost was 96.6% lower than that of the rock wool ceiling board due to the use of discounted nighttime cheap electricity.

A thermally enhanced frame wall that reduces peak air-conditioning demand in residential buildings was presented by Zhang et al. [212]. Two identical test houses (1.83 x 1.83 x 1.22 m) of conventional residential construction were used for the experimental study. One house was used as a control house and the other as a retrofit house with the PCM frame wall. The results showed that the retrofit house using the PCM frame wall with a 10% PCM concentration can reduce the wall peak heat flux and space cooling load about 15% and 8.6% respectively, as compared to the control house. It is also showed that the west and north walls achieved more heat rate reductions than the south wall and the load shifting was spread over many hours from about midnight until about 13:00 pm.

The application of PCM wallboards in buildings for peak load reductions was studied by Shilei et al [215]. A test was conducted in a 5mx3.3 mx2.8 m experimental room with a 1.5 m x1.5 m window in the south wall and a 1 m x 2 m wooden door in the north wall. The results showed that the PCM wallboard room could greatly reduce the operating cost of HVAC systems and transfer electric power peak load to valley. When indoor temperature exceeds 18.5 ºC in summer, the PCM in wallboards will melt and absorb 39.1 kJ/kg of energy before completely melting at 24.3 ºC, which can maintain indoor temperature in the comfortable range and decrease the cooling load of air-conditioning.

1.4.3 PCM for air-conditioning applications

The use of PCM to store coolness have been developed for air conditioning applications, where cold is collected and stored from ambient air during night, and it is released indoors during the hottest hours of the day. This concept is known as free-cooling [69,214]. Regarding suitable PCM for this type of applications and the type of installations themselves, Domínguez et al. [216] have described both the materials (along with their advantages) and some installation types, concluding that PCM in microcapsules facilitate the use of free cooling. Also, Domínguez and García [217] have reviewed the possibilities of PCM in the field of the air conditioning; they described several installations of climatization where PCM have been satisfactorily incorporated and diverse types of installations including systems of thermal energy production as well as those that take advantage of free cooling in direct form, or indirect form by means of evaporative systems, or those that take advantage of residual heats or cogeneration.

Very recently, Stritih and Butala [218] studied the amount of stored cold in an experimental setup with paraffin as phase change material, and proposed a polynomial equation to calculate the air cooling time and with this the cold storage for a variety of velocities and inlet air temperatures. The authors claim that their model will calculate temperature fields in certain time in paraffin area as well as air temperatures.

Free-cooling (Figure 11) was also studied by Zalba et al. [69,219]. An installation which allows testing the performance of PCM in such systems was designed and constructed. The main influence parameters were determined theoretically and experiments are performed following the Design of Experiments strategy. With the empirical model developed in this work, a real free-cooling system was designed and economically evaluated (Figure 12).

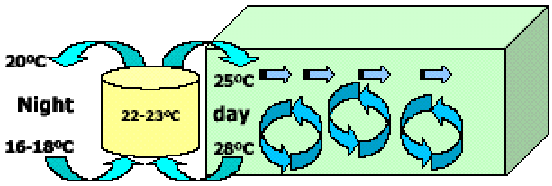


Figure 11. Concept of free-cooling [219].

An interesting project developed at the University of South Australia [220] is a solar air space heating system. The principle is to capture the sun heat during the day, to transfer it to a storage facility, and then retrieve it later when needed. The system consists of an air based roof integrated collector (Figure 13) and a thermal storage unit containing PCM (Figure 14).

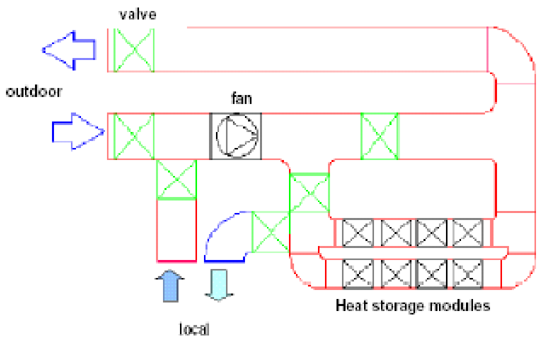


Figure 12. General outline of a free-cooling installation [219].

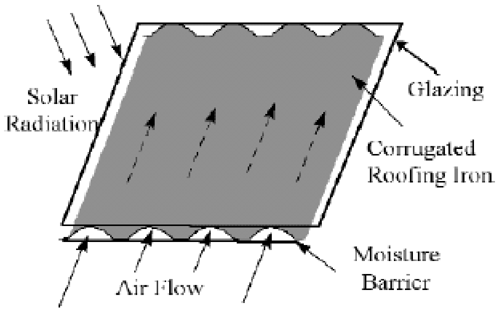


Figure 13. Air based roof integrated collector [220].

Figure 14. Thermal storage unit with PCM [220].

A new proposal is the use of a floor supply air conditioning system with latent heat storage. The main idea is still similar to free-cooling, but using different parts of the building [221-223].

This idea was developed by Takeda et al. [221]. Cold energy is stored in building structures and granulated PCM at night. Granulated PCM (Figure 15) particle diameter of around 3 mm, is paved a few centimetres in thickness under the floor space (Figure 16). Packed PCM is breathable and PCM can directly exchange heat with the air.

Figure 15. Granulated PCM used by Takeda et al. [221].

Parameshwaran et al. [224] developed a new combined variable air volume (VAV)-based chilled water air conditioning system and thermal energy storage (TES) system (Figure 17). The system was experimentally investigated for summer and winter climatic conditions under demand controlled ventilation (DCV) and DCV combined with the economizer cycle ventilation (ECV) to substantiate its energy savings capability. Based on the results, in the DCV and combined DCV-ECV modes, the system achieved 28% and 47% of per day average energy conservative potential, respectively, while compared to the conventional chilled water-based air-conditioning system. Similarly, the VAV-TES system yielded an on-peak total energy savings of 38% and 42%, respectively, for the same operating conditions.

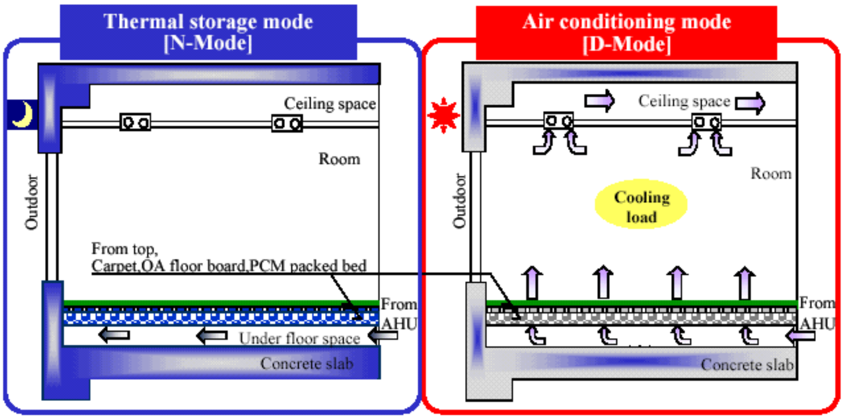


Figure 16. PCM floor supply air conditioning system [221].

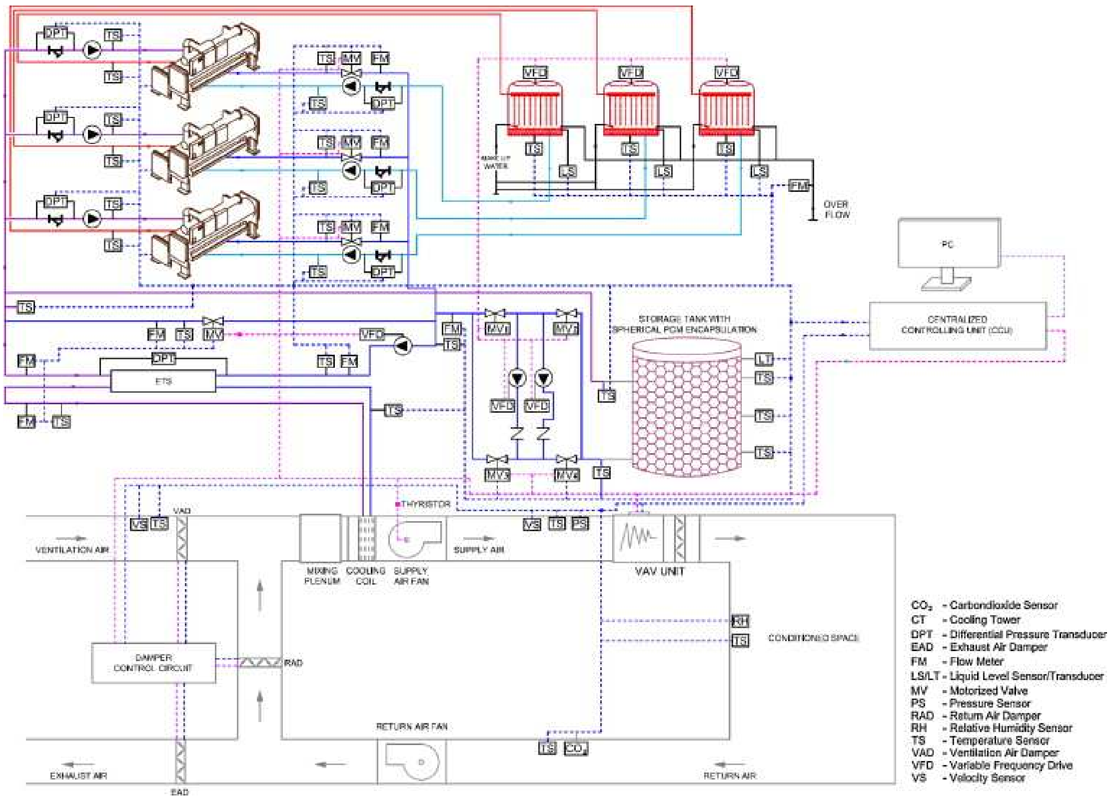


Figure 17. Schematic representation of the VAV–TES air conditioning system [224].

1.4.4 Some examples of PCM building applications

1.4.4.1 Wallboards impregnated with PCM

New construction systems tend to use of light and prefabricated materials in order to reduce costs and time of construction. Thermal inertia of the buildings is therefore reduced, resulting in higher incidence of the weather conditions in the thermal comfort. Wallboards enhanced with PCM will provide thermal storage distributed throughout the complete building, enabling passive solar design and off-peak cooling in traditional frame constructions with a typical low thermal mass. The performance of the wallboards will depend on several factors: the melting temperature of the PCM, the temperature range over which melting occurs, the latent capacity per unit area of the wall, how the PCM are incorporated in the wallboard, the orientation of the wall, climatic conditions, direct solar gains, etc. However, because not all factors can be taken into account, most studies on PCM enhanced wallboards deal with the choice of the phase change material, the manufacturing methods and the method of testing [20].

An interesting possibility in building applications is the impregnation of PCM into porous construction materials, such as plasterboard, wallboards or concrete blocks impregnated with PCM [225], and underfloor heating with latent heat storage, to increase thermal mass [145,200]. The use of wallboards containing PCM is an interesting approach to reduce the temperature oscillations. The wall large heat transfer area supports large heat transfer between the wall and the space [21]. The low price and extended use of wallboards is also a strong point of this technology.

Scalat et al. [226] tested a full scale latent heat storage wallboard. Two identical rooms were used; one with ordinary gypsum wallboard and the other one with PCM impregnated gypsum wallboard. The PCM was 50% butyl stearate and 48% butyl palmitate. For both heating and cooling operation the PCM wallboard room exhibited a better thermal behaviour. The volatile organic compounds were also studied and the results showed a comparable air quality for both rooms.

In 1997 Athienitis et al. [227] studied experimentally and numerically the behaviour of PCM-gypsum in a full scale outdoor test room. The PCM gypsum board contained a proportion of 25% by weight of butyl stearate. An explicit non-linear finite difference model using the enthalpy method was developed to simulate the transient heat transfer process in the walls, showing a root mean square (rms) difference of 0.25 ºC with the experimental results. They demonstrated that the use of PCM gypsum board may reduce the maximum room temperature by about 4 ºC during the day time and increase the surface temperature of the PCM-gypsum wall 1.5 ºC during the melting process (7-11 hours). These effects can reduce the heating load at night significantly. Nevertheless, the authors considered more experimental work should be done, comparing two identical test-rooms with and without PCM under the same working conditions.

Fang and Zhang [228] developed a new composite by blending an organic PCM with an organic-modified montmorillonite. They fabricated and tested several gypsum boards with PCM in small rooms (70x70x70 mm), consisting of five conventional gypsum boards and a top gypsum-PCM board. The tested board contained: no PCM, 20% of PCM, and 50% of PCM. The results showed a reduction of the indoor temperature variation (40, 35, and 31 ºC respectively), improving with the increase of PCM used in the board.

Oliver et al. [229] studied the suitability of including PCM in gypsum boards to multiply their thermal energy storage capacity. The thermal storage capacity of several constructive materials was evaluated and compared, whose use and application is similar to the gypsum boards: panelling of a wall and partition wall. An experimental facility was designed and operated for their study of the new compound material, exchanging heat with air. The influence of different parameters and system variables (working temperature, air velocity, display of the phase change materials, and location in the building...) were studied to establish a latent heat storage system which, complemented with passive strategies (solar gains, natural ventilation), could reduce the acclimatization energy consumption in buildings. They demonstrated that a 1.5 cm-thick gypsum board including 44.5% in weight of PCM is able to store 5 times the thermal energy of a current gypsum board with the same thickness, and the same amount to 11.5 cm brick layer, in the comfort temperature range (20-30 °C), maintaining the required mechanical and physical properties.

Borreguero et al. [230] analyzed the feasibility of incorporating microcapsules containing PCM, previously obtained by a suspension polymerization process, in gypsum wallboards to increase the wall energy storage capacity. The thermal behaviour of three gypsum wallboards, one without PCM and the others doped with 4.7% and 7.5% by weight of microcapsules containing Rubitherm® RT27 was studied. Results showed that the higher the amount of microcapsules containing PCM incorporated to the gypsum wallboard, the lower or higher the external wall temperature for heating or cooling process, respectively. Besides, the incorporation of the microcapsules to the wall increased the time required to achieve the final steady state, verifying that the material insulation capacity was enhanced by increasing the PCM content in the wall.

A new approach to incorporate PCM in wallboards was studied by Schossig et al. [138]. They developed a micro-encapsulated PCM, allowing an easy application, good heat transfer and no need for protection against destruction (Figure 18). An experimental setup was build and two different PCM were tested. The results demonstrated the benefits of using PCM with lower internal temperatures (up to 4 ºC lower) and a delay of one hour on the maximum temperature (Figure 19). An increase of the thermal comfort is also achieved. The main limitation of the system is the discharging of the PCM at night. For this purpose an active cooling system is under development. Another approach is to mould into concrete containers of relatively large size (compared to the thickness of the wall or ceiling), which are filled with phase change material [203].

Ahmad et al. [231] studied experimentally the behaviour of wallboards containing PCM. Three types of wallboard were tested: (i) a polycarbonate panel filled with paraffin granulates; (ii) a polycarbonate panel filled with polyethylene glycol PEG 600; (iii) a PVC panel filled with PEG 600 and coupled to a vacuum insulation panel (VIP) (Figure 20). In the first case, the low thermal conductivity reduced the stored heat during the operation. This problem was solved for the second case, but some structural problems appeared because of the liquation process (resulting in cracks in the panel).

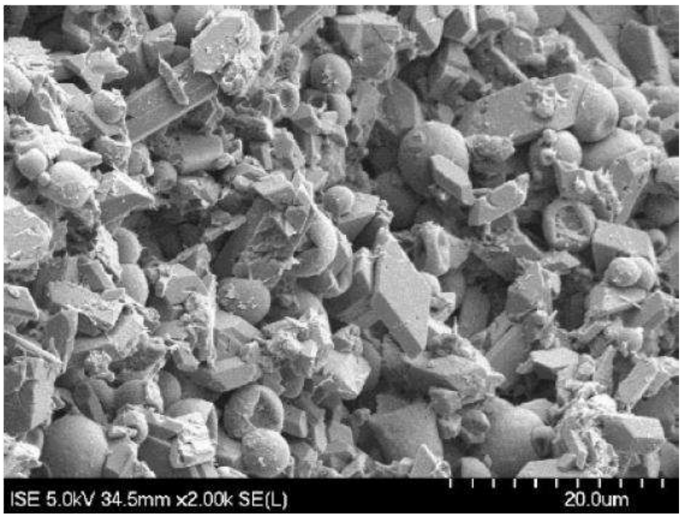


Figure 18. SEM-picture of microencapsulated PCM in gypsum [138].

Structural stability was achieved by using PEG and VIP panels. A numerical model was also used and validated and the system was experimentally tested in a test cell, achieving the storage of the solar energy with a high reduction of the inside temperature [232].

Hasse et al. [233] studied thermally the behaviour of honeycomb panels filled with PCM (paraffin) for short-term heat storage. The response of the PCM panel to temperature variations was studied with a specific test bench. Temperature and flux measurements showed a significant thermal inertia increase compared to samples filled with air and water. Modelling and numerical simulation were carried out and validated with the experimental results.

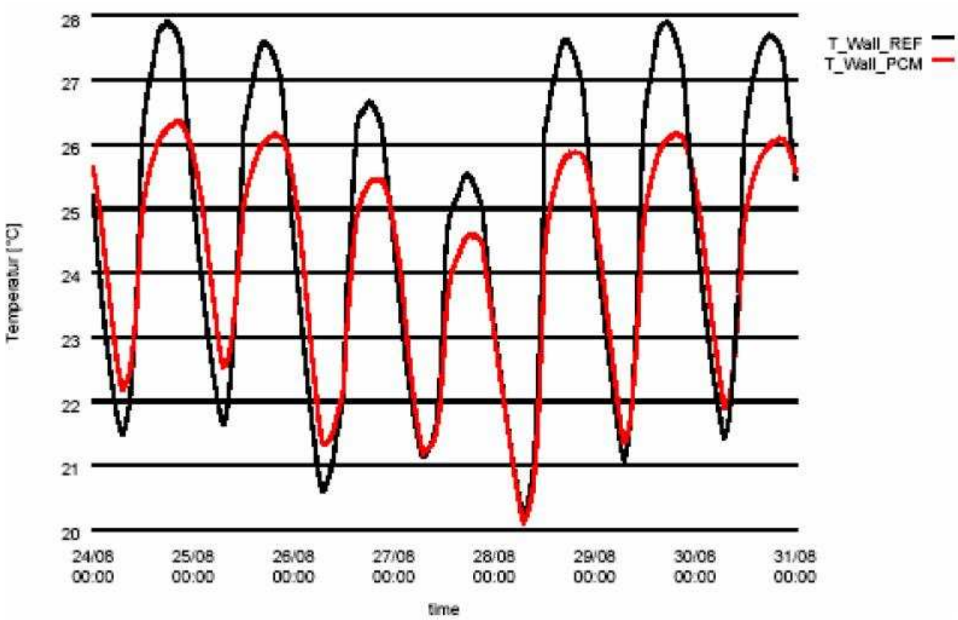


Figure 19. Wall temperatures with night ventilation and shading [138].

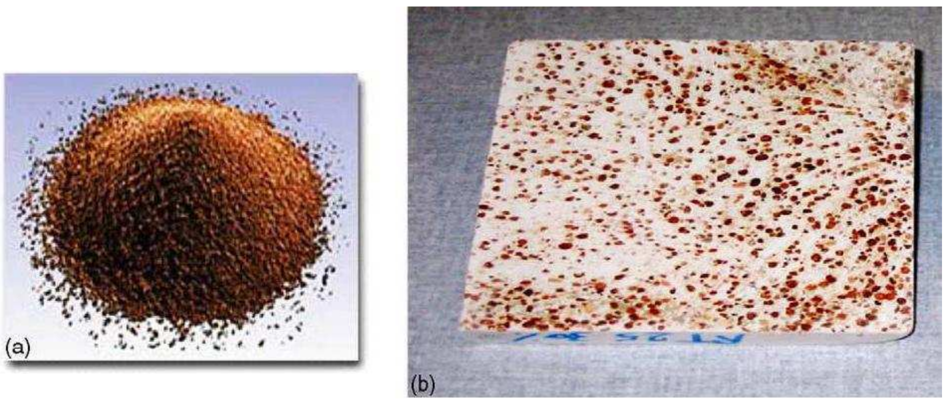


Figure 20. (a) Granulates filled with paraffin and (b) gypsum-granulate sample [231].

Quanying et al. [234] studied the thermal performance of shape-stabilized phase change material wallboards and common wallboard. Shape-stabilized PCM consisted of paraffin and high-density polyethylene as support materials. The wallboards were prepared by shape-stabilized PCM and grout with the building materials in mass proportions of 5%, 10%, and 15%. The phase change temperature of the shape-stabilized paraffin was 27.5 °C and the maximum content of paraffin in the shape-stabilized PCM was 70%. The energy-saving effect and feasibility of shape-stabilized

PCM wallboard were compared with those of ordinary wallboards. Their main observations were the following:

- During the heating process, the higher the content of the shape-stabilized phase change, the lower the surface temperature of the wallboard, and the smoother the temperature changes.
- In the cooling process, the fluctuation of the temperature in the PCM wallboard is small.
- The bigger the content of PCM, the smaller the thermal flow and its fluctuation.
- There is no leakage during the heating process, and it is not necessary for shape-stabilized PCM to be loaded by the containers.

Castellón [17] presents a bibliographical compilation of substances that have been studied by different researchers for their potential use as PCM including their thermophysical properties, but only taking into consideration substances with melting temperatures of 16 to 30 ºC as they were meant for applications in buildings. A list of commercially available PCM along with their thermophysical properties as given by the manufacturers may also be found at the same work.

Chen et al. [235] studied theoretically a new kind of phase change material based on paraffin for energy-storing wallboard. The simulation and calculation were made using the software MATLAB to analyze and solve the heat transfer problem of the PCM setup room. It was found that the heat storing/releasing ability of the new PCM is significantly higher than that of ordinary materials. The result indicates that applying proper PCM to the inner surface of the north wall in the ordinary room can not only enhance the indoor thermal-comfort dramatically, but also increases the utilization rate of the solar radiation, so the heating energy consuming is decreased and the goal of saving energy is achieved. It was determined that the seasonal heating energy-saving rate can get to 17% or higher if the parameters of the PCM are the following: the phase change temperature is set at 23 °C, the thickness is set at 30 mm, the phase change enthalpy is set at 60 kJ/kg, and the heating temperature is set at 20 °C.

Yan et al. [236] prepared and studied four types of shape-stabilized PCM, consisting of paraffin and high-density polyethylene. The paraffin used in the experiment were mixtures of liquid paraffin and 46# paraffin, liquid paraffin and 48# paraffin, liquid paraffin and n-octadecane, and n-heptadecane and 48# paraffin, respectively. The phase-change temperatures of these mixtures are between 21 and 28 °C, and they have a high phase-change latent heat. The polyethylene was mixed in proportions of 50-90% with paraffin mixtures. The phase-change temperatures, the phase-change latent heats, and the uniformity and stability of the shape-stabilized PCM were studied experimentally by the DSC method. The results showed that prepared shape-stabilized PCM are ideal thermal storage materials to be used in wallboards.

Mixtures of liquid paraffin and stearic acid, myristic acid, lauric acid and palmitic acid have also been prepared and investigated. Thermal properties of several mixtures were studied experimentally by the DSC. The results showed that the phase-change temperatures and the phase-change latent heats of mixtures decrease with the increasing mass content of liquid paraffin. The phase change temperatures of mixtures of liquid paraffin and palmitic acid, myristic acid and stearic acid are more than 30 °C, so they are not suitable for wallboard. When the mass contents of liquid paraffin are 60-80%, the phase-change temperatures of the mixture of liquid paraffin and lauric acid are 20.7-28.6 °C and the phase change latent heats are 35-90 J/g. So mixtures of liquid paraffin and lauric acid are suitable phase change materials for use at wallboards [237].

1.4.4.2 Wood-lightweight-concrete

An important disadvantage of lightweight buildings is their low thermal mass. They tend to have high temperature fluctuations, which results in a high heating and cooling demand. The application of PCM in such buildings is very promising because of their capability to smooth temperature variations [193].

An example was developed by Mehling et al. [238]. They studied the inclusion of PCM in wood-lightweight-concrete. Wood-lightweight-concrete is a mixture of cement, wood chips or saw dust (less than 15 wt.%), water and additives. It has advantages such as good thermal insulation (between 0.15 and 0.75 W/m·K), noise insulation, good mechanical properties (density between 600 and 1,700 kg/m^3), and a heat capacity between 0.39 and 0.48 kJ/kg·ºC with a density of 1,300 kg/m^3. Its applications are building indoors, outer wall construction, storey buildings and prefabrication.

The idea of combining PCM with wood-lightweight-concrete would increase the thermal storage capacity and get lighter and thinner wall elements with improved thermal performance. The PCM chosen for such application was Rubitherm granulate GR 40, 1 – 3 mm, and GR 50, 0.2 – 0.6 mm (Figure 21). Mixtures of 20% wood replaced by paraffin, or mixtures with additional 20% PCM were tested. They concluded that PCM can be combined with wood-lightweight-concrete (Figure 22), and that the mechanical properties do not seem to change significantly.


Figure 21. Rubitherm granulate GR 40, 1 – 3 mm [238].

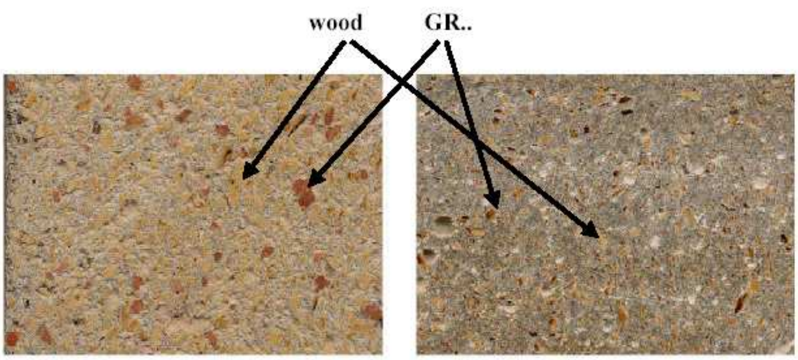


Figure 22. PCM in wood-lightweight-concrete [238].

1.4.4.3 Concrete blocks impregnated with PCM

A possibility for applying PCM in building constructions is PCM enhanced concrete or the so-called thermocrete. Thermocrete is a heat storage medium combining an appropriate PCM with a concrete matrix or open-cell cements to produce low cost storage materials with structural and thermostatic properties [20].

The benefits of using PCM in concrete depend on the amount of PCM absorbed. The absorption of the phase change material into the concrete is proposed to avoid a precipitation of incongruent melting PCM [137]. A very important consideration in the use of these thermal storage building materials is the stability of the PCM in the concrete throughout its service life. Several phase change materials have been tested and so has been a modified concrete for the stability of PCM [133,239,240].

The use of PCM in concrete blocks was studied by Khudair [241]. In this study, paraffin RT20 as PCM was successfully impregnated into gypsum wallboards, pumice aggregates and concrete, showing a significant thermal storage effect. Measured and simulated thermal performances of full scale buildings showed that the PCM-building materials have managed to smooth out the daily fluctuation of indoor air temperature by lowering the diurnal peak temperatures and maintaining a pleasant temperature. PCM-buildings materials could be installed with the same techniques and equipment used for conventional building materials.

Lee et al. [242] studied and presented the results of macro-scale test that compare the thermal storage performance of ordinary concrete blocks with those which have been impregnated with two types of PCM, butyl stearate and commercial paraffin. PCM-building materials could be installed with the same techniques and equipment used for conventional building materials.

Another technique consists on introducing the PCM directly into the hollows of the construction blocks. Salyer et al. developed some methods to contain PCM [243] and applied them to solid hollow-core building blocks [244]. A new composition (K-18/HDPE/EVA/ABS melt-mix), which can be mechanically mixed to form dry pellets that contain the PCM, was developed. It was demonstrated that using PCM/HDPE pellets, PCM/silica dry powder, or the PCM melt-mix into the hollow-core space of concrete blocks can accommodate large quantities of PCM, resulting in a large thermal storage.

Lamberg et al. [245] studied numerically the effect of including PCM in concrete and aggregate concrete elements (ACO) for Helsinki and Lisbon weather conditions. Results showed that night ventilation is needed to enhance the weak heat transfer between structure and air. The effect of the PCM concrete structure on indoor comfort was small in Helsinki, but the indoor temperature and the predicted percentage of unsatisfied people could be reduced in the PCM ACO room both in Helsinki and especially in Lisbon.

Castellón [17] and Cabeza et al. [133] determined experimentally the benefits of a new composite material, mixing Micronal® from BASF with concrete. The study, in the framework of the European project MOPCON, demonstrated the improvements that can be achieved, reducing the temperature up to 4 ºC. Ibáñez et al. [246] studied numerically the behaviour of the new PCM-concrete and the results were validated with the experimental set-up.

Shi et al. [247] studied experimentally the use of PCM (paraffin) in mass concrete in order to prevent thermal cracks. As the latent heat of PCM is released or absorbed at a certain temperature in a mass of concrete, PCM can be used to control temperature stress and prevent temperature cracking. The temperature distribution was tested in the middle area of a PCM mass concrete for temperature control. The compressive strength and permeability of PCM mass concrete were tested, and microscopic pore structure of PCM mortar was also investigated. The results showed that the compressive strength of concrete is reduced by adding PCM, but the anti-permeability of concrete is enhanced. The total porosity of PCM mortar did not change much compared to that of ordinary mortar, however, the pore diameter became bigger; the maximum temperature in mass concrete was also decreased by adding PCM; moreover, the rate of temperature increasing process and temperature dropping process were lowered, thus temperature crack formation in the mass of concrete could be prevented.

Gao et al. [248] investigated the influence of pre-embedded phase change materials on internal temperature rise of mass concrete. They employed a semi-adiabatic device to measure the temperature of cement paste, mortar and concrete with different contents of PCM at different hydration age. According to the relationship between cement hydration heat, latent heat and specific heat of PCM in different phase, a calculation formula of internal maximum adiabatic temperature rise of concrete with pre-embedded PCM was derived. The results showed that with the increase of pre-embedded PCM content, the reduction ratio of adiabatic temperature rise is increased, the appearance time of temperature peak is prolonged, and the curve of the semi-adiabatic internal temperature becomes gentle. It was also observed that with an increase of cement content in concrete, the reduction ratio of internal temperature rise was increased in the same content ratio of PCM.

Hunger et al. [249] performed a series of experiments using different amounts of PCM in self-compacting concrete mixes. The study focused on the direct mixing of micro-encapsulated PCM with concrete and its influence on the material properties. The fresh concrete properties and the hardened properties are investigated. The hardened properties comprise strength tests and an assessment of the thermal properties. It was shown that increasing PCM amounts led to lower thermal conductivity and increased heat capacity, which both significantly improved the thermal performance of concrete. On the other hand a significant loss in strength and micro-structural analysis both indicated that a large part of the capsules was destroyed during the mixing process and released its paraffin wax filling into the surrounding matrix, however, the compressive strength of our specimens still satisfied the demands of most structural applications.

1.4.4.4 Sandwich panel with PCM

The use of PCM in sandwich panel can constitute the solution to the overheating problems of lightweight buildings. Sandwich panels are characterized by low thermal inertia. The addition of PCM will increase the thermal inertia of the wall and will absorb heat when the wall is subjected to solar radiation. This constructive solution is largely used in industrial sites which present high temperature fluctuations since they have no cooling systems. The use of PCM can increase the human comfort and improve the working conditions.

Different prototypes of sandwich panels containing PCM have been tested and simulated. The results demonstrated a good behaviour and a large improvement when an air layer between the PCM and the external metal is added [17,250]. Castellón et al. [196] demonstrated the feasibility of using microencapsulated PCM in sandwich panels in order to increase their thermal inertia and to reduce the energy demand of the final buildings. They used three different methods. In case 1, the PCM was added mixing the microencapsulated PCM with one of the components of the polyurethane. In the other two cases, the PCM was added either a step before (case 2) or a step after (case 3) to the addition of the polyurethane to the metal sheets. The results showed that in case 1 the effect of PCM was overlapped by a possible increase in thermal conductivity, but an increase of thermal inertia was found in case 3. In case 2, different results were obtained due to the poor distribution of the PCM. Some samples showed the effect of the PCM (higher thermal inertia), and other sample results were similar to the conventional sandwich panel. In both cases (2 and 3), it was concluded that it is required to industrialize the process to improve the results.

Konuklu and Paksoy [251] developed and tested a PCM sandwich panel in order to evaluate the resulting decrease in heating and cooling loads of a test cabin in Adana, Turkey, where Mediterranean climate prevails. The panel was formed by a macropackage of microencapsulated PCM layer together with an insulation panel. Two different PCM, with melting points of 26 °C and 23 °C, were used in the panel. The temperature distribution in the cabin was measured for four different cases. In summer, the maximum average temperature reduction achieved in the cabin was 2.5 °C when only the PCM was used. This corresponded to a summer cooling load reduction of 7%. In winter, the maximum average temperature increase achieved in the cabin was 2.2 °C with the PCM sandwich panel. The winter heating load was decreased by 17%. Energies conserved in cooling and heating were calculated as 186 kWh/year and 206 kWh/year, respectively.

1.4.4.5 Brick with PCM

Alawadhi [252] studied numerically the behaviour of a PCM-brick composite for hot climates (Kuwait city). The PCM was introduced in the cylindrical holes of the bricks, with different amounts, PCM materials and locations studied. The model was bidimensional and used the finite elements method and the effective heat capacity to simulate the PCM. In order to evaluate the thermal effectiveness, the internal heat flux of the PCM-brick and the conventional brick were compared. Results showed a reduction of the heat flux up to 24.2% when using the best configuration. An increase on the PCM quantity resulted in better savings, being the best location the centreline of the brick.

Castell et al. [195] tested the inclusion of PCM in both conventional and alveolar brick for a Mediterranean construction under real conditions. Their experimental setup consisted on several cubicles whose thermal performance throughout the experiments time was measured. For each construction material, macroencapsulated PCM was added in one cubicle (RT-27 and SP-25 A8). The cubicles had a domestic heat pump as a cooling system and the energy consumption was registered to determine the energy savings achieved. The free-floating experiments showed that the PCM could reduce the peak temperatures up to 1 °C and smooth out the daily fluctuations. Moreover, the electrical energy consumption was reduced in the PCM cubicles in about 15%. These energy savings resulted in a CO_2 emissions reduction of about 1-1.5 kg/year/m^2.

1.4.4.6 Night ventilation with PCM

The high energy demands due to cooling loads can be reduced using cold storage at night by means of a free-cooling system, as exposed in section 1.4.3.

With this in mind, Stritih and Butala [253] studied experimentally and numerically the ceiling and floor free-cooling principle. The cold storage filled with paraffin was located in an air duct that was left in cold air at night. During daytime hot air was led through the air duct, which was cooled down due to the accumulated cold. The storage consisted of paraffin melting at 22 ºC with internal and external fins in order to increase the thermal power. Results showed a reduction of the peak temperatures leading to smaller room temperature fluctuations and a reduction of the cooling demand. A numerical model to simulate the behaviour of the free-cooling system was developed using control volumes and the enthalpy method, as well as standardized differential method. It was validated with experimental results showing a good agreement [253].

Arkar et al. [254,255] investigated the free cooling efficiency in a heavyweight and lightweight low energy building. They used a mechanical ventilation system with two latent heat thermal energy storages, one for cooling the fresh supply air and the other for cooling the re-circulated indoor air. The storage system consisted of spherical encapsulated PCM. A numerical model was developed and experimentally validated to simulate the system. Results showed the potential of free cooling with PCM to reduce the size of mechanical ventilation systems and enable better comfort conditions and fresh air to the building.

Very recently, Raj and Velraj [256] reviewed the work carried out by various researchers on free cooling. In addition the major challenges and facts posed in the use of phase change material for free cooling system design such as thermal resistance of air and phase change materials, geometry of encapsulation are discussed in detail. Also the method of energy efficient charging and discharging, effect of phase change temperature, insulation and geographical location are also discussed in this work. Their work also provides a list of the PCM candidates used for free cooling.

1.4.4.7 Under floor heating with latent heat storage

Zhang et al. [177,178] studied experimentally and numerically an under-floor electric heating system with shape-stabilized PCM plates. They also developed a model to simulate the behaviour of a shape-stabilized PCM floor system to absorb the solar radiation energy in the daytime and release the heat at night during winter [257]. The model considered one-dimensional heat transfer and constant thermal properties (except for the specific heat of the PCM). It was validated with experimental results obtained in a test cabin, showing a relatively good agreement. The model was used for a parametric study of different factors on the PCM behaviour. Obtained conclusions were:

- The suitable melting temperature of the PCM is roughly equal to the average indoor air temperature of sunny winter days.
- The heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ and 0.5 W/m·K.
- The thickness of shape-stabilized PCM plate should not be larger than 20 mm.
- The air-gap between PCM plates and the floor should be as small as possible.

Zeng et al. [258] developed and studied experimentally a novel structure of an integrated water pipe floor heating system using shape-stabilized phase change materials for thermal energy storage in the day time for heating at night. The thermal performances of the floors with and without the PCM were compared under the intermittent heating condition. The results showed that the energy storage ratio of the

PCM floor is much higher than that of the non-PCM floor; the PCM floor heating system could provide stable heat flux and prevent a large attenuation of the floor surface temperature. Also, the PCM floor heating system dampened the indoor temperature swing by about 50% and increased the minimum indoor air temperature by 2-3 °C under experimental conditions.

Deng et al. [259] studied the application of PCM in a floor radiation heating system. The composite granule PCM were prepared by sol-gel method and the PCM gypsum mortar was prepared by using the composite granule PCM. Based on the floor heating experiment platform, floor heating experiments were performed by using PCM mortar and common mortar separately to obtain the characteristics of charging and discharging latent heat energy of the containing PCM floor and to analyze the indoor temperature distribution. The results showed that PCM mortar as filled materials in floor heating system improved the indoor temperature environment and lowered the thickness and load of floor heating system.

1.4.4.8 Windows

Buddhi and Sharma [260] measured the transmittance of solar radiation through phase change material at different temperatures and thickness. Stearic acid was used as a PCM. They found that transmittance of the PCM was more than that of glass with the same thickness and suggested a new application of PCM in windows/walls as a transparent insulating material.

A subject related work was that of Ismail et al.[261,262] who, in order to diminish the solar gain in buildings, studied the possibility of using a window with a PCM curtain. This window is double sheeted with a gap between the sheets and an air vent at the top corner; the gap can be filled with PCM that upon freezing would prevent the temperature of the internal ambient from decreasing. Similarly, Merker et al. [263] have developed a new PCM-shading system to avoid overheating around the window area.

1.4.4.9 Roofs

The development of a thermally activated ceiling panel for incorporation in lightweight and retrofitted buildings was studied by Koschenz and Lehmann [32]. The designed system consisted on PCM microencapsulated and incorporated in gypsum wallboards. This mixture was enclosed in steel sheets and a capillary water tube system was used for an active control of the thermal mass. They developed a numerical model for computating the thermal behaviour of the wall and ceiling systems incorporating PCM. The model was based on the finite-difference and the Crank-Nicolson method and integrated in TRNSYS. The model predicted some requirements for the ceiling: 5 cm of panel thickness, 25% by weight of PCM in the gypsum and a thermal conductivity of 1.2 W/m·K (achieved by using aluminium fins). The validation of the model with experimental tests done in the laboratory showed a good agreement.

A similar system was studied by Pasupathy et al. [264]. They studied numerically and experimentally the behaviour of an inorganic eutectic PCM incorporated in a roof. Different cases were tested: (i) using a PCM thickness of 2.5 cm, (ii) using 3 cm of thickness, (iii) water-cooling the PCM. For the first case, the introduction of PCM helped in achieving a constant temperature at the ceiling during the months of December to April, but it had a negative effect during May to November. Using more

PCM did not improve the system because the material was not cooling down at night. Finally, water was used to control the PCM temperature and cool it down when necessary. The system worked properly, but the amount of required cold water was not easily available during summer periods.

1.4.4.10 Building insulation

Studies on PCM enhanced PU-foam and cellulose have been performed during the last decade. The PCM enhanced open-cell PU-foam was commonly installed in two layers of 6 mm between three low-emittance aluminium foils and installed on top of the mineral wool insulated studs. The PU-foam contained 0.49 kg/m^2 PCM with amelting point of 25.5 ºC and a maximum enthalpy of 140 kJ/kg. Hot-box measurements showed that it takes 3 h to fully charge the PCM and that thermal excitations of 22 ºC where reduced with 1.6 ºC. Comparison of heat fluxes with traditional constructions showed also a potential reduction of 40% in the wall-generated peak-hour cooling load. The same method has been applied on attic constructions, which resulted in a decreased attic summer air temperature from 43 to 32ºC. Microencapsulated paraffin PCM have been mixed with conventional loose-fill cellulose insulation at a rate of 22 wt% and installed in residential wall cavities without major modifications of the manufacturing or installation processes. The measured results of pilot projects are strongly depending on wall orientation and the location. Nevertheless, clear reductions of both cooling and heating loads are noticed [20].

Evers et al. [265] developed and tested PCM-enhanced cellulose insulation for use in frame walls. Two types of PCM, paraffin-based and hydrated salt-based, were mixed into loose-fill cellulose insulation at concentrations of 10% and 20% (by the weight of the wallboard) in a 1.22 m × 1.22 m (48 in × 48 in) frame wall cavity. The thermally-enhanced frame walls were heated and allowed to cool down in a dynamic wall simulator that replicated the sun exposure over a building wall on a typical summer day. The peak heat fluxes, total "daily" heat flows, and surface and air temperatures were measured. Results showed that the paraffin-based PCM-enhanced insulation reduced the average peak heat flux by up to 9.2% and reduced the average total "daily" heat flow up to 1.2%. However, because of the hydroscopic behavior of un-encapsulated hydrated salt, the hydrated salt-based PCM-enhanced insulation did not provide any thermal storage benefit.

Xiao et al. [266] installed a shape-stabilized PCM panel on the inner surface of a lightweight wall to lower the highest inner surface temperature and to improve its summer insulation performance. The effects of melting temperature and thickness of the PCM panel on the highest inner surface temperature were analyzed using an enthalpy model for west-facing wall in Beijing. The difference of thermal performance between the PCM panel and the traditional concrete layer was compared. The results showed that the PCM panel could lower the highest inner surface temperature of the lightweight wall greatly in summer with a modest increase in the weight.

1.4.4.11 Trombe wall

A Trombe wall is a primary example of an indirect gain approach. It consists of a thick masonry wall on the south side of a house. A single or double layer of glass or plastic glazing is mounted about 10 cm in front of the walls surface. Solar heat is collected in the space between the wall and the glazing. The outside surface of the wall is black coloured so it absorbs heat, which is then stored by the walls mass. Heat is distributed from the Trombe wall to the house over a period of several hours. When the indoor temperature falls below that of the walls surface, heat begins to radiate into the room. Heat loss from the Trombe wall can be controlled by an insulating curtain that is closed at night in the space between the glazing and the wall. Traditionally, Trombe walls relay on sensible heat storage but, because of the potential for greater heat storage per unit mass, the PCM Trombe wall is an attractive concept still awaiting successful implementation.

A wall filled with PCM was constructed on the south side of a house. The wall was heated during the day by incoming solar radiation, melting the PCM. At night the heat was withdrawn to warm the house. For a given amount of heat storage, the phase change units require less space than walls or Trombe walls, and are much lighter in weight. These are, therefore, much more convenient to make use of in retrofit applications of buildings. Salt hydrates and hydrocarbons were used as PCM in the Trombe wall [33].

Telkes [192] proposed the inclusion of PCM in walls, partitions, ceilings and floors to serve as temperature regulators. The PCM have been used to replace masonry in a Trombe wall. Askew [267] used a collector panel made of a thin slab of paraffin wax and mounted it behind the double-glazing of the building, concluding that the thermal efficiencies are comparable with the conventional flat plate collectors. Farouk and Guceri [268] studied the usefulness of a PCM wall installed in a building for night time home heating using glauber salt mixture and SUNOCO P-116 wax. It was observed that if the PCM wall is designed properly, it eliminates some of the undesirable features of the masonry walls with comparable results.

Bourdeau [269] tested two passive storage collector walls using calcium chloride hexahydrate (melting point 29 ºC) as a phase change material. He concluded that an 8.1 cm PCM wall has slightly better thermal performance than a 40 cm thick masonry wall.

Experimental and theoretical tests were conducted to investigate the reliability of PCM as a Trombe wall [270-272] using sodium sulfate decahydrate (melting point 32 ºC) as a phase change material in south facing Trombe wall. Trombe wall with PCM of smaller thickness was more desirable in comparison to an ordinary masonry wall for providing efficient thermal energy storage. Knowler [273] used commercial grade paraffin wax with metallic additives for increasing the overall conductivity and efficiency in the Trombe wall.

Castellón et al. [274] studied a Trombe wall added to the south facade in order to investigate if the effect of the PCM can be used all year long in a Mediterranean climate to reduce both cooling and heating demands. The authors recommended using the Trombe wall from April to June and from October to November or December.

1.4.5 Other PCM application examples

Other different possible building applications for PCM have been studied, especially trying to improve the performances of technical installations such as hot water heat stores, pipe insulation, cool thermal energy storage, and latent heat thermal storage systems. In addition, the improvement of double facades with PCM has been studied to achieve a better control of the cavity temperature [20].

Polymerisation of PCM has also been studied for other applications, such as for insulation in clothing or bedding articles [117,275]. Mondal [276] reviews the working principle of PCM and their applications for smart temperature regulated textiles, the different types of employed PCM, related concepts, and required comfort conditions. Barghava and Singh [277], Parthiban et al. [278], and Ocepek and Tavečer [279] also reviewed the use of PCM in sensitive textiles. Bendkowska and Wrzosek [280] studied the thermoregulation properties of PCM nonwovens, identifying the thermoregulating properties of the printed nonwoven sample with micro- PCM as dependent on the position of the micro-PCM layer.

Inaba [111] proposed using the storage substance integrated with the building materials without encapsulation ("Shape-stabilised paraffin": 74% paraffin + 26% HDPE [high-density polyethylene]). Structural stability is achieved using high-density polyethylene which retains the paraffin when in liquid phase. Chamarthy and Utturkar [281] have studied theoretically the potential use of PCM in electronics cooling applications. Lin et al. [282] analyzed the potential application of microencapsulated PCM for the thermal control of microelectronics and the thermal management of modern microsystems and optoelectronic technologies. The authors evaluated the thermal performance of a PCM (manufactured as powder with 10-30 μm size) mixed substrate, and results showed that the manufacturing process does not destroy the structure of the PCM microcapsules. The use of microencapsulated PCM has also been considered to improve the thermoregulating properties of natural leather by coating PCM into leather; by means of mechanical characterization, it has been observed that tensile strength and elongation at break are not significantly affected by this coating treatment [283].

Takakuwa et al. [284] designed an electronic module intended for cooling electronic equipment, including paraffin as the PCM and measured its transient temperature rise. The effects of the diameter of pin fins and heat dissipation values were investigated as design parameters. The results showed that the temperature rise values were controlled by the thermal absorption effect due to the latent heat of the PCM. It was also confirmed that the proposed thermal network method with an equivalent specific heat model has strong potential for use in the analysis of electronic modules using PCM. The cooling of electronic devices by PCM application has also been studied by Lafdi et al. [285], who developed a numerical model to solve the set out energy conservation equations, and by Faraji and Qarnia, [286] who performed numerical simulations to analyze the process involved parameters.

A method for satellite power testing using PCM has been devised. Central to the solar power system are series of metal cells which contain a PCM that is liquid under high temperature, which then freezes during hours of cold darkness, releasing its latent heat. The heat released can then be used to generate electricity by driving thermoelectric units. Because the systems generate at least three times more power than batteries of comparable size, they are seen as a possible alternative to conventional satellite solar power systems that rely on batteries. By having a hot converter at the start of a trip, auto emissions, such as hydrocarbons and carbon monoxide, can be reduced dramatically by up to 80%. A ventilation nighttime cooling system has been designed by John et al. [287] (a novel combination of PCM and heat pipes) as an alternative to air conditioning. The system offers substantial benefits in terms of reducing or eliminating the need for air conditioning and thereby significantly reducing CO_2 emissions and saving energy in buildings [117].

Kim et al. [288] conducted a simulation to validate a car engine cooling system (cooling inventory) that utilizes the heat load averaging capabilities of a phase change material. Three prototypes were designed: full size, down sized, and a down sized prototype with a heat accumulator containing the PCM inside. When the full size of the cooling inventory was downsized by 30%, this smaller design failed to dissipate the peak heat load and led to a significant increase in the coolant temperature, around 25 °C greater than that in the full size system. However, the peak heat load was successfully averaged out in the downsized system with a heat accumulator. Experimental studies are currently on-going so the simulation results may be validated and a suitable PCM for the application may be selected.

PCM are also being considered for application in medical applications. Braxmeier et al. [289] developed and validated a mathematical model to predict the thermal behaviour of a heat application device based on a phase change material for the heat treatment of Mycobacterium ulcerans infection (Buruli ulcer). The thermal model allows the prediction of skin surface temperatures and an optimization of the amount of PCM with respect to discharge time. A first prototype was manufactured and used in a proof-of-principal trial in Cameroon. The experimental data were analysed and yielded no difference in thermoregulatory response between people living in hot or moderate climate. Short-term maximum skin surface temperatures of 42 ºC are tolerable; the PCM bandage keeps the skin surface temperature above 40 ºC for about 4 to 5 hours. The PCM bandage is easy to apply, cheap, and thus is well suited for use in low-resource countries.

1.5 Objectives

The following objectives have been pursued in this thesis:

- To quantify the potential energy savings and CO_2 emissions by means of employing TES, basing on reasonable deployment scenarios at the diverse applications in the buildings and industry sectors along the next 10 years in Spain and Europe.
- To review the state-of-the-art on the use of phase change materials (PCM) for thermal energy storage (TES) applications, especially in buildings.
- To analyze the use of awnings in buildings which incorporate PCM within their structure (as an application of TES), both in passive building modes and also under partially controlled temperature modes.
- To evaluate the effect of reducing the solar radiation that reaches the building wall over the inner temperature, the wall temperature, and the PCM activation; comparing these variables with those measured in buildings without awnings.
- To analyze the combined influence of awnings and PCM over comfort conditions inside the building, if attained, to see whether they are improved or not and to quantify for how long these conditions may be maintained.
- To study the behaviour of the consumed energy at buildings with attached awnings as a result of maintaining a partially controlled environment inside, so it may be determined if an energetic saving is produced (along with its correspondent CO_2 emissions reduction), with respect to the buildings without awnings.

2 Potential of Thermal Energy Storage and CO_2 emissions reductions in Spain and Europe

2.1 Introduction to Potential of TES and CO_2 emissions reduction in Spain and Europe

Thermal energy storage (TES) is nowadays presented as one of the most feasible solutions in facing the challenge of achieving energy savings and environmentally correct behaviours. Its potential applications have led to R&D activities and to the development of various technology types. However, so far there is no available data on a national scale in Spain and furthermore, on a continental level in Europe, to corroborate the associated energetic and environmental benefits derived from TES usage. This is why, based on a previous potential calculation initiative model performed in Germany, it is intended to provide a first overview of the Spanish TES potential as well as an European overview. Load reductions, energy savings, and CO_2 emissions reductions are tackled for the buildings and industrial sector. A 10-year scenario from the present day has been considered to estimate the potential effects TES may exert over the mentioned sectors, assuming the implicated variables will go through moderate changes within that period of time. The potential CO_2 emissions reduction derived from TES implementation is also considered as the potential TES benefits may not only affect energy matters but environmental ones as well. In both cases it was expected to confirm that TES implementation related benefits depend linearly on the amount of implementation.

2.2 Methodology

2.2.1 Considered cases and evaluated parameters

Two main large sectors are to be distinguished: buildings and industry, each one grouping cases or sub-categories in which TES may be applied. The cases considered for the buildings sector are seasonal solar thermal systems, district/central heating, short term solar thermal systems, and passive cold systems. As for the industrial sector the considered cases are combined heat and power (CHP, also called cogeneration), industry (heating and cooling systems), power stations and transport, and concentrated solar power plants.

In order to determine the TES potential, the required parameters are related to energy and CO_2 emissions. Within the energy field, two quantities show the potential to be determined: the derived thermal load reduction and thermal/electrical energy savings.

The thermal load reduction refers to the reduction of capacity from the one that would have been consumed under the same working conditions without employing any type of energy storage. The energy savings simply refer to the "heat" or "cold" that is stored and may be reutilized, thus not needing to be generated "again" by the application. The CO_2 emissions reduction is the one achieved as a result of reusing stored energy, therefore not consuming fossil fuels or other greenhouse gas emitting energy source during the energy generation and thus preventing emissions from going into the atmosphere.

As it may be demonstrated, all three parameters depend on each other and their obtaining may differ from case to case and as required values for each one are not the same. The following section describes shortly the systems where TES may be used and presents the equations that intervene in the proposed calculation model.

2.2.2 Applications brief description and calculation procedure

2.2.2.1 Nomenclature

Table 4 summarizes the employed variables during the calculation process, and Table 5 shows the subscripts and Greek letters employed at the proposed calculation procedure.

Variables	Definition	Units
%I	implementation percentage	
%N	new buildings yearly construction completion percentage	
%R	buildings yearly renovation percentage	
a	solar collector area per building	m^2/building
B	building stock	
c	specific heat	kJ/kg·ºC
COP	coefficient of performance	-
E	replaced energy	GWh_{th}
F	water volume flow rate	m^3/s
f	weighted CO_2 emissions conversion factor	g CO_2/kWh_{th}
H	average heating load	GW_{th}
L	potential load reduction	MW_{th}
lr	expected/estimated load reduction per building	kW_{th}/building
P	installed power	MW_{th}
R	greenhouse gas emissions reduction	T
s	solar collector utilized solar gains	kWh_{th}/m^2
t	number of years of the considered scenario	-
T	temperature	ºC
y	yearly operating hours (h)	h

Table 4. List of variables, definitions and units.

2.2.2.2 Building sector

Seasonal solar thermal systems

A seasonal solar thermal storage system is a system designed to retain heat deposited during the hot summer months for use during colder winter weather. The heat is typically captured using solar collectors, although other energy sources are sometimes used separately or in parallel. The three required parameters to calculate the potential in this type of systems are given by the following equations:

$$L = \{[lr \cdot t \cdot (\%R + \%N)] \cdot B\} \cdot \%I_{stge}$$

Eq. 1

$$E = L \cdot y$$

Eq. 2

$$R_{CO_2} = f \cdot E$$

Eq. 3

	Symbol	Definition
Greek letters	Δ	increase
	ρ	water density (kg/m^3)
Subscripts	E	electricity associated value
	eq	equivalent value
	CO_2	CO_2 associated value
	CHP	combined heat and power (cogeneration) associated value
	i	assigned order to data within summation calculations
	av	average value
	l	losses associated value
	p	constant pressure associated value
	N	nominal value
	stge	storage associated value
	p,stge	predicted value associated to storage
	N,stge	nominal value associated to storage
	N,nostge/ref	reference nominal value not associated to storage
	nostge/ref	reference value not associated to storage

Table 5. Employed subscripts and Greek letters.

It should be pointed out that energy consumption in households is shaped by the characteristics of energy using equipment as well as the thermal integrity characteristics of houses. Renovation of houses for energy purposes, often as part of other modernisation work, also impacts on energy consumption [2], as it is seen in Eq. 1.

A parameter which influences indirectly the energy consumption in buildings is the population. This may not be so evident given that while population grows very slowly in the EU, the number of households increases faster because the number of persons per household decreases steadily [2]. Indeed, though the population does not appear explicitly in the proposed equations, based on the previous facts it goes implicit within the building stock variable (B).

The three equations are equally valid for all cases in the building sector, however, some of the parameters are different for specific systems and the respective variations are presented when it corresponds.

District and central heating systems

District heating is a system for distributing heat generated in a centralized location for residential and commercial heating requirements such as space heating and water heating. The heat is often obtained from a CHP plant burning fossil fuels but increasingly employing biomass, although heat-only boiler stations, geothermal heating and central solar heating are also used, as well as nuclear power.

A central heating system provides warmth to the whole interior of a building (or portion of a building) from one point to multiple rooms. The heat generation occurs in one place, such as a furnace room in a house or a mechanical room in a large building. The most common method of heat generation involves the combustion of fossil fuel in a furnace or boiler. The resultant heat then gets distributed: typically by forced-air through ductwork, by water circulating through pipes, or by steam fed through pipes. Increasingly, buildings utilize solar-powered heat sources, in which case the distribution system normally uses water circulation.

In this case, the only parameter whose calculation is different is the load reduction, which is obtained through the following equation:

$$L = H \cdot t \cdot \%lr$$

Eq. 4

Solar short term systems

A solar short term system consists generically of the following parts: solar collector, solar collector loop, storage subsystem, control subsystem, auxiliary subsystem, and a heat distribution subsystem [290]. From sunrise to sunset, the solar collectors absorb the solar energy and raise the temperature of a heat transfer fluid running through an insulated piping system or collector loop that connects the array of collectors. The heated fluid travels along the piping system until it arrives at a heat exchanger which transfers heat to the water stored in a short-term storage tank or to a central or district heating system. The heat transfer fluid carries on through its loop back to the solar collector system [291].

The potential energy savings for these systems are calculated with:

$$E = \{[t \cdot a \cdot s \cdot (\%R + \%N)] \cdot B\} \cdot \% I_{stge}$$

Eq. 5

It may be observed the direct influence of the collector area (also related to the collector type) over the energy parameter, but also the influence of the solar gains collectors may provide, which at the same time depend on the solar irradiation, a variable parameter that changes with the geographical position and is therefore different for each zone.

Passive cold systems

A passive house is a building in which a comfortable interior climate can be maintained without active heating or cooling systems. It is possible to achieve acceptable levels of summertime thermal comfort under the projected warmer future climates using passive cooling measures with modern building materials and modern design methods. Aside from conventional strategies, phase change materials (PCM) present themselves as a viable option in passive buildings [13]. Indeed, though the use of PCM has been studied for other types of energy storage applications, such as in packed bed systems [292], or in single basin solar stills [293], and despite its thermal degradation after long cycling [294], perhaps one of their greatest fields of usage is buildings.

The use of PCM in buildings, as part of the possible active or passive systems that may optimise the use of energy for heating and cooling purposes, may be particularly determinant [2]. To cite a remarkable example of this, it is worth mentioning the work by Castell et al., who performed experiments in cubicles holding PCM within a Mediterranean environment (Spain) in order to study the effects of PCM when used for free-cooling purposes; they concluded that the electrical energy consumption was reduced in about 15%, which resulted in a reduction of the CO_2 emissions of about 1–1.5 kg/year·m^2 [195].

Another experimental study is that of Xiao et al. [295], who obtained simplified theoretical equations to model the behaviour of PCM for energy storage in a lightweight passive solar room, and validated the model with experimental results measured under the climatic conditions of Beijing, concluding that he optimal phase change temperature depends on the average indoor air temperature and the radiation absorbed by the PCM panels; that the interior PCM has little effect on average indoor air temperature; and that the amplitude of the indoor air temperature fluctuation depends on the product of surface heat transfer coefficient and the area of the PCM panels.

Indeed, PCM application in buildings is the case it is dealt with. Since this case lies within the buildings category, equations governing these storage systems are the same ones employed for seasonal solar thermal systems, adding the achieved electrical energy savings (Eq. 6) as a result of not using electrical air-conditioned equipment at the building. It results into just introducing the equipment coefficient of performance (COP) so the saved thermal energy may be translated into electrical:

$$E_e = \frac{E}{COP}$$

Eq. 6

2.2.2.3 Industrial sector

Cogeneration

Cogeneration or Combined Heat and Power (CHP), is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat. It is one of the most common forms of energy recycling. While a conventional power plant emits the heat created as a by-product of electricity generation into the natural environment through cooling towers, flue gas, or by other means, CHP captures the by-product heat for domestic or industrial heating purposes, either very close to the plant, or especially as hot water for district heating with temperatures ranging from approximately 80 to 130 °C [296].

Equations governing this application are:

$$L_{CHP} = [(1 + \%N \cdot t) \cdot B] \cdot \% I_{CHP} \cdot P_{CHP}$$

Eq. 7

$$E_{CHP} = L_{CHP} \cdot y \cdot \% I_{stge}$$

Eq. 8

The potential CO_2 emissions reduction is calculated by using the obtained replaced energy in Eq. 3.

Industrial heating systems

This category covers three groups of applications: power stations, industry (generically speaking), and transport.

A power station is an industrial facility for the generation of electric power. At the center of nearly all power stations is a generator, a rotating machine that converts mechanical energy into electrical energy by creating relative motion between a magnetic field and a conductor. The energy source harnessed to turn the generator varies widely. It depends chiefly on which fuels are easily available and on the types of technology that the power company has access to.

The power sector is the main source of CO_2 emissions in the EU-25, mainly because of the high share of coal consumed in this sector, and represents the main potential for emission at the same time [5].

Industry refers to the production of an economic good (either material or a service) within an economy. European industry spans several industrial sectors, the stronger ones are: automotive (almost 34% of vehicles in the world are manufactured in Europe and the EU has a share of 7.6% in the manufacturing sector with big names as Volkswagen, Mercedes-Benz, Aston Martin, BMW, Ferrari, Jaguar and Lamborghini), aerospace (the majority consists on aircraft technology, while the remaining deals with space and missile programs), defense (including space, aeronautics, electronics, military vehicles, ships, armoury), chemicals (among the main products are petrochemicals, polymers, and fine chemicals), biotechnology, and food (it is the largest importer and second largest exporter in the world) [297]. The remaining sectors cover consumer goods, forest products, plastics, agriculture, domestic appliances, furniture, automation & tooling, electronics, metallurgy, textiles, paper & printing, and marine dredging [298].

The transport sector in the EU covers both passengers and freight transport by road, plane or railway and when the sector energetic aspects are addressed, the sector infrastructure is included as well. At this point it is remarkable to mention that as global vehicle production continues to increase, motor vehicles have become important high temperature systems and, furthermore, carbon dioxide emissions due to vehicle usage have a large impact on climate change [299].

Based on this, TES is considered to have potential to be applied on vehicles mainly due to the utilization of excess heat emitted as an exhaust gas from a muffler and an effluent gas from a radiator, increase of the efficiency of cold production for cabin and container cooling, and providing a heat source of cabin and for managing container heat for electric an fuel cell vehicles [300].

Aside from the previous points, it is thought that the potentially stored thermal energy could also be reutilized at the very sector infrastructures as TES technologies are also expected to allow for this throughout the considered time scenario.
The potential load reduction (L) for the industrial sector is calculated using Eq. 4 and the energy savings are obtained through the following relation:

$$E = (L \cdot y + E_l \cdot t) \cdot \% I_{stge}$$

Eq. 9

It may be observed that Eq. 9 is very similar to Eq. 8, where the energy savings are obtained by multiplying the load reduction by the operating hours and the storage implementation, only that in this case, the energy conversion losses from power stations are added to those energy savings coming from industry and transport only.

Industrial cooling systems

One type of industrial application where TES might be employed has been found, and that is, a regasification terminal. A regasification terminal is an industrial installation that lies between that of liquefied natural gas and the natural gas distribution net. In it the process of converting liquefied natural gas into natural gas takes place. In such terminals, the gas load from the methane ships is reintroduced into cryogenic tanks, where the gas initial temperature (-160 ºC) is maintained.

During the regasification, the gas is transported towards the vaporization systems, where temperature is risen by using sea water, thus turning liquid into gas [301]. It is the amount of "cold" the gas gives off during this process is the one which is wasted, since the sea water is directly returned to the sea after completion of the process.

Currently, six countries in Europe feature this type of terminals, totalizing a number of 15 plants: Spain (Barcelona, Cartagena, Huelva, Sagunto, Mugardos, and Bilbao), Belgium (Zeebrugge), France (Fos-sur-Mer, Montoir), Italy (Panigaglia, Porto Viro), Greece (Revithoussa), and the UK (South Hook, Dragon, both in South Wales, and Grain) [302].

The proposed equation for this case is the following:

$$E = (F \cdot \rho \cdot c_p \cdot \Delta T \cdot y \cdot t) \cdot \%\, I_{stge}$$

Eq. 10

Input data for Eq. 10 are those referred to the sea water employed during the regasification process, while the density and specific heat are determined by the fluid itself, the volume flow and temperature increase are terminal generic design parameters.

Concentrated solar power plants

Concentrated solar power plants produce renewable heat or electricity (generally, in the latter case, through steam) by using lenses or mirrors and tracking systems to focus a large area of sunlight onto a small area. The concentrated light is then used as heat or as a heat source for electricity generation. A wide range of concentrating technologies exist, including the parabolic trough, Stirling dish, concentrating linear Fresnel reflector, solar chimney, and solar power tower. Each concentration method is capable of producing high temperatures and correspondingly high thermodynamic efficiencies, but they vary in the way that they track the Sun and focus light [303].

High temperature concentrated solar energy can be used for cogeneration of electricity and process heat, with possible applications such as the combined production of industrial heat, district cooling, and sea water desalination. If TES systems are part of the plant, solar heat collected during the daytime can be stored in systems based on concrete, steam, molten salt, ceramics, or PCM. At night, it can be extracted from the storage to run the power block continuously [304].

As possibly inferred, the main benefit from employing TES in CSP plants is the electrical energy which does not have to be generated by the plant during its regular operation but thanks to the storage system. Even just a few hours of thermal storage are sufficient to allow CSP plants to serve up to around 70% of the intermediate and peak load, however, thermal storage cannot fulfill the role of supplying backup power for days in which direct irradiance is not sufficient to operate the CSP solar field [305]. As it is an energetic parameter, the electrical energy savings are simply given by:

$$E_e = P_{N,stge} \cdot y_{stge} \cdot t$$

Eq. 11

As seen, only parameters related to plants holding TES are involved and not those from other operating plants, though as it will be explained latter, data from plants without TES are used to calculate the operating hours of plants with TES. The correspondent CO_2 emissions reduction is obtained by using Eq. 3.

2.2.3 General assumptions

The assumed baseline scenario quantifies the TES energy savings over the period to 2020 for the EU (employing EU-25 data mainly), arising from a continuation of the previously described background and taking that current trends in terms of energy, transport and CO_2 emissions will continue along the considered period, which has led to some specific assumptions as listed next:

- The energy mix is taken as constant.
- Within the building sector, energy consumption and space heating needs are expected to experience a very slow increase in the medium term [2], which is why these needs are taken as constant.
- Input data within the industrial sector is also taken as constant as they are also expected to go through very slow variations in the medium term.

2.2.4 Input data obtaining and specific assumptions

2.2.4.1 CO_2 emissions factor

The variable f is required to obtain the potential CO_2 emissions reduction both for Spain and Europe. Following the German methodology, this is done based on the Spanish and European energy mixes respectively, weighing the individual factors respect from the energy source usage percentage. Input data and obtained factors for Spain [306,307] and Europe [308,309] are shown in Table 6.

As for the electrical CO_2 emissions reduction factor, it is given directly by data sources and needs no weighing. The factors are: 649 g CO_2/kWh_e for Spain [307] and 476 g CO_2/kWh_e for Europe [309].

Energy source	**Consumption percentage**		**Conversion factor (g CO_2/kWh_{th})**	
	Spain	Europe	Spain	Europe
Natural gas	22%	24%	204	202
Fuel Oil	48%	39%	244	279
Coal	14%	17%	347	351
Weighted factor			251	271

Table 6. Determination of the weighted CO_2 emissions factor for Spain and Europe.

2.2.4.2 Building sector input data

Three data are initially required: the building stock (both for housing and non-housing applications), the rate of renovation, and the rate of completion of buildings for both cases. This type of data is available in national statistical sources of information. However, if the renovation and new buildings percentages are not directly found, they may be calculated by using data from past years, an example employing EU-25 data (mainly provided by Eurostat [310]) is shown in Table 7.

If insufficient data is available, the values may be assumed based on bibliographical sources as well. Both for Spain and Europe the percentages have been assumed to be equal for housing and non-housing buildings when necessary.

Period	Building stock (B) (thousands of buildings)	New buildings (thousands of buildings)	Buildings rate of completion (%N)
2003	188,313	---	
2004	189,557	1,244	0.66%
2005	192,996	3,439	1.81%
2006	195,593	2,597	1.35%
%N mean value			1.27%

Table 7. Example of calculation of the housing new buildings completion percentage in the EU-25.

Other necessary data are the load reduction, the storage implementation percentage, the yearly operating hours and the scenario covered period of time. As mentioned before, a short scenario period is desired, so this last variable has been set to ten years both for Spain and the EU. The storage implementation percentage is to be assumed in all cases, though if existing data is on hand it may be used as well. The load reduction must be estimated. This may be done through the heating and cooling demands or through the actual heating and cooling consumptions if more suitable, the average building area and the yearly operating hours for each system.

When dealing with passive cold systems the COP is required, this variable value is that of commercial air-conditioning equipment and again an average value may be assumed.

Regarding solar short term systems, the solar collector area per building (average values may be used or assumptions taken as the case) and solar collector utilized solar gains are required too. The solar gains are given indirectly by the yearly irradiation at the considered region and the solar collectors features. Correspondent data sources are to be consulted to the fore.

In reference to district/central heating systems, the heating load and load reduction percentage are required. While this last one may be assumed, the heating load may be obtained directly when available or calculated based on the heating demand.

Table 8 shows input data for both calculations within the building sector, summarizing information found at the main available sources for the sector [310-321]. On reading the tables, bold characters represent data directly available in literature or obtained based on information provided there, italic characters represent assumed numbers, and plain characters stand for calculated results.

2.2.4.3 Industrial sector input data

Most parameters for the industrial sector are obtained the same way as those for the building sector, that is, by direct literature consulting, deduction or simply assumption. An exception to this are those required to estimate the CSP plants potential, which are not found directly in literature and may not be assumed as information regarding storage in this kind of plants is limited. As stated in Eq. 13, a necessary parameter is

the yearly operating hours during which the TES system is operational; so therefore, this value was estimated based on the energy generated by those plants with TES systems and the energy generated by an equivalent plant without TES systems.
First, the energy generated during storage hours must be obtained for each plant holding a storage system; this is done with:

$$E_{stge} = E_{p,stge} - \left(\frac{P_{N,stge}}{P_{N,nostge/ref}} \right) \cdot E_{nostge/ref}$$

Eq. 12

System	Variable and symbol	Units	Building category	Spain	EU-25
Seasonal solar thermal systems	Building stock (B)		Housing	**86,592,809**	**195,593,000**
			Non-housing	**13,926**	**287,629**
	Buildings rate of renovation (%R)			**0.13%**	**1.50%**
	Buildings rate of completion (%N)		Housing	**2.20%**	**1.27%**
			Non-housing	**4.93%**	**1.27%**
	Expected/estimated load reduction per building (lr)	kW_{th}/building	Housing	*2*	*10*
			Non-housing	*95*	*95*
	Storage implementation percentage ($\%I_{stge}$)			*5%*	*5%*
	Yearly operating hours (y)	h		*1,825*	*1,825*
District/central heating	Average heating load (H)	GW_{th}		**20**	**1,454**
	Expected/estimated load reduction percentage (%lr)			*10%*	*10%*
	Yearly operating hours (y)	h		*1,825*	*1,600*
Short term solar thermal	Expected/estimated load reduction per building (lr)	kW_{th}/building		**7**	**11**
	solar collector area per building (a)	m^2/building		**10**	**15**
	solar collector utilized solar gains (s)	kWh_{th}/m^2		**730**	**537**
	Storage implementation percentage ($\%I_{stge}$)		Housing	*96%*	*73%*
			Non-housing	*98%*	*73%*
Passive cold systems	Expected/estimated load reduction per building (lr)	kW_{th}/building	Housing	*1*	*6*
			Non-housing	*74*	*75*
	Storage implementation percentage ($\%I_{stge}$)			*3%*	*3%*
	Coefficient of performance (COP)			**2.7**	**2.8**
	Yearly operating hours (y)	h		*1,825*	*1,825*

Table 8. Building sector input data values

The goal is to determine which fraction of the predicted energy generation in CSP plants is generated thanks to TES systems. For this, a plant not featuring TES is selected as a reference and each CSP plant nominal power is compared to that of the reference, using the result as a weighing factor. This process is to be followed and done for each plant. At the present case the chosen reference has been the Alvarado I plant in Spain. Then, the average storage operating hours are obtained by dividing the calculated energy generation amounts by the sum of each plant nominal power, that is:

$$y_{stge} = \frac{\sum_{i=0}^{n} E_{stge,i}}{\sum_{i=0}^{n} P_{Nstge,i}}$$

Eq. 13

Obtained results for EU-25 are shown in Table 9, which gathers data about the found plants at the time of elaborating this document. The same procedure has been applied to Spain alone in order to determine its national potential, though results are not shown here as Spain holds the majority of plants in the continent and are already included at the table. Table 10 presents required data to determine the industrial sector TES potential, according to main found information [310,322-325].

Country	Plant	Nominal installed power (MW_e)	Includes thermal energy storage	Predicted yearly energy generation (GWh_e)	Estimated yearly energy generation during storage operation hours (GWh_e)	Storage yearly operating hours (h)
Spain	PS10	**11**	**X**	**26**	4	324
	PS20	**20**		**50.6**		
	Andasol 1	**50**	**X**	**170**	68	1,360
	Solar 3	**15**	**X**	**105**	74	4,960
	Puertollano	**50**		**114.2**		
	Alvarado I	**50**		**102**		
	Puerto Errado I	**1.4**	**X**	**2.8**	0.5	330
Italy	Archimedes	**4.72**	**X**	**9.2**	12.5	2,640
France	Solenha	**12**	**X**	**60**	48	3,960
Germany	Jülich	**1.5**	**X**	**1**	0.5	330
					y_{stge}	**2,164**

Table 9. Concentrated solar power plants data and estimated results.

System		Variable and symbol		Units	Spain	EU-25
CHP		Buildings completion percentage (%N)	Housing		**2.20%**	**1.27%**
			Non-housing		**4.93%**	**1.27%**
		Cogeneration implementation percentage ($\%I_{CHP}$)			*5%*	**10.2%**
		CHP installed power per building (P_{CHP})		MW_{th}	**9**	**8**
		Yearly operating hours (y)		h	**4,500**	**4,500**
		Storage implementation percentage ($\%I_{stge}$)			*15%*	*15%*
Industrial systems	Heating	Average heating load (H)		GW_{th}	**748**	**7,522**
		Yearly operating hours (y)		h	**1,680**	**1,760**
		Expected/estimated load reduction percentage (%lr)			*5%*	*5%*
		Power stations energy conversion losses (E_l)		GWh_{th}	**12,991**	**132,815**
		Storage implementation percentage ($\%I_{stge}$)			*3%*	*3%*
	Cooling	Water volume flow rate (F)		(m^3/s)	**3.472**	**3.472**
		Water density (ρ)		Kg/m^3	**1,027**	**1,027**
		specific heat (c_p)		kJ/kg·ºC	**4.189**	**4.189**
		Temperature increase (ΔT)		ºC	**8**	**8**
		Yearly operating hours (y)		h	*4,380*	*4,380*
		Storage implementation percentage ($\%I_{stge}$)			*17%*	*40%*
		Coefficient of performance (COP)		-	*3.5*	*3.5*
CSP plants		Nominal power of plants holding TES ($P_{N,stge}$)		MW_e	*77*	*96*
		Storage yearly operating hours (y_{stge})		h	**1,892**	**2,164**

Table 10. Industrial sector input data values.

2.3 Final results of TES potential

Global TES potential results are shown in Table 11. Numbers provided at the original German model are also presented so comparisons are able to be made. Since the model did not consider a 10-year scenario for all categories, original numbers have been updated in order to perform the respective comparison. The breakdown of the obtained values by sector and system is shown in Table 12.

Parameter and symbol	Units	Germany	Spain	EU-25
Load reduction (L)	MW	480,844	541,266	5,854,139
Replaced thermal energy (E)	GWh_{th}	662,291	826,263	9,527,227
Replaced electrical energy (E_e)	GWh_e	n.a.*	3,431	17,526
CO_2 emissions reduction (R_{CO2})	T	165,572,663	207,670,938	2,579,088,559

Table 11. Final TES potential results for Germany, Spain and the enlarged EU-25.
*: Not available

Sector	System	Parameter and units	Germany	Spain	EU-25
Buildings	Seasonal solar thermal	L (MW_{th})	1,001	2,294	25,287
		E (GWh_{th})	1,801	4,186	46,150
		R_{CO2} (T)	450,322	1,049,089	12,517,676
	District/central heating	L (MW_{th})	57,000	19,642	1,453,863
		E (GWh_{th})	87,384	35,846	2,326,182
		R_{CO2} (T)	21,845,972	8,983,685	630,957,558
	Solar short term	L (MW_{th})	16,011	135,093	416,180
		E (GWh_{th})	2,664	140,883	319,269
		R_{CO2} (T)	666,008	35,307,388	86,599,153
	Passive cold	L (MW_{th})	n.a.*	699	9,944
		E (GWh_{th})	n.a.*	1,275	18,148
		E_e (GWh_e)	n.a.*	472	6,481
		R_{CO2} (T)	n.a.*	306,519	3,085,135
Industrial	CHP	L (MW_{th})	5,888	9,354	187,790
		E (GWh_{th})	5,299	6,314	126,758
		R_{CO2} (T)	1,324,732	1,582,403	34,382,153
	Heating	L (MW_{th})	400,944	374,185	3,761,074
		E (GWh_{th})	565,143	632,528	6,659,335
		R_{CO2} (T)	141,285,629	158,521,473	1,806,289,626
	Cooling	E (GWh_{th})	n.a.*	5,231	31,386
		E_e (GWh_e)	n.a.*	1,495	8,967
		R_{CO2} (T)	n.a.*	969,980	4,268,512
	CSP	E_e (GWh_e)	n.a.*	1,464	2,077
		R_{CO2} (T)	n.a.*	950,401	988,747

Table 12. Final TES potential results breakdown by sector and system for Germany, Spain and the EU-25.
*: Not available

A graphic comparison between the obtained results for each of the parameters has been performed. First the potential load reduction is assessed as seen in Figure 23. Load potential reductions obtained for Germany and Spain are 8% and 9%, respectively, from the European reduction value. Should this potential values become a reality, thermal and electric capacities of the energy equipment to be installed in the near future at the considered sectors would be lower than those projected, which may entail parallel benefits aside from those derived from TES itself.

Figure 24 compares the obtained potential replaced energy values for the three cases. As expected, German and Spanish results maintain the same proportions to the potential replaced energy at the EU, as those observed at the load reduction comparison.

Results obtained for the EU-25 in terms of energy savings have been compared to the energy consumption in the EU-15 and EU-27 during 2005 so a more accurate idea of the TES potential may be given. The comparison is shown in Figure 25 Fig. 3. The potential savings account for an 8% and 7% at the EU-15 and EU-27, respectively, giving an approximate average value of 7.5% energy savings as a result of only TES application.

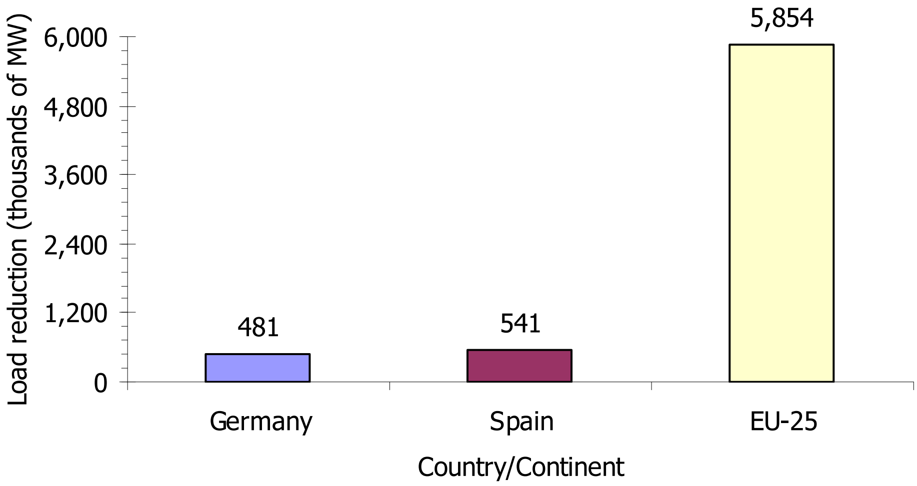


Figure 23. Potential load reduction over ten years by TES systems in Germany, Spain and the EU-25.

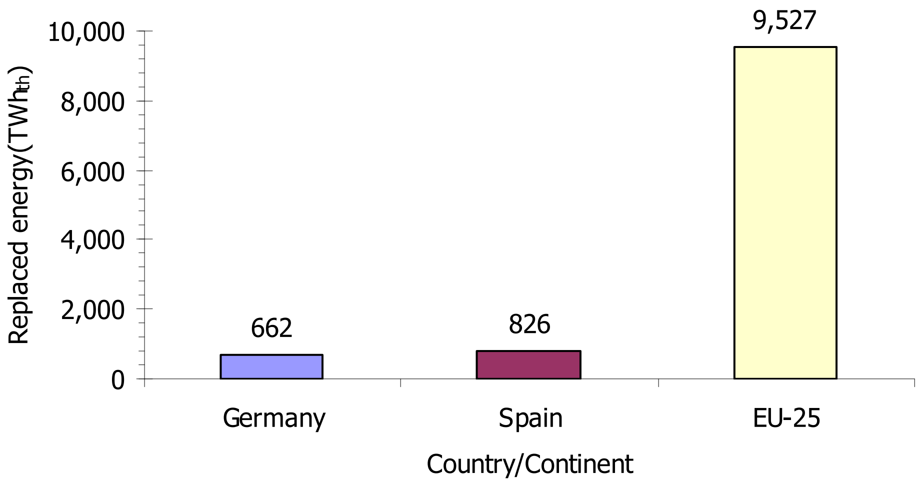


Figure 24. Potential replaced energy over ten years by TES systems in Germany, Spain and the EU-25.

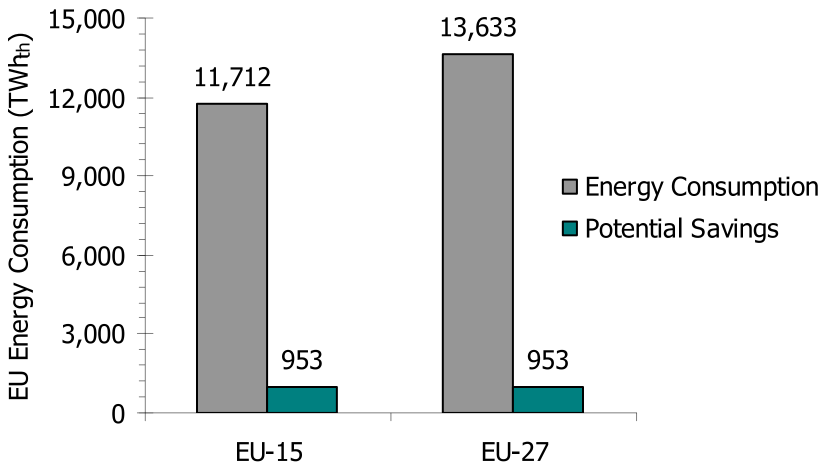


Figure 25. Comparison of potential yearly energy savings by TES systems in the EU-15 and EU-27 using 2005 figures. Based on [310].

As for the potential electrical energy savings, the respective comparison between regions is shown in Figure 26 and Figure 27. Germany is not considered in this occasion as applications considered at the original model were such that did not hold electricity savings among their potential.

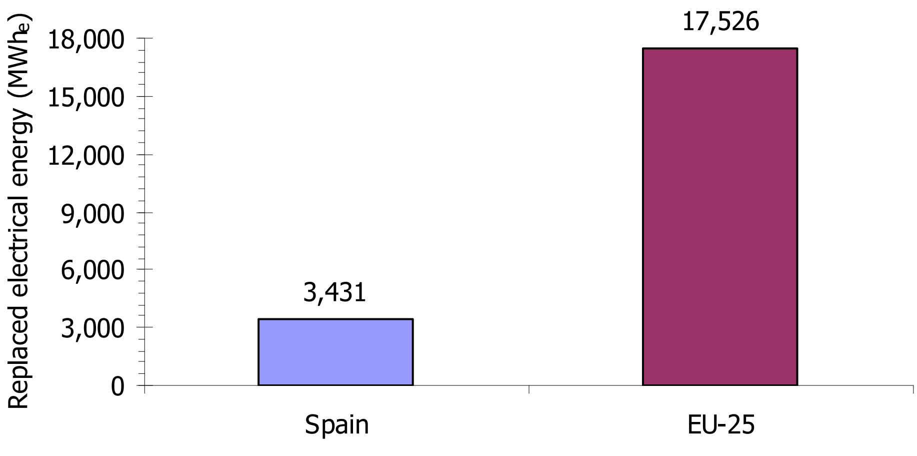


Figure 26. Potential electrical energy savings over ten years by TES systems in Spain and the EU-25.

It may be appreciated that Spanish share of savings gets to a 20% of the potential whole for the EU-25, highlighting that, as seen in Table 9, Spain is the country where most CSP plants are operating in the continent and where a large number of buildings may be found, aside from the regasification terminals it holds (all of them applications whose main contribution to the TES potential is the saving of electricity), and therefore establishing it as the nation which features more potential when it comes to saving electrical energy.

As seen in Figure 27, savings account modestly for a 0.1% both at the EU-15 and EU-27, mainly because of the still low implementation of the applications which may hold TES and provide electricity savings simultaneously (passive houses, CSP plants, and regasification terminals), rather than the storage implementation itself. As there are many CSP plants under project or during the last stage of design, particularly in Spain [326], it is expected that TES is taken under consideration. Likewise, both if the passive house application and the regasification terminals would spread out more within the EU, this contribution to energy savings would be expected to grow perhaps considerably more.

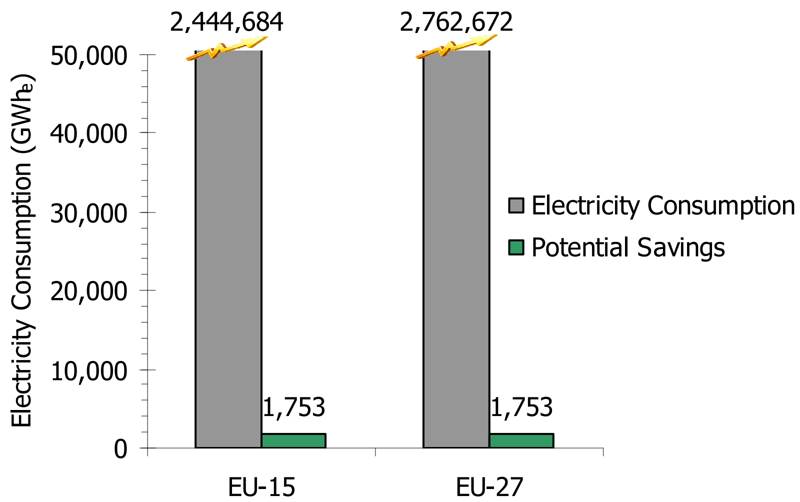


Figure 27. Comparison of potential yearly electrical energy savings by TES systems in the EU-15 and EU-17 using 2005 figures. Based on [310].

Last, the potential CO_2 emissions reductions are compared. Figure 28 shows obtained results for the three evaluated regions. Contributions from Germany and Spain to potential reductions at the EU maintain proportions as observed with the previously evaluated parameters. The comparison between potential reductions at the EU and the emissions amount is performed next.

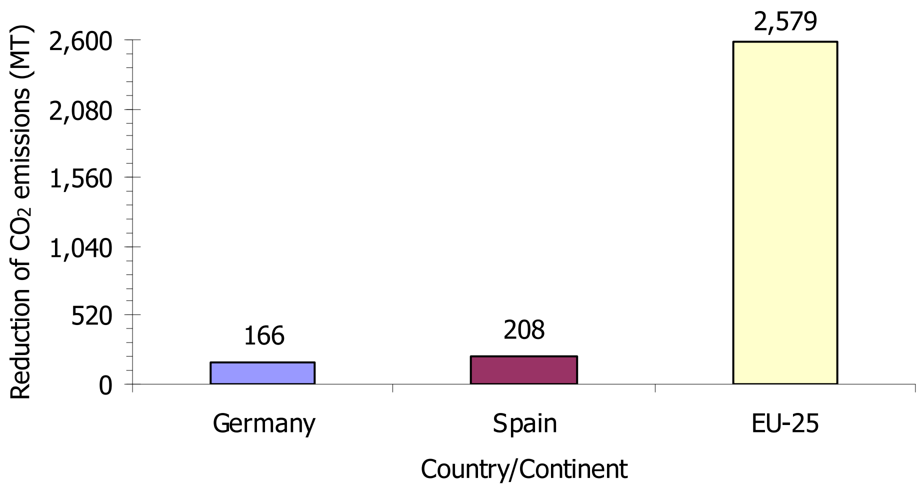


Figure 28. Potential CO_2 emissions reduction over ten years by TES systems in Germany, Spain and the EU-25.

In this case, aside from the 2005 reference year, 1990 is also considered as from that year on, greenhouse gas emissions began to be measured as stated at the Kyoto Protocol [8]. The comparison is given in Figure 29 for the EU-15 and EU-27. It may be observed that the potential reductions account approximately for a 6% and 5% both for 1990 and 2005 at the EU-15 and the EU-27, therefore, an average CO_2 reduction of 5.5% within the EU might be expected.

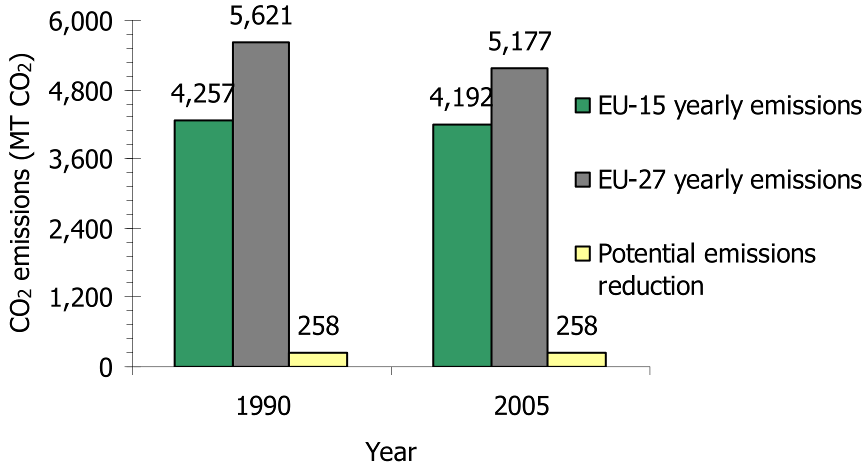


Figure 29. Comparison of potential yearly CO_2 emissions reduction by TES systems at the EU-15 and the EU-27 using 1990 and 2005 figures. Based on [327].

2.4 Parametrical study of the obtained results

As the calculation procedure involved some assumptions regarding specific variables for each studied case, a parametrical study was performed showing the dependence of the obtained results on the storage implementation. Results of the parametrical study are shown graphically next.

The potential load reduction dependence over storage implementation for different categories may be appreciated from Figure 30 to Figure 34 (as in some cases the expected/potential load reduction factor has been noticed to exert more influence than the storage implementation parameter over final results, some graphics include this factor rather than the storage implementation).

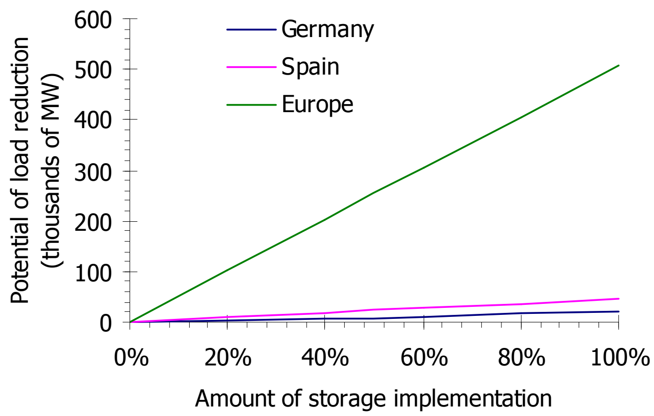


Figure 30. Influence of storage implementation over seasonal solar thermal systems load reduction.

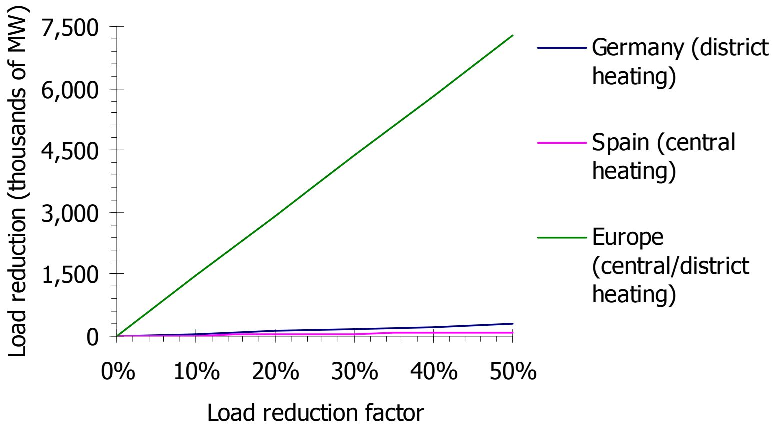


Figure 31. Influence of load reduction factor over district/central heating systems load potential reduction.

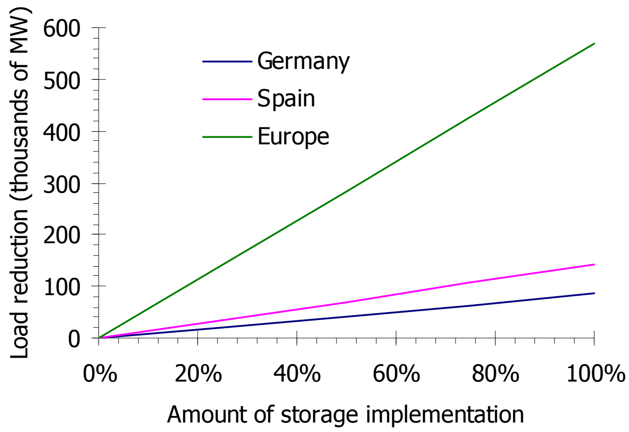


Figure 32. Influence of the amount of storage implementation over short term solar thermal systems potential load reduction.

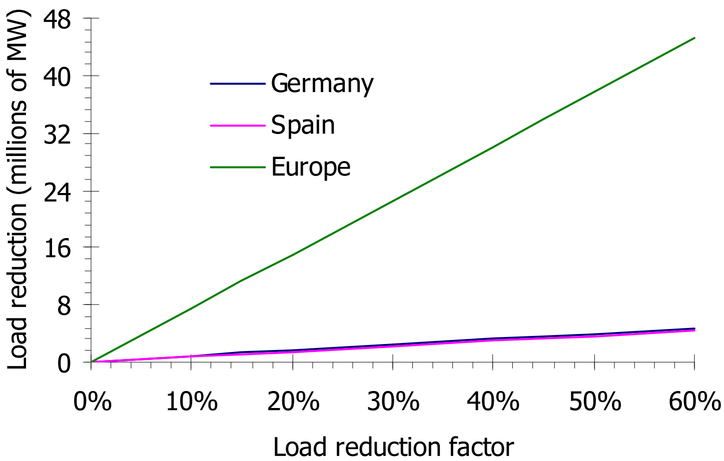


Figure 33. Influence of the load reduction factor over industrial potential load reduction.

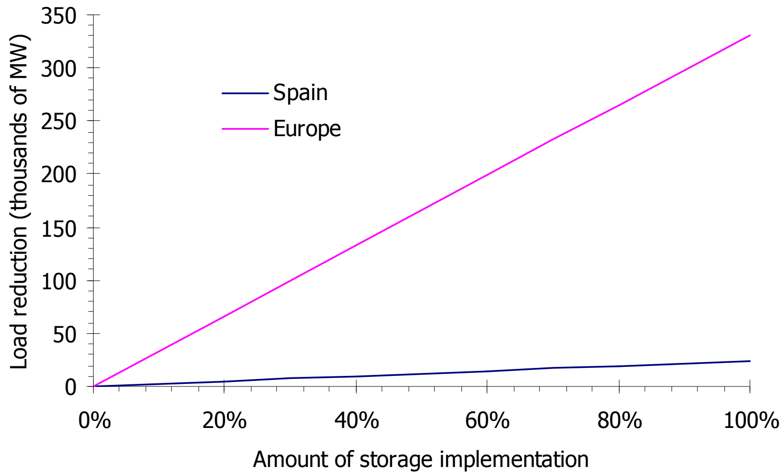


Figure 34. Influence of the amount of storage implementation over passive cold storage systems potential load reduction.

As expected, all load potential reductions show a linear dependence respect to the storage implementation or load reduction factor considered for each case, that is, the more TES systems are installed the higher the accomplished load reduction.

In comparing Spanish values to the German model it is observed that Spain shows a higher increase tendency than Germany in cases involving solar energy and the building stock (higher in the first case), but not in the district/central heating category, where German values are higher. Industrial increase tendencies follow a similar pattern for both countries and present similar increase tendencies. Contribution from Spain to the potential load reduction in Europe is slightly higher than that of Germany, though it must be taken into account that German calculations did not include some of the considered cases Spain did both for the building and industrial sectors.

Energy savings dependency on storage implementation or potential load reduction (when it corresponds) is given in Figure 35 to Figure 41.

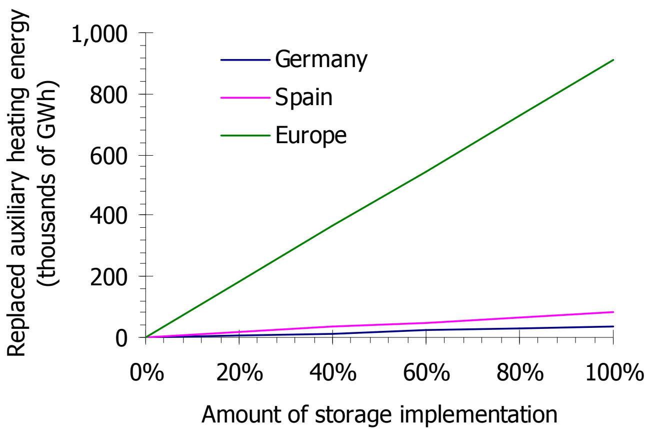


Figure 35. Influence of storage implementation over seasonal solar thermal systems auxiliary heating energy replacement.

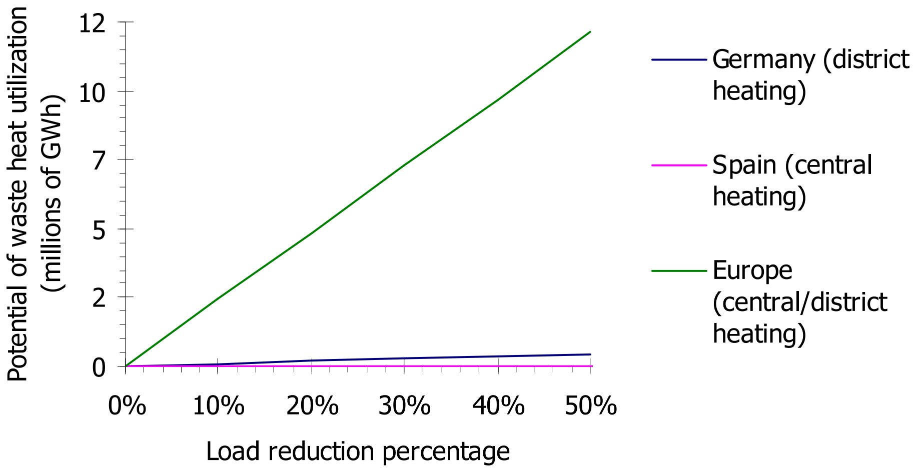


Figure 36. Influence of load reduction percentage over district/central heating systems potential waste heat utilization.

As values for Europe are much higher than those for Spain, the respective influence of the load reduction percentage over their potential waste heat utilization is shown separately for Germany and Spain in Figure 37.

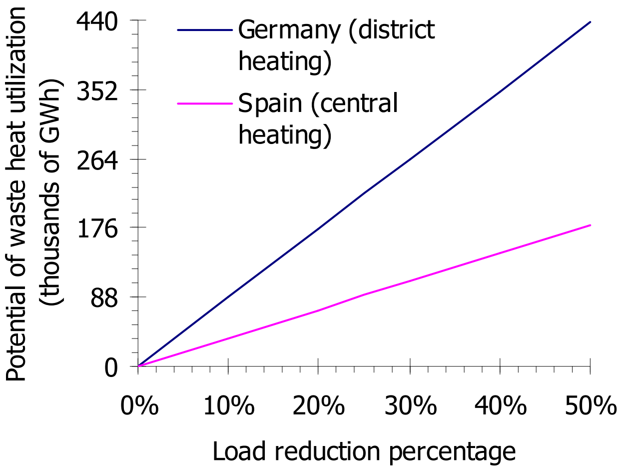


Figure 37. Influence of load reduction percentage over German and Spanish district/central heating systems potential waste heat utilization.

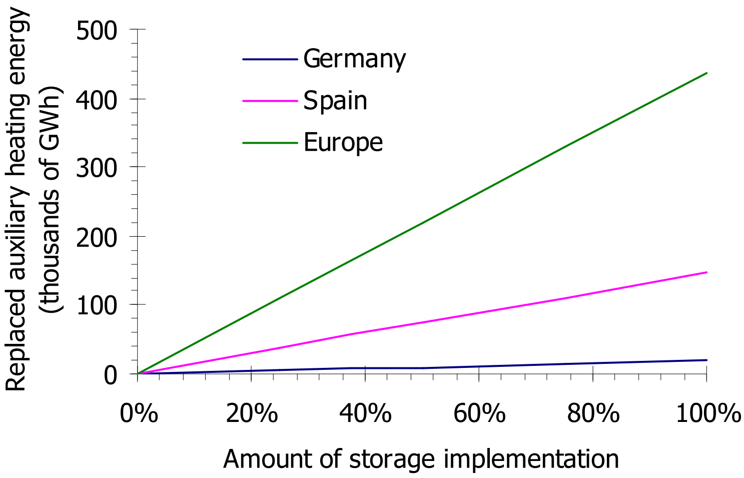


Figure 38. Influence of the amount of storage implementation over short term solar thermal systems potential replaced auxiliary energy.

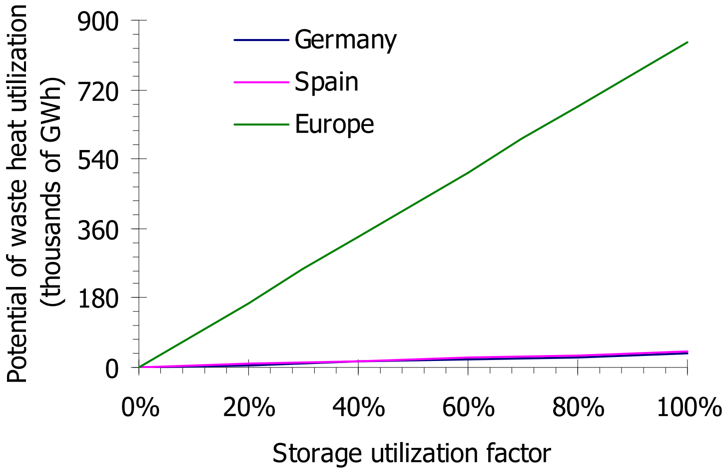


Figure 39. Influence of the storage utilization factor over cogeneration installations potential waste heat utilization.

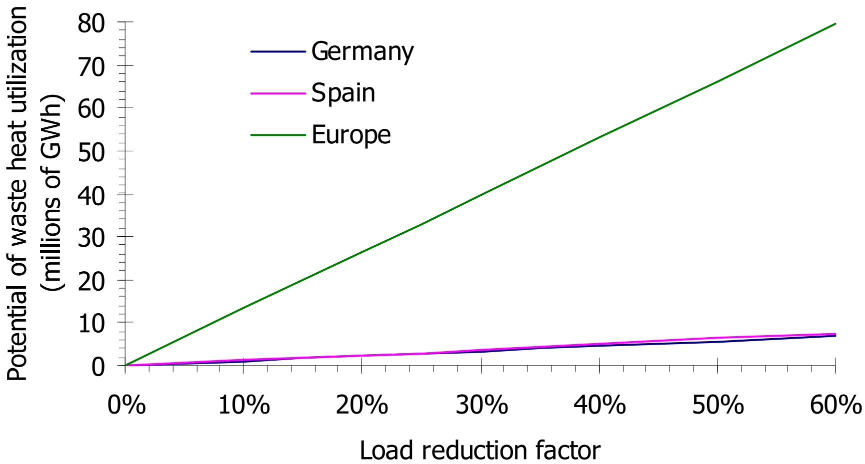


Figure 40. Influence of the load reduction factor over industrial potential waste heat utilization.

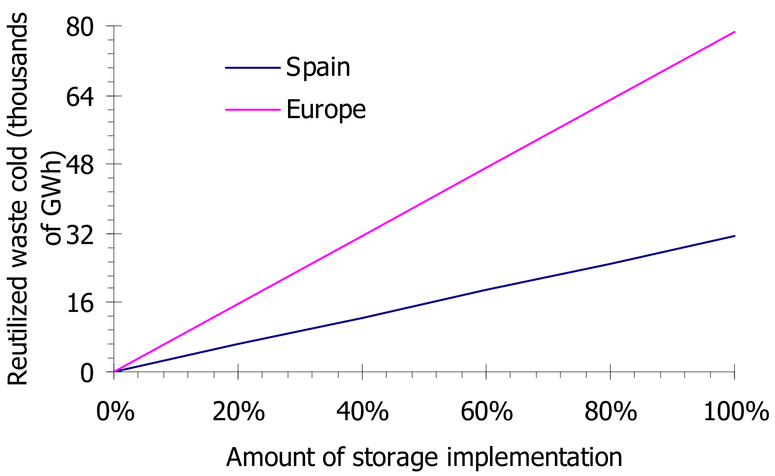


Figure 41. Influence of the amount of storage implementation over the industrial potential waste cold utilization.

It is noted that Spain shows predominant values in those categories involving solar short term systems in buildings when compared to Germany. Both countries exhibit a very low energy reutilization potential within district/central heating systems when compared to European values. As for industrial values, final potential results do not represent a large portion of the whole European potential, though if considered individually their potential is considered to be high. The remaining categories do not show any particularities as their tendencies follow expected trends.

The influence of storage implementation over electrical energy savings is shown in Figure 42 and Figure 43. Since these types of results are not available in the original German model, results comparison has only been able to be performed with the Spanish one.

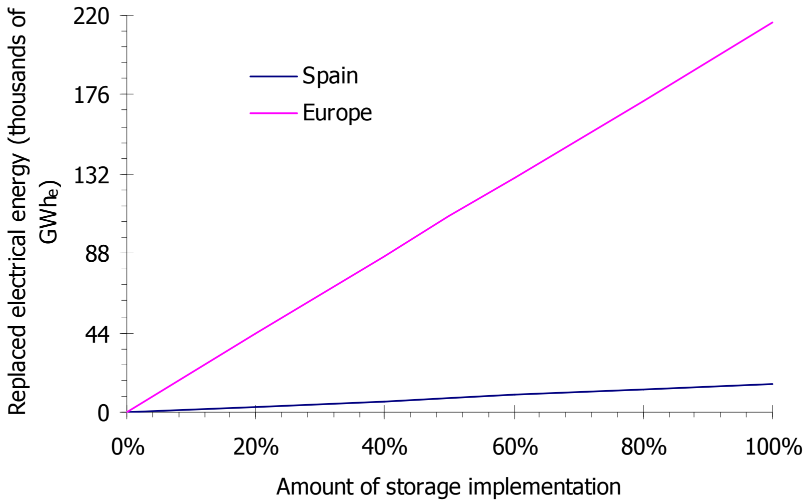


Figure 42. Influence of the amount of storage implementation over passive cold storage systems potential electrical energy replacement.

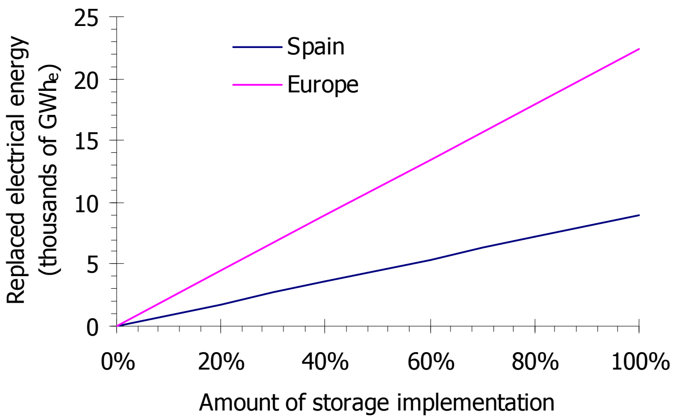


Figure 43. Influence of the amount of implementation over industrial waste cold potential electrical energy replacement.

The comparison between the emissions reduction dependence and the storage implementation or load reduction for all three cases is presented in Figure 44 to Figure 51. Since all calculations depend on linear CO_2 emission conversion factors, results are also linear, following similar trends to those observed for previous parameters.

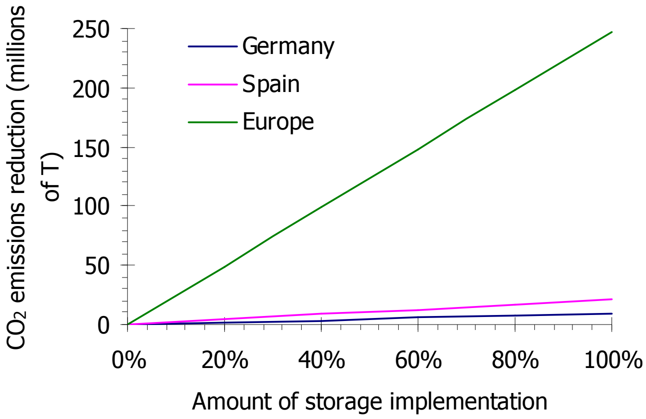


Figure 44. Influence of storage implementation on seasonal solar thermal systems CO_2 emissions reduction.

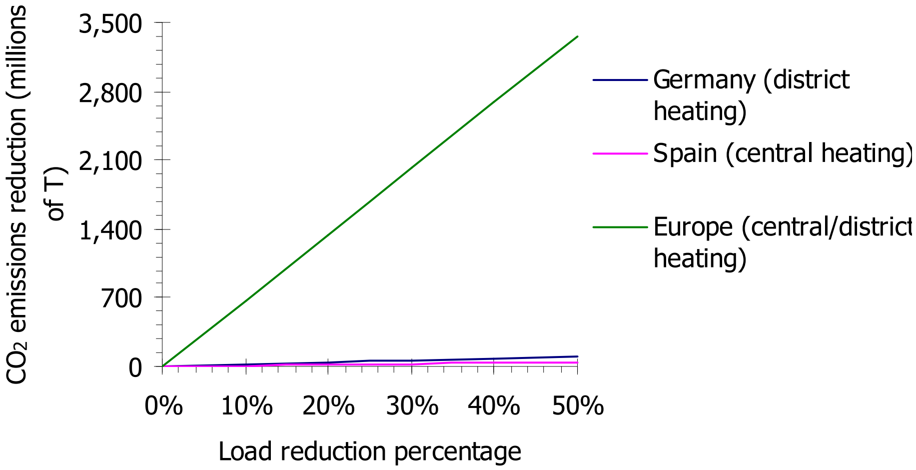


Figure 45. Influence of load reduction percentage over district/heating systems CO_2 emissions reduction.

As values for Europe are much higher than those of Spain, these last ones are shown separately in Figure 45 along with German values.

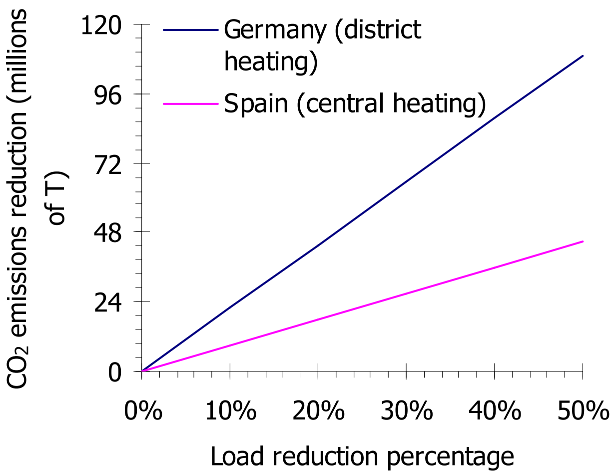


Figure 46. Influence of load reduction percentage over district/heating systems CO_2 emissions reduction in Germany and Spain.

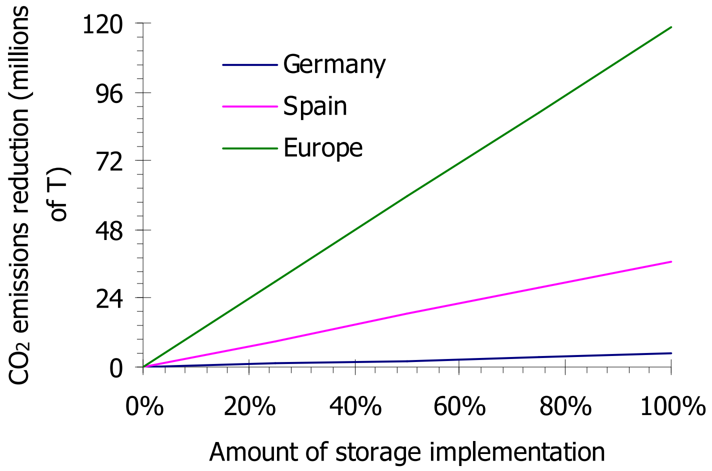


Figure 47. Influence of the amount of storage implementation over short term solar thermal systems potential CO_2 emissions reduction.

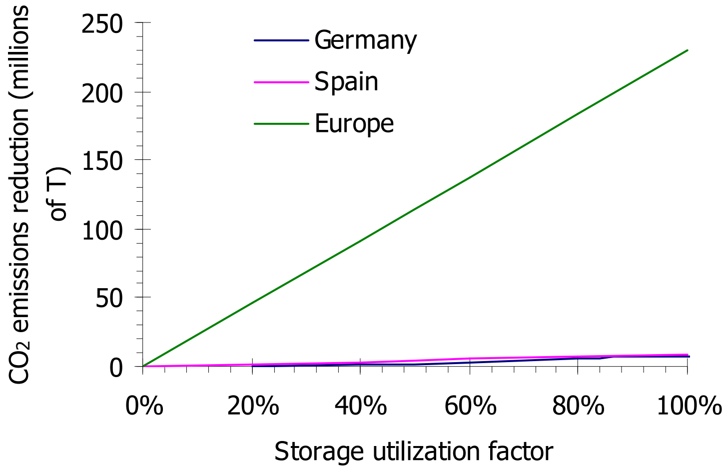


Figure 48. Influence of the storage utilization factor over cogeneration installations potential CO_2 emissions reduction.

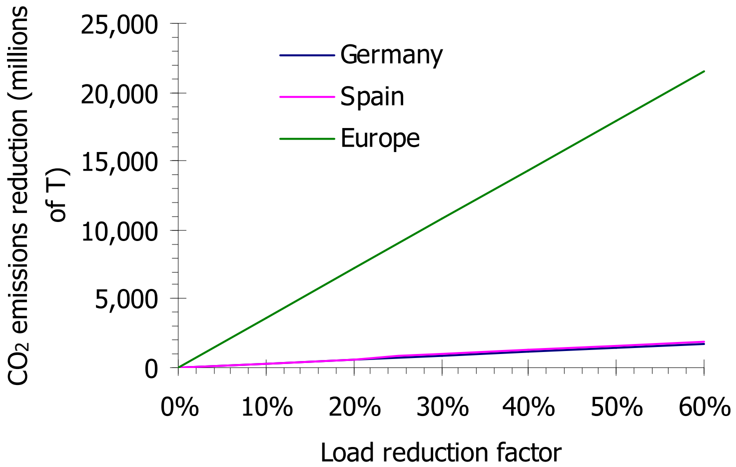


Figure 49. Influence of the load reduction factor over industrial potential CO_2 emissions reduction.

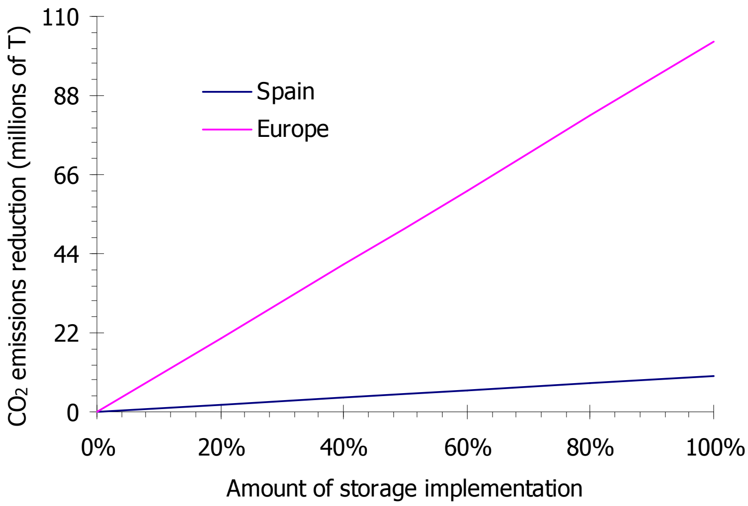


Figure 50. Influence of the amount of storage implementation over passive cold storage systems potential CO_2 emissions reduction in Spain and Europe.

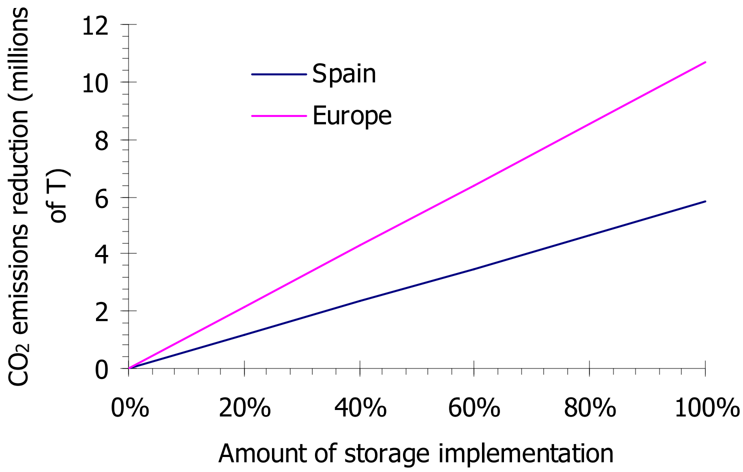


Figure 51. Influence of the amount of storage implementation over industrial waste cold storage systems potential CO_2 emissions reduction in Spain and Europe.

2.5 Conclusions

- It has been determined that the potential load reduction at the EU may be of 1,160,695 MW_{th} during the next ten years, which is considered may exert a strong influence over power capacities to be installed over that period. Germany and Spain shares in this reduction are of 8% and 9%, respectively.
- Yearly potential energy savings at the EU is estimated to be 7.5%.
- Regarding electrical energy savings, Spain has got a contribution of 20% of the overall savings at the EU, which account for a 0.1% of the electrical energy consumption.
- Finally, the estimated potential CO_2 emissions reduction in the EU is an average of 5.5% (based on 1990 and 2005 levels).
- The number of buildings and the industrial waste energy have a stronger influence on final results than any other considered input data.

3 Experimental analysis of passive TES application with PCM and awnings

3.1 Background

In 2004, Castellón started a study about the potential use of Phase Change Materials (PCM) in buildings. The work consisted on analyzing the different existing possibilities of integrating PCM into building materials by reviewing previous research work on the subject, performing some experimental laboratory work about the PCM properties and their compatibility with construction materials, and analyzing results obtained at a real experimental set-up at a real location where microencapsulated PCM was actually integrated into small concrete buildings (cubicles) with no insulation material in a Mediterranean climate. Thermal and practical aspects were addressed. The main goal was to present the use of PCM as a viable technique of energy storage to minimize the use of non-renewable energy for heating and/or air conditioning purposes in buildings, since their energy demand is not always met by the energy supply. Gathered information, experimental results, and conclusions led to the execution of a PhD thesis in 2008 [17].

It had been detected then that due to the very high outdoors temperatures during the summer, PCM could not solidify completely on some days and therefore its effects over the building were lower than expected. This is why in 2008 it was desired to carry on with the experimental work. It was set out that a reduction of the solar radiation reaching the walls containing PCM would help the material solidify during summer time, and that the potential energy savings would then increase. Since these aspects could be achieved by means of providing shadows to the walls, awnings were attached to the cubicles and the same types of experiments and a similar analysis to that performed by Castellón were performed. This chapter deals with this part of the task and presents the analysis of the obtained experimental results from 2008 to 2009 and compares them with those obtained previously.

3.2 Experimental set-up description

3.2.1 Location of the cubicles

The experimental set-up is located in Puigverd de Lleida, Spain, 25 km away from the city of Lleida, capital of the province with the same name at Catalonia, Spain. Figure 52 shows the location of the experimental site in Europe.

3.2.2 Weather of Lleida

According to the Spanish Standard for energy efficiency in buildings [328] there are twelve different climatic zones in Spain. Regarding winter, five categories are defined depending on the severity of the season, with "A" the most benign and "E" the most severe. As for summer, four categories are defined, with "1" the most benign and "4" the most severe. Lleida has a Mediterranean arid climate, and of continental tendency, characteristic of the valley the city is located at. Winters are dry and very cold, and summers are hot. The yearly average rainfall is very limited, of about 275 mm, with peak values during spring and summer drought. It is common to experience temperatures of some Celsius degrees below zero in winter and up to 40 ºC in summer. During winter season it is very characteristic to see the fog that usually covers the valley for days [329].

Table 13 shows the weather description of Lleida following the CTE classification. Figure 53 and Figure 54 show a typical year in Lleida for temperature and solar radiation [18].

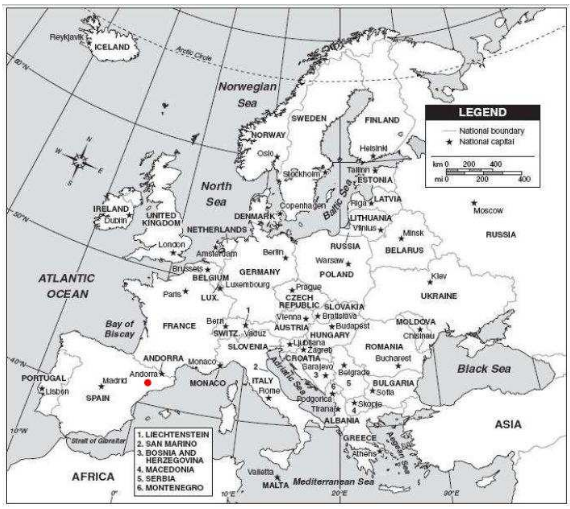


Figure 52. Location of Puigverd de Lleida in Europe [18].

City	Winter zone	Summer zone	Climatic zone	Comments
Lleida	D	3	D3	It represents well the continental weather of inland cities such as Madrid

Table 13. Climatic zone according to the CTE classification.

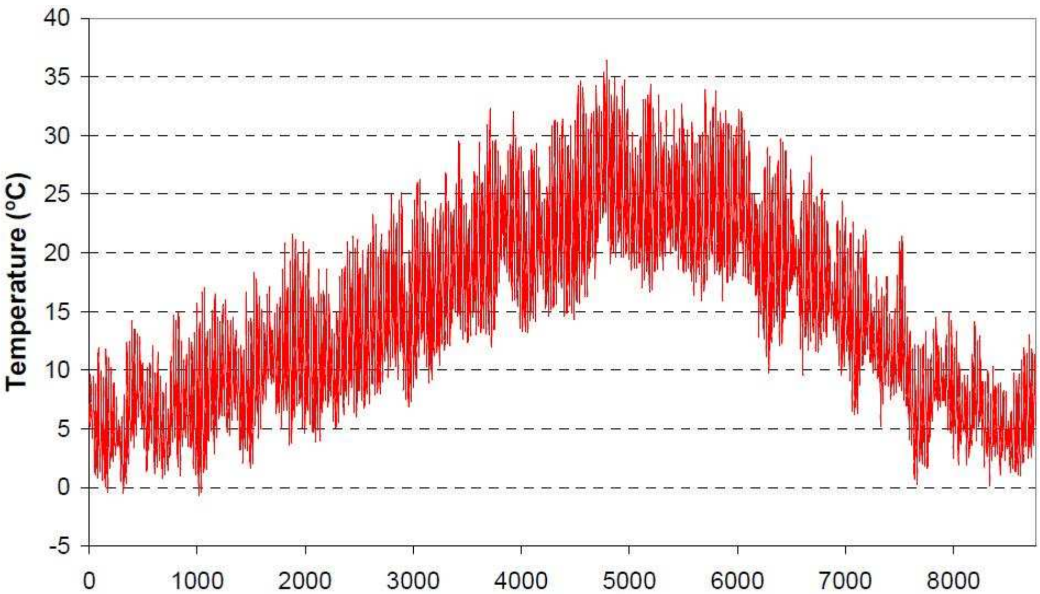


Figure 53. Weather data for a typical year in Lleida: temperature.

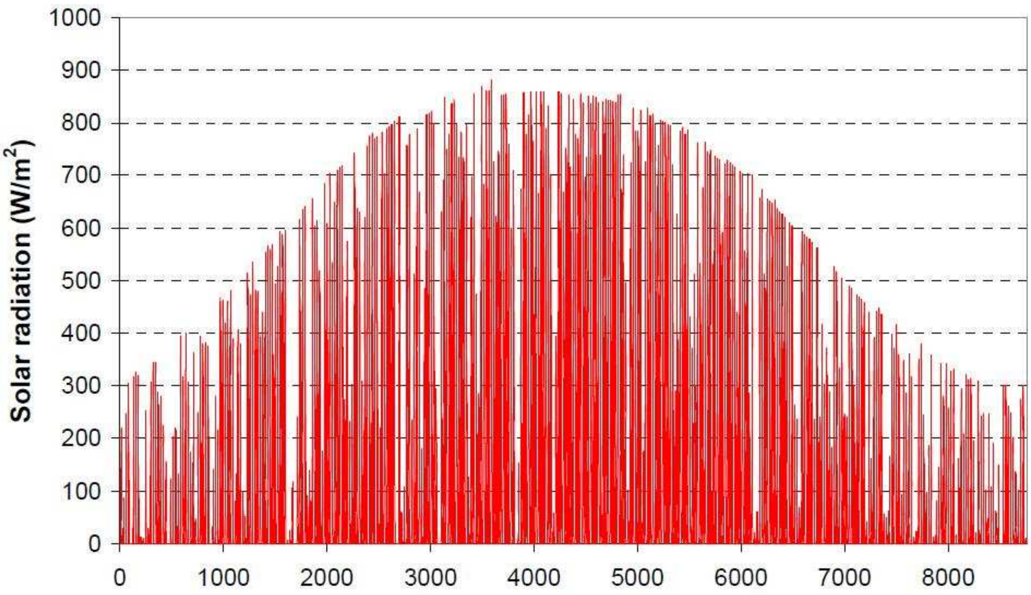


Figure 54. Weather data for a typical year in Lleida: Solar radiation.

3.2.3 Experimental set-up main constructive details

In 2004 the research group GREA from the University of Lleida began the construction of a unique set-up on a European and World level, so the storage of thermal energy at low temperature in buildings could be evaluated. The set-up consists on several cubicles that simulate buildings in which different building materials (mainly PCM) have been included. The cubicles that were utilized by Castellón are briefly described next. Additionally, cubicles utilized by Castell [18] (who also performed a PhD thesis on the use of PCM in buildings at the same experimental set-up), are described.

Castellón's experimental set-up consists of two identically shaped cubicles of concrete, built with the union of six panels. One cubicle is built with conventional concrete and the other one with a concrete containing about 5% in weight of microencapsulated PCM (Micronal®PCM, from BASF; with a melting point of 26 ºC, and a phase change enthalpy of 110 kJ/kg [17,204]), mixed with the concrete in three of the panels (South, West and Roof walls) (Figure 55).

Figure 55. View of the concrete cubicles (2006).

A PCM with such melting point was chosen because of, aside from integration aspects into the concrete, the climatic conditions. A lower PCM melting point would have implied that the material would have remained molten most of the time during hot seasons, therefore not storing heat and not contributing to maintain comfort conditions inside the cubicles. The requisites for attaining comfort conditions inside the cubicles are addressed later on in this document.

The dimensions of the cubicles are 2.64 x 2.64 x 2.52 m and the panels are 0.12 m thick. The distribution of the windows is the following: one window of 1.7 x 0.6 m at the East and West wall, four windows of 0.75 x 0.4 m at the South wall and the door in the North wall.

For night ventilation during summer days South wall windows can be opened. The cubicles are not insulated as the goal was to test the effect of the PCM alone. Further details on the cubicles design and construction were given by Castellón back in 2008 [17].

All the cubicles were oriented exactly to the South, and the distance between them was calculated in order to avoid shadows. It was also verified that there were no elements creating shadows on the cubicles in their surroundings. A general view of the cubicles is shown in Figure 56.

Figure 56. Experimental set-up at Puigverd de Lleida (2005).

As for the cubicles utilized by Castell, they have the same inner dimensions as those of Castellón. Castell worked with 5 cubicles built with traditional brick (conventional and alveolar), different insulation types, with/without PCM in the walls (employing RT-27 and SP-25 PCM in the conventional brick and alveolar brick cubicles respectively, with theoretical melting points of 27 ºC and 28 ºC), and with/without a heat pump in order to provide a controlled environment at the inside.

The whole installation allows performing different types of experiments:

- Free-floating: the cubicle inner temperature is not controlled and it oscillates according to the climatic conditions; this allows determining transitory parameters of the buildings, such as the time delay that is produced between outside and inside temperature peaks.
- Controlled temperature: the cubicle inner temperature is controlled by means of a heating or air-conditioning system; this allows registering the systems energy consumption and the savings that may be achieved with the tested technologies.
- Comfort conditions: the inner temperature is also controlled, but in this case the systems do not work continuously but according to a schedule that simulates the real conditions of different types of buildings (households, offices, museums, theatres, etc.).
- Internal gains: it consists on simulating inner elements that generate heat inside buildings (occupants, electronic equipment, machinery, etc.) under real working conditions, so the solutions and constructive systems for more specific cases may be studied.

Out of the mentioned experiment types, only the first two ones were performed at the cubicles utilized by Castellón and Castell, though under different configurations as it is explained latter on in section 3.3.1.

Aside from the PhD thesis performed by Castellón and Castell employing data measured at the set-up as mentioned in section 3.1, some scientific publications have been derived based on the research experiments performed by the group (some already cited in chapter 1). Among them one may find: a study to use PCM in brick for passive cooling applications [195], a introduction to the cubicles as a way of testing PCM with construction materials [147], a life cycle assessment of the inclusion of PCM in experimental buildings [330], a experimental study of the PCM inclusion in building envelopes [194], a study of the effect of PCM in sandwich panels [196], a study on the improvement of thermal comfort in concrete buildings using PCM [331], and a study on the use of microencapsulated PCM in concrete walls for energy savings [133].

3.2.4 Awning dimensions

As one of the main goals is to compare the effect of adding shadows to the cubicles over the PCM activation and the cubicle inner temperature and as one way to activate the solidification of PCM during summer time is to decrease the number of hours of direct solar radiation on the walls of the cubicle, the experimental set up was slightly modified in order to add shadows to the South, West, and East walls and also the roof of both cubicles during June, July and August.

Shadows were provided by adding an awning at the top of the cubicles, as shown in Figure 57. In order to evaluate the dimensions of the awning, the Sun trajectory during June, July, and August in Lleida was assessed using the solar altitude (α) and the solar azimuth (γ). Employed concepts and equations are shown next [332].

Figure 57. View of the cubicles with awning; July 30th, 2008 at 13:30 pm.

In order to be able to calculate the solar altitude and azimuth, two other previous parameters need to be defined. The first one is the declension angle. The declension angle shows the Sun displacement in reference to the equator. Its maximum value is of 23º27' (23.45º) on the summer solstice and its minimum value is of -23º27' (-23.45º) on the winter solstice. During the equinoxes its value is zero since that is the time when the Earth trajectory intersects the equator plane. The declension angle is given by the following equation:

$$\delta = 23.45º \cdot \sin\left[360 \cdot \left(\frac{284+n}{365}\right)\right]$$

Eq. 14

where δ = declension angle
n = considered calendar day (1≤n≤365)

The second parameter to be defined is the hour angle, which shows the Sun displacement respect of its position at noon. This angle depends on the solar time, which is the displayed time by a clock to which no correction has been applied. The hour angle is obtained as follows:

$$\omega = 15 \cdot (12 - h)$$

Eq. 15

where ω = hour angle
h = solar time

The solar altitude is a magnitude that depends on the previous two angles and the latitude of the place to which calculations are performed; it is defined as the angle a sunray forms with the horizon plane of the considered geographical place; its value goes from zero (at sunrise) to its maximum (at noon). As for the geographical latitude corresponding to Lleida, it is of 41,35º. The solar altitude is defined by the following equation:

$$\sin(\alpha) = \sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \cdot \cos(\omega)$$

Eq. 16

where α = solar altitude
φ = geographical latitude

Finally, the solar azimuth is defined as the displacement of the vertical plane containing the Sun respect of its position at noon measured on the horizon plane; it is considered positive during the morning and negative during the afternoon. The equation shown next is employed for latitudes greater than 10º and places located at the Northern hemisphere and it is applied when the time of the day for which calculations are performed is known.

$$\cos(\gamma) = \frac{\sin(\varphi) \cdot \sin(\alpha) - \sin(\delta)}{\cos(\varphi) \cdot \cos(\alpha)}$$

Eq. 17

where γ = solar azimuth

After performing a parametrical study using all previous parameters, results indicated that a 4.4 m x 4 m awning installed 12 cm above the roof of the cubicles (3 m x 3 m) would be appropriate. With this awning East wall would be partially covered during the morning (half covered at 10 am). Then, East and West walls would be totally covered from 1 pm to 3 pm. The West wall would be partially covered in the afternoon (half covered at 5 pm). Half of the South wall would be shadowed at 10 am, being totally covered at noon, and partially covered again in the afternoon. The roof is protected all day long.

Figure 58 shows the awnings dimensions.

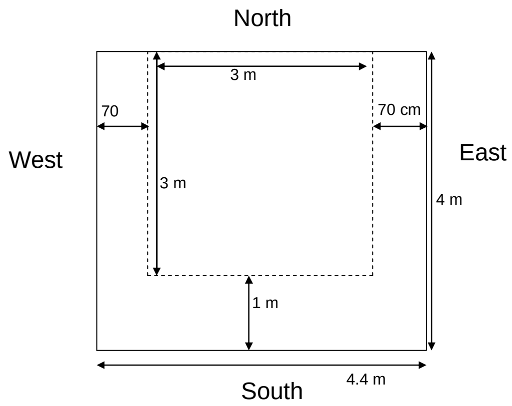


Figure 58. A bird's eye view of the roof of the cubicle with an awning.

3.2.5 Instrumentation

There are three main variables which were to be measured in order to generate the required experimental data: wall temperature, the heat flux through the walls and the external solar radiation. To do so, the correspondent sensors were installed at the set-up as described next.

Temperature sensors (PT-100 DIN B) were installed on the internal surface of each wall on the external surface, and at the middle of the room at heights of 1.2 m and 2.0 m, protected to avoid the radiation from the walls. A heat flux sensor (HUKSEFLUX HFP01 with a ±5% precision) was installed on the internal surface of the South wall (Figure 59). A meteorological station was installed nearby so the outdoors temperature could be measured (Figure 60). Finally, the solar radiation was registered by a HUKSEFLUX LP02 pyranometer on top of each cubicle (Figure 61). Additionally, in order to prevent solar radiation from coming in direct contact with the temperature sensors in the middle of the cubicles, blinds were attached to the windows (Figure 62). Another parameter that was measured is the electrical energy consumption of the cubicle (see section 3.4.5.5), using a PECA 15 sensor (Figure 63). All the instrumentation was connected to a data logger connected to a computer (Figure 64).

Figure 59. Instrumentation: heat flux sensor (left) and temperature sensor in the middle of the cubicles (right).

Figure 60. Meteorological station.

Figure 61. Solarimeter placed on top of the cubicles.

Figure 62. Image of the cubicles with blinds at the windows. Left (outer view), right (inner view).

Figure 63. Electrical energy consumption measurement device.

Figure 64. Data logger and computer installed in the cubicles.

3.3 Methodology

3.3.1 Performed experiments

During 2005 and 2006, as part of Castellón's work [17], measurements were performed in order to compare results and to analyze the behaviour of the cubicles. As the goal was to continue this work, measurements were also performed from January 2007 to September 2009. However, awnings were attached to the cubicles during two specific periods: from August to September 2008 (later they were removed until December) and during the considered fraction of 2009.

Additionally, an auxiliary heating system (a radiator) was used inside the cubicles for some weeks during 2006 and 2009, with and without awnings respectively, so the effect of keeping the cubicle inner temperature constant (while climatic conditions allow for it) over the parameters to be analyzed could be appreciated. Besides, it was desired to see how the mentioned experimental conditions affected the radiator electrical energy consumption, as energy consumption is a very important parameter from both an economical and energetic point of view, since a reduction on the energy consumption represents more energy efficiency, less primary energy consumption and more economical savings. During the partially controlled temperature experiments, the electrical energy consumption of the radiator was registered every 5 minutes. Unfortunately, the consumed energy was only measured during 2009.

Data were taken under the following conditions:

- Closed windows all day long.
- Open windows all day long.
- Free-cooling, that is, open windows at night and closed during the day (performed in summer only), so the PCM could solidify during the night, giving coldness during the hot days of summer.
- Closed windows all day long with a heating system (radiator) with a set point of 25 ºC inside the cubicles.

3.3.2 Climatic data comparison criteria

To perform a comparison among existing data, two external conditions had to be compared in advance: the outdoors temperature and solar radiation. The criterion behind this is: if the respective measurements of the climatic conditions of two periods of time exhibit similar values, and the performed experiments during both periods are the same, then the obtained results at both periods of time are comparable with one another.

As data sets were grouped in weeks, weeks with approximately the same outdoors temperature and the same solar radiation would be compared. Though predictable, it must be mentioned that no weeks with equal climatic data could be found.

The employed criterion to consider whether one week was similar to the other was:

- Temperature upper and lower limits should not differ from each other in more than ±3 ºC (an estimate variation of 7%).
- Solar radiation limits should not differ from each other in more than ±(60-100) W/m^2 (approximately 15 to 18%).

The criterion applied to radiation values admits a higher variation than for temperature values simply because radiation is more likely to exhibit wider oscillations than temperature during a day and along a week.

3.3.3 PCM melting range

As mentioned in section 3.2.3, the employed PCM (Micronal from BASF) has a theoretical melting point of 26 ºC; however, as melting processes may not occur specifically at that temperature but at slightly higher or lower values, a criterion must be established in order to be able to evaluate the PCM activation and behavior. This has been made based on the laboratory DSC tests performed over the PCM, whose results were evaluated by Castellón [17].

Part of the obtained graphical results from those tests are presented as the specific heat variation as a function of the PCM temperature (Figure 65). As it may be seen by a characteristic change in the curve of the graphic, the PCM melting takes place at not only one temperature value but within a temperature range of approximately 25 to 29 ºC, which is the range in which the material goes through a phase change and therefore, is active. This is therefore the range which has been successively employed to determine when the PCM was active, and perform the correspondent observations and/or commentaries.

3.3.4 Operative comfort temperature

One of the goals of this study is to determine the influence the awnings exert over the human comfort inside the cubicles. There are different methods, qualitative or quantitative, to evaluate the human comfort level under some determinate climatic conditions [333], such as "operative comfort temperature", "effective temperature", "humid operative temperature", "heat stress index", etc.

In order to estimate the human comfort in the cubicles the chosen method has been the "operative comfort temperature" (T_o). The reason is that humidity values inside of the cubicles were not measured and the operative comfort temperature is a parameter that does not require relative humidity values. It has been considered that there are comfortable climatic conditions inside the cubicles if the operative comfort temperature lies between the recommended values at the standard ISO 7730 and EN-27730. These values are:

- 23 to 26 ºC for summer months
- 20 to 24 ºC for winter months

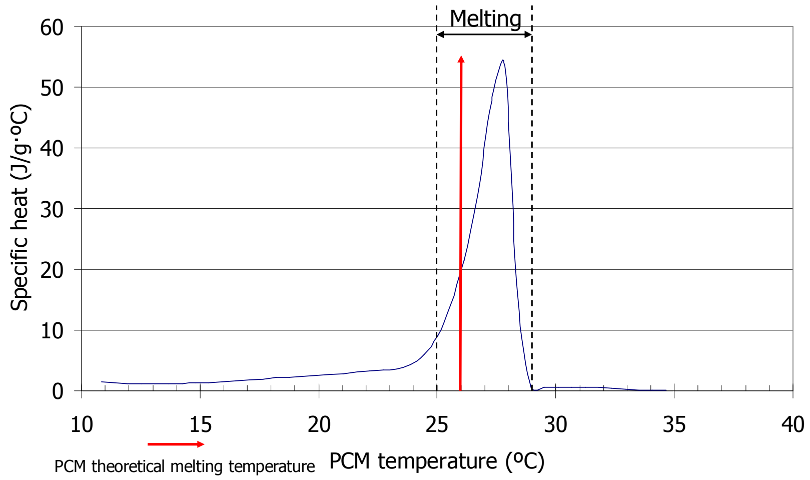


Figure 65. Specific heat vs. Temperature variation for MICRONAL PCM from BASF.

As for which months are considered as "summer" or "winter", the following criterion has been used:

- Summer: May to September
- Winter: October to April

The operative comfort temperature is defined with the following expression:

$$T_0 = \frac{h_r \cdot T_{rm} + h_c \cdot T_a}{h_r + h_c}$$

where T_o = operative comfort temperature (ºC)

h_r = linear radioactive heat transfer coefficient (W/m^2·K)

h_c = convective heat transfer coefficient (W/m^2·K)

T_{rm} = mean radiant temperature (ºC)

T_a = ambient air temperature (ºC).

The value of h_r is typically a constant for usual values of inner temperatures and takes a value of about 4.7 W/m^2·K. Regarding the value of h_c, it may be estimated as 4 W/m^2·K for a person standing up in air with a speed among 0 and 0.15 m/s.

The mean radiant temperature for a person in the center of a cubic volume can be calculated according to the following expression:

$$T_{rm} = \frac{T_f + 0.15 \cdot (T_{p1} + T_{p2} + T_{p3} + T_{p4}) + 0.4 \cdot T_s}{2}$$

where T_t = surface temperature of the floor (ºC)

T_{p1}, T_{p2} , T_{p3} , T_{p4}, = surface temperatures of the walls (ºC)

T_s = superficial temperature of the ceiling (ºC)

3.4 Results analysis and comparison

3.4.1 Comparable weeks

According to the previously explained comparison criteria, four weeks (one for each experiment type) were found in order to perform the respective comparisons. Found coincidences for each case and cubicle type are summarized in Table 14.

Experiment	With awnings			Without awnings		
	Year	Month	Week	Year	Month	Week
Closed Windows	2009	February	4	2008	February	2
Open Windows	2008	August	1	2006	July	4
Free-cooling	2008	September	1	2007	July	4
Closed windows with a heating system (radiator)	2009	May	3	2006	August	4

Table 14. Comparable weeks according to experiment and cubicle type

3.4.2 Free-cooling experiments

3.4.2.1 Climatic data

A comparison between the outside temperatures and solar radiation respectively is shown in Figure 66 and Figure 67 for the correspondent weeks.

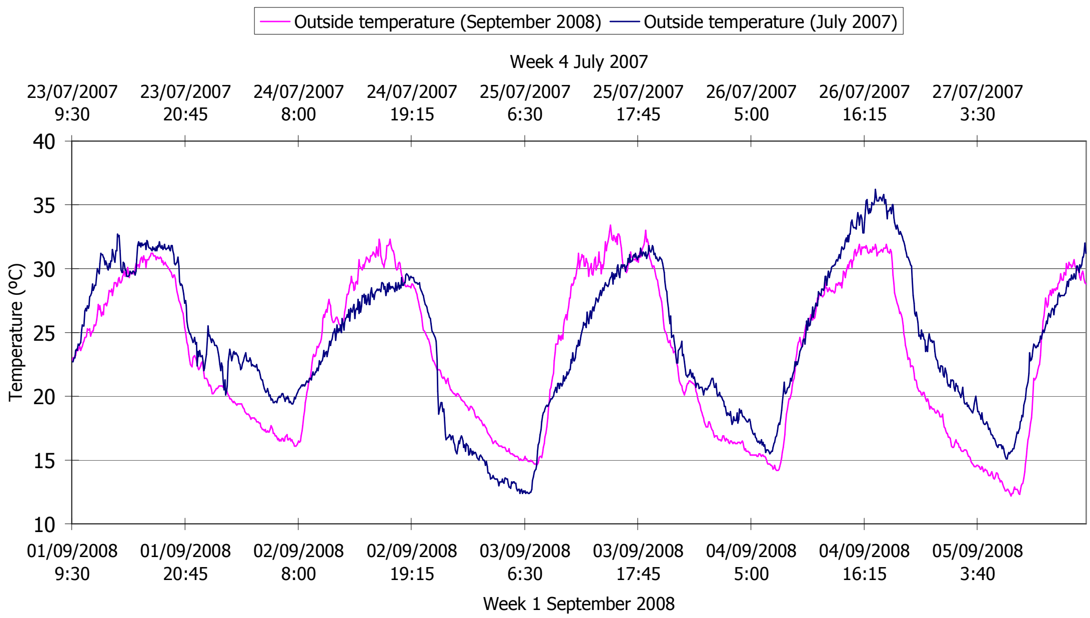


Figure 66. Comparison of the selected weeks outside temperature (free-cooling experiments).

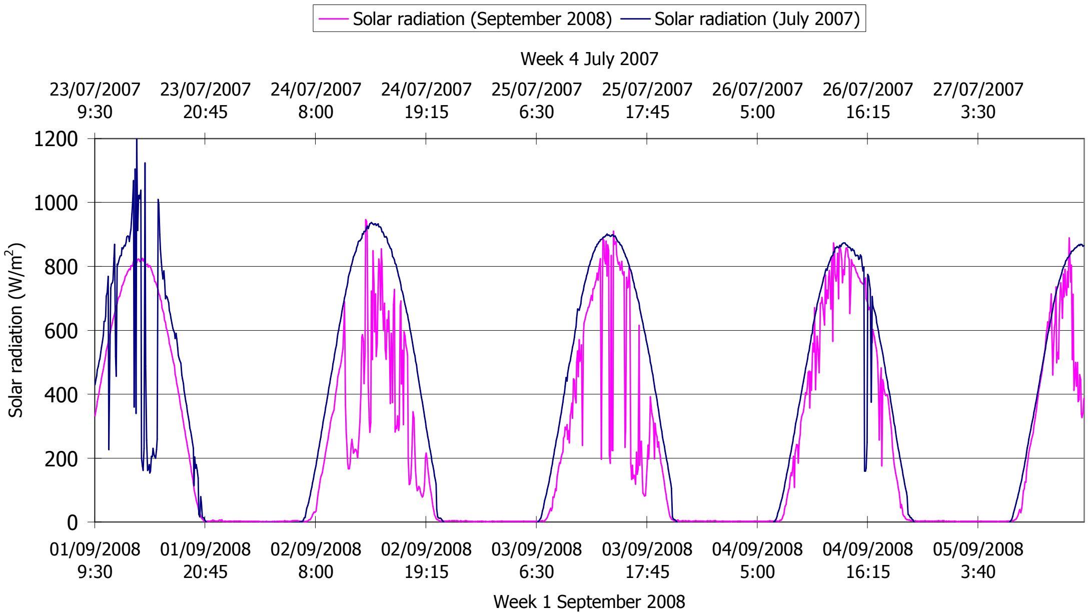


Figure 67. Comparison of the selected weeks solar radiation (free-cooling experiments).

3.4.2.2 Wall temperature and heat flux

Regarding experimental parameters, the following aspects are to be analyzed: the wall temperature, the cubicle inner temperature (measured at a height of 1.2 and 2.0 m), and the operative comfort temperature. Since microencapsulated PCM is part of the concrete panels of the wall, its temperature could not be measured directly, but the analysis of its behavior and effects is discussed when analyzing the wall temperature.

So first the wall temperature is going to be addressed. Figure 68 shows a comparison of this parameter for the selected weeks. Figure 68 shows that the wall temperature in cubicles with awnings is up to 3-4 ºC (6%) lower than that of cubicles without awnings (Figure 69).

This change in the wall temperature is attributed to the PCM, which functions as an insulation material, not letting all the outside heat in the cubicle, as already the wall temperature is lower in cubicles with PCM. This effect, however, results from PCM storing the heat, that is, the material does not behave as a heat barrier but as a "heat container", which will later release this energy to the inside when outside temperatures go down, which is the moment when this heat is more necessary to maintain comfort conditions inside the cubicle, which will be analyzed latter on this document.

It must be noticed that the presence of awnings does help PCM work, as the shadows produced by awnings diminish the amount of solar radiation reaching the walls and these do not overheat that much, thus making it easier for PCM to solidify at night after storing energy in the daytime while melting. The shadows allow for this to mostly repeat daily. On the other hand, when PCM accomplishes to complete full phase change cycles (complete meltings and solidifications), its effects are more noticeable and the time during which it works is then higher. This last aspect is related to the PCM activation, and is addressed in more detail later on this section.

Therefore, in short terms it may be said that the lower wall temperature peak values are attained as a result of a combined effect of the heat storage by PCM and the solar radiation reduction on the wall by awnings (a PCM-awnings effect).

Another effect which has also been noticed is that in the cubicles with PCM and awnings, the inner south wall temperature arrive at its peak value in about 3:10 hours later than in the cubicles without PCM and awnings. In cubicles without awnings a similar effect is observed, only that in this case, the delay is of about 2:20 hours. Therefore, the use of awnings has increased the mentioned delay in 50 minutes (36%) (Figure 70).

This time delay is the result of an improvement of the wall thermal inertia, that is, the ability of the wall materials to conduct and store heat during the day and reradiate it latter when outside temperatures go down. The mentioned improvement is attributed to the effect of PCM over wall temperature by means of thermal storage. Aside from the action of PCM alone, the shadows generated by awnings have greatly contributed to this in the respective cubicles by prolonging the time along which PCM is active, as explained previously, thus causing the PCM to exert a higher effect over the wall thermal inertia. In short terms, a second major effect of the combination of PCM and awnings is a higher wall thermal inertia.

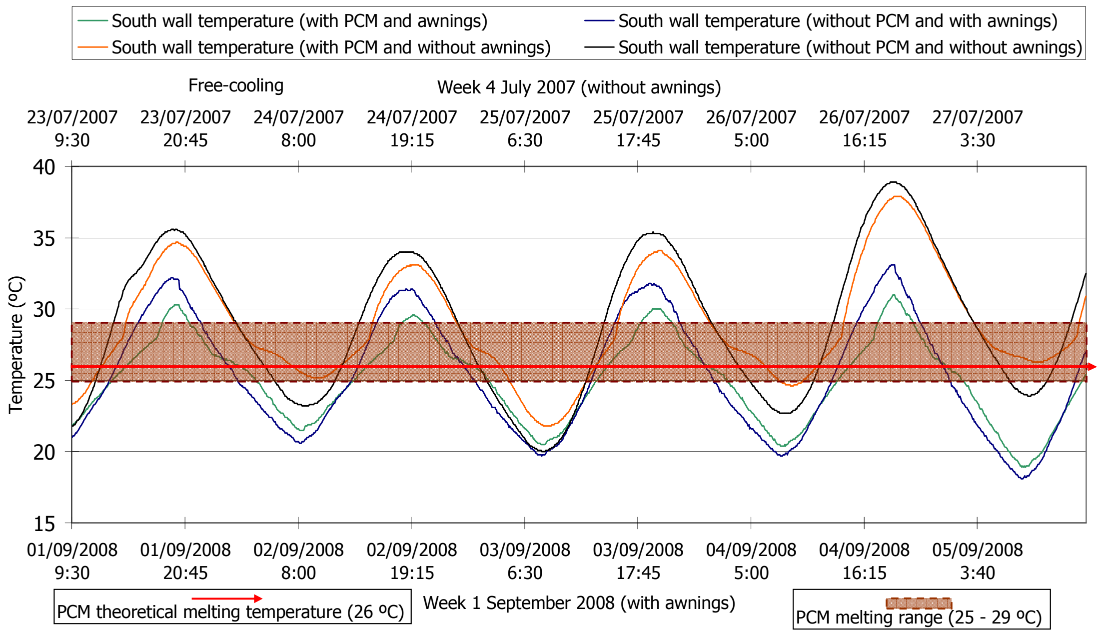


Figure 68. South wall temperature for cubicles with and without awnings during free-cooling experiments.

As it may be appreciated in Figure 68, PCM is active in both cubicle types, however, it should be highlighted that, thanks to the presence of awnings in the respective cubicles, the PCM has been able to perform complete phase change cycles, that is, it has been able to completely solidify or melt.

This phenomenon does not take place the whole time in the cubicles without awnings, where despite the PCM is active, it is noticed that it does not get to solidify completely on some days, mainly due to the overheating by solar radiation at daytime and the high ambient night temperatures during summer months.

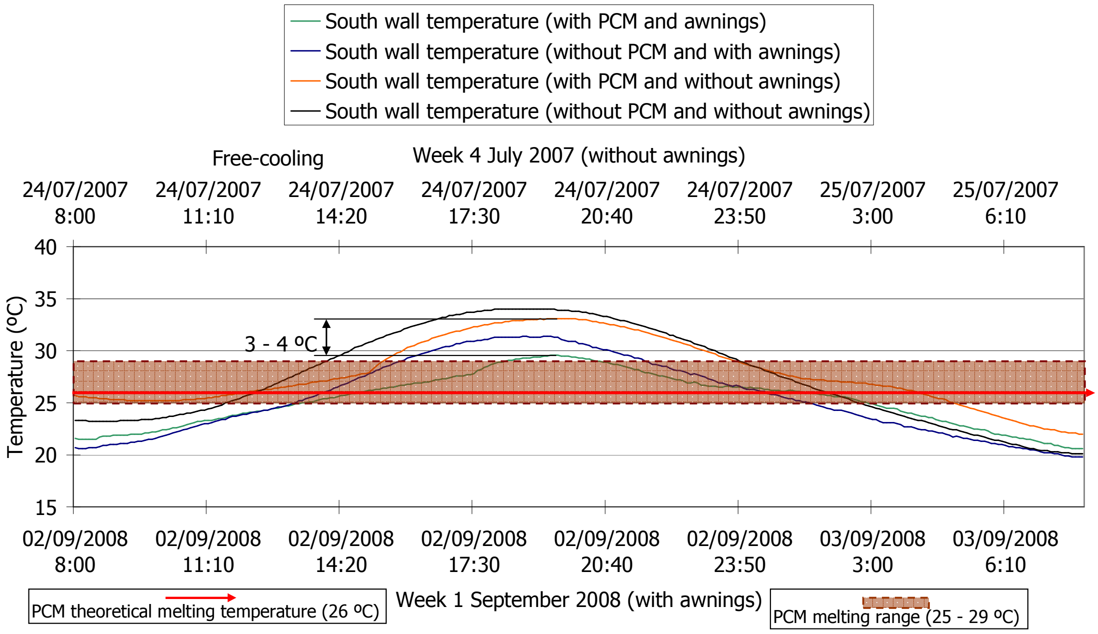


Figure 69. Detail of the south wall temperature for cubicles with and without awnings showing temperature differences during free-cooling experiments.

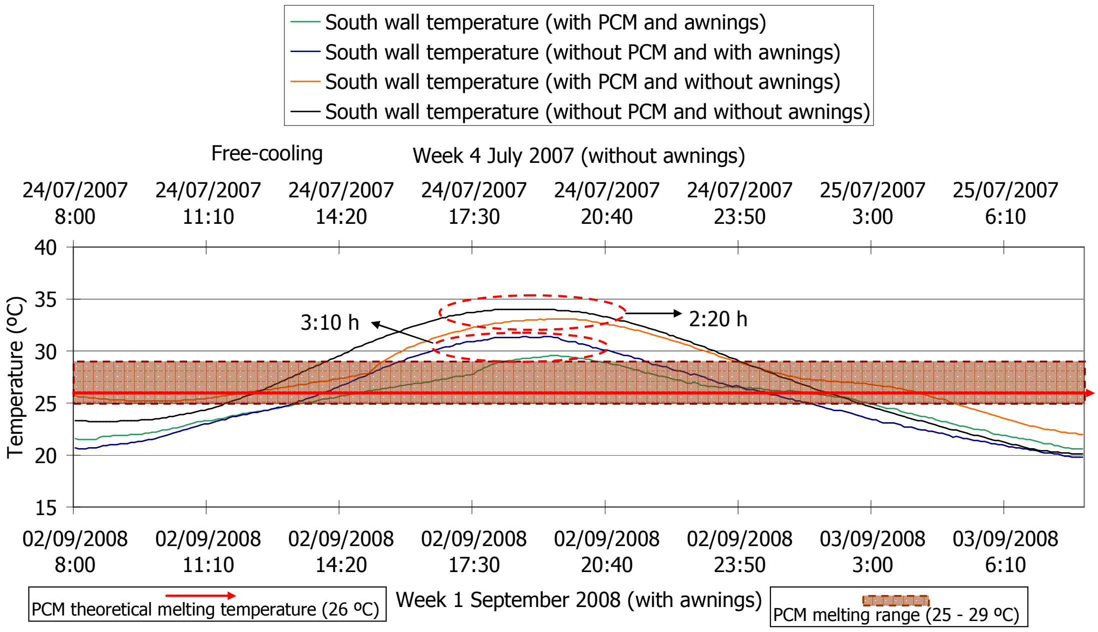


Figure 70. Detail of the south wall temperature for cubicles with and without awnings showing temperature delays during free-cooling experiments.

This is graphically seen by following the temperature values on the chart; PCM solidification is observed when the temperatures are below the melting range low limit, while PCM melting takes place when temperatures are above the range upper limit. An incomplete melting or solidification would occur if temperature values went up or down inside the melting range, getting close to the limits but without leaving the highlighted area.

Another aspect to be considered is the effect awnings may have over PCM activation. One way of tackling this aspect is to quantify the time the PCM has remained active during the considered weeks. Since data were registered every 5 minutes, it allowed quantifying the time PCM temperature stayed within the PCM melting range, that is, the time PCM was active. By knowing how many hours the PCM was active and the total time during which measurements were registered, the time percentage of PCM activation could be determined. This may be seen in Figure 71, where it is appreciated that adding awnings to the cubicles increased in 4% the PCM active hours per week.

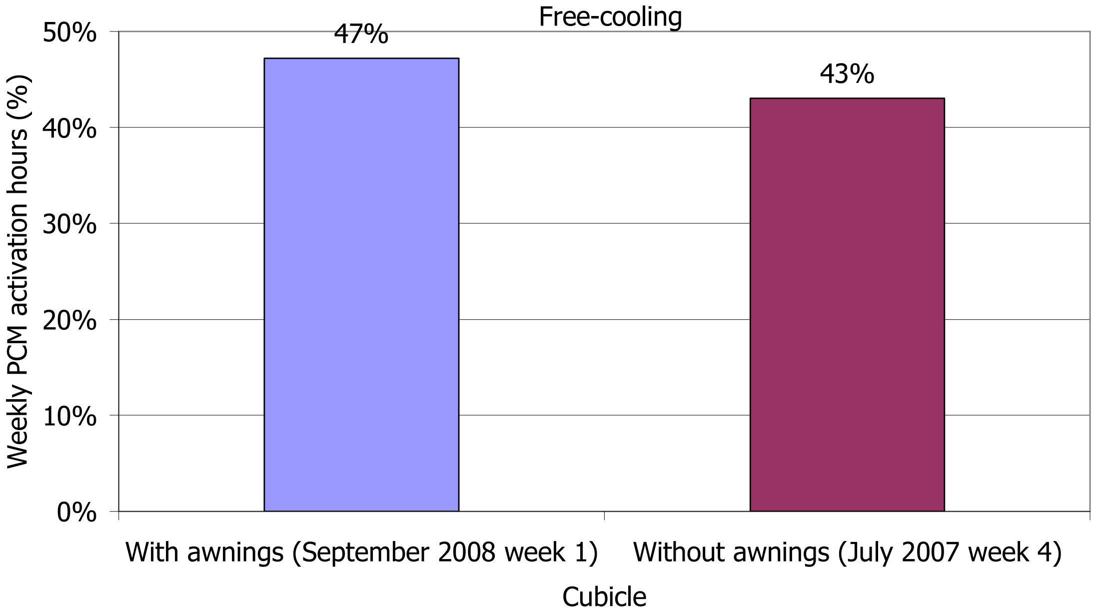


Figure 71. PCM active hours percentage for cubicles with and without awnings during free-cooling experiments.

Another measured parameter was the heat flux through the south wall, which is presented in Figure 72. It is observed that the heat flux in cubicles with awnings exhibited higher values in 17.5 W/m^2 (146%) than that in cubicles without awnings (Figure 73), and a wider range of variation (both with and without PCM). It is also noticed that the flux in cubicles with PCM and without awnings reached its peak values long after (13:20 hours) the flux in cubicles without awnings and without PCM. This phenomenon is not reproduced in cubicles with awnings, where peak values in the wall with PCM were attained in a shorter time period (5:08 hours) if compared to the one just mentioned for cubicles without awnings (Figure 74). This time delay is then 8:12 hours (62%) lower in cubicles with awnings.

As expected, the heat flux increase and decrease tendencies match those of wall temperatures, however, the flux of the wall in cubicles without PCM and no awnings tends to increase much faster than the other fluxes (though the flux in the wall with PCM and awnings shows a similar behavior, it is not that much pronounced), and then its general tendency is to decrease, decreasing steadily when the wall temperature matches the PCM melting range, and then decreasing along as the temperature goes down. This behavior is not observed at walls with PCM in the two studied cubicle types. The fluxes of walls with awnings showed a regular behavior, that is, it mostly reproduced along the week.

The wall heat flux behavior is related to the thermal inertia. In the cases where PCM is present, as there is an inertia improvement, the flux takes longer to reach its peak values because of the thermal storage that takes place as the PCM goes through phase change. When there is no inertia increase (i.e. no PCM is present), the effect just described in the paragraph before is observed in the correspondent cubicles.

When awnings are present, the described effects are accentuated in the correspondent cubicles, as PCM is allowed to work better and a higher inertia is accomplished, as already explained when analyzing the wall temperature behavior.

The behaviour of the heat flux is also conditioned by the temperature difference between that of the wall, and either the outside temperature or the cubicle inner temperature; therefore the direction changes of the heat flux and the time when this direction changes happen take place randomly according to which of these temperatures is lower or higher than that of the wall temperature. Additionally, when PCM is present, the amount of heat it can store before temperature differences change enough as to cause PCM to release it exerts an influence on the wall heat flux.

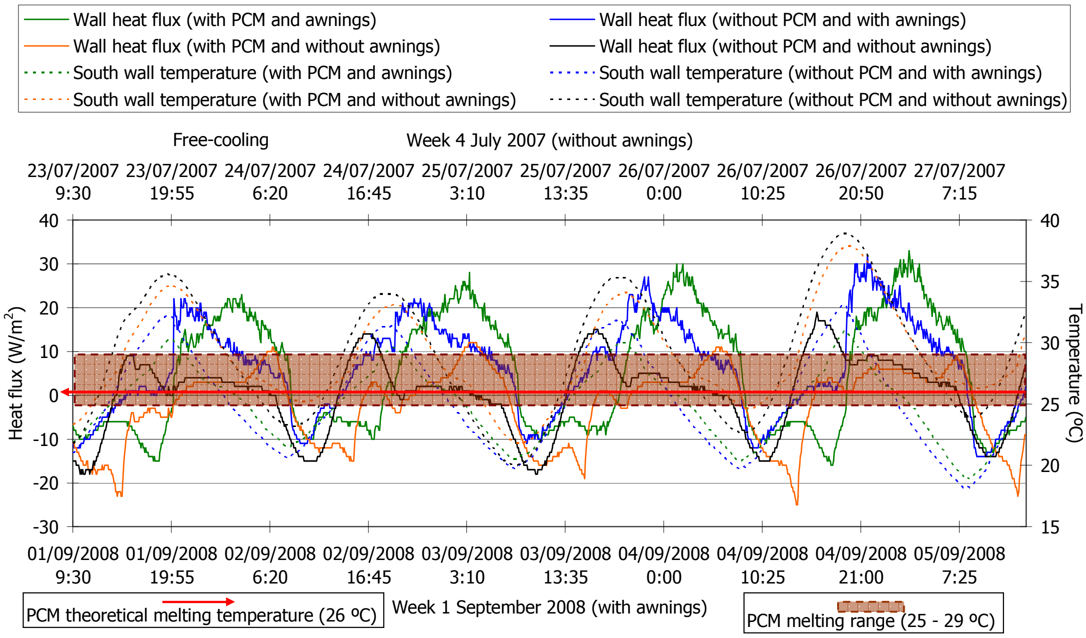


Figure 72. Measured heat flux through the south wall in cubicles with and without awnings during free-cooling experiments.

The flux of the PCM wall in cubicles without awnings attains its peak values when that of the wall without PCM has already started to decrease. Also, flux at walls with PCM and no awnings shows a slight tendency to remain more stable than that of walls without PCM when the wall goes through phase change temperatures. On the other hand, as the wall temperature rises every day, it is observed that the flux of walls with PCM and no awnings first decreases and then starts incrementing (as seen with a peak pointing downwards at Figure 72), while the flux of walls without PCM increments its values as already described previously.

The shadows produced by the awnings on the wall, aside from aiding to enhance the thermal inertia, are responsible for the more steady variation of the heat flux since the wall is less exposed to the changing solar radiation at the outside. The effect of PCM alone while storing energy (and increasing thermal inertia) in cubicles without awnings is observed over the heat flux as this one shows a more stable pattern. Another evidence of the thermal inertia enhancement by the PCM is the peak pointing downwards observed at the flux in cubicles without awnings.

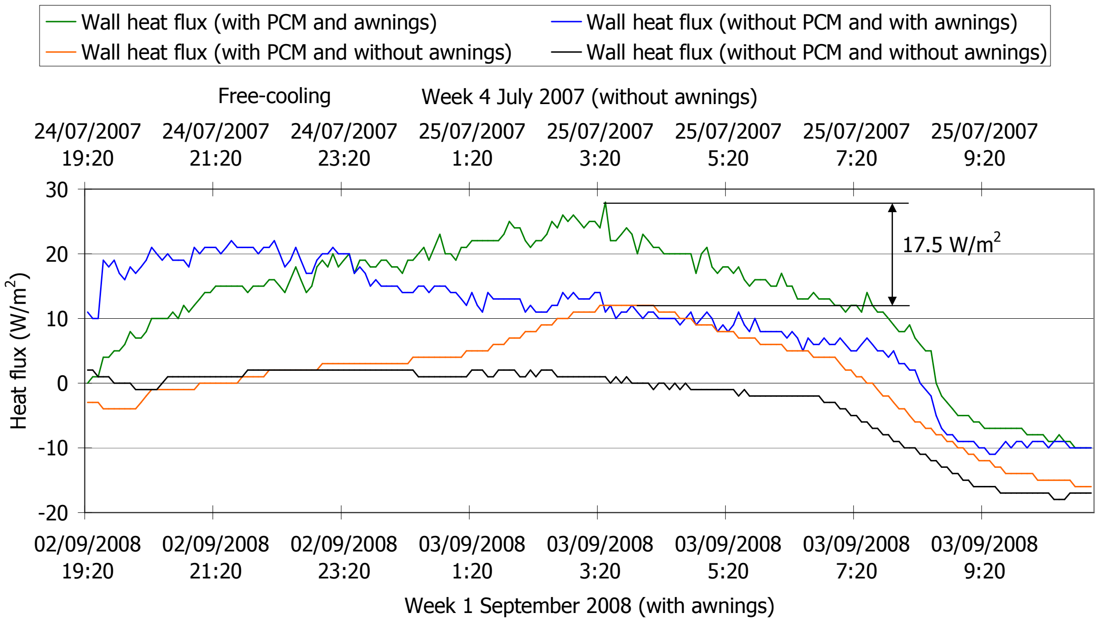


Figure 73. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux differences during free-cooling experiments.

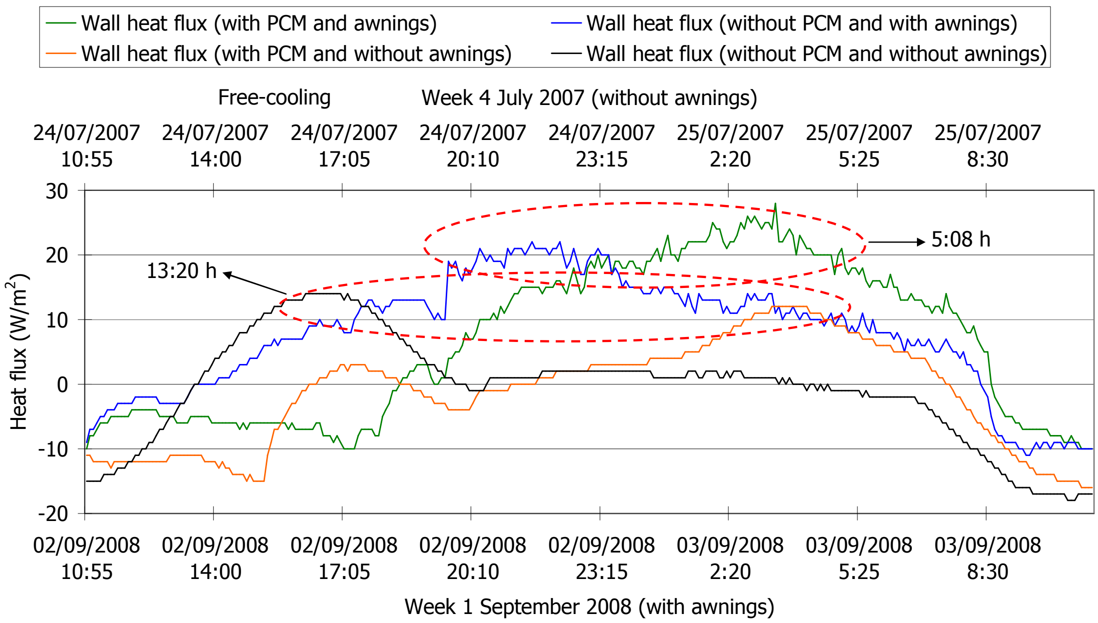


Figure 74. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux delays during free-cooling experiments.

3.4.2.3 Cubicle inner temperature

As mentioned in section 3.2.5, the cubicles inner temperature was measured at heights of 1.2 and 2.0 m respectively. First, obtained measurements at 1.2 m are to be discussed (Figure 75). The highest inner temperatures in cubicles with PCM and awnings are at least 1 ºC lower than those in cubicles with awnings and no PCM. The same phenomenon takes place in cubicles without awnings.

Inner temperatures in cubicles without awnings oscillate between 21 and 26 ºC approximately. It should be highlighted that the lowest values in cubicles with PCM mostly stayed within the comfort zone (Figure 75). Cubicles with PCM and no awnings have their highest inner temperature values only about 0.8 ºC lower than those in cubicles without PCM.

It is observed at Figure 76 that the inner temperatures in cubicles with PCM and awnings are 4 to 6 ºC (around 18%) lower than those in cubicles with PCM and no awnings. Another aspect to be mentioned is that inner temperatures in cubicles with PCM and awnings reach their peak values around 2 hours later than those with awnings and no PCM, while in cubicles with PCM and no awnings this delay is only of about 1:25 hours. The use of awnings has increased the mentioned delay in 35 minutes (41%) (Figure 77).

Cubicle inner temperature values basically depend on: the sensor position (height inside the cubicle), wall inner temperatures, and the heat transfer that takes place between the walls and the location the sensor is at (in this case by natural convection and radiation). The relation between the inner temperature and the wall temperature is then directly proportional, that is, any changes in the wall temperature will affect directly the inner temperature.

This is why the observed effects with the inner temperature are similar to those observed with the south wall temperature, The influence of PCM alone (insulation effect, heat storage, and thermal inertia improvement), and of the PCM-awnings combination over inner temperatures is the same one as already described when analyzing the wall temperatures at the previous section.

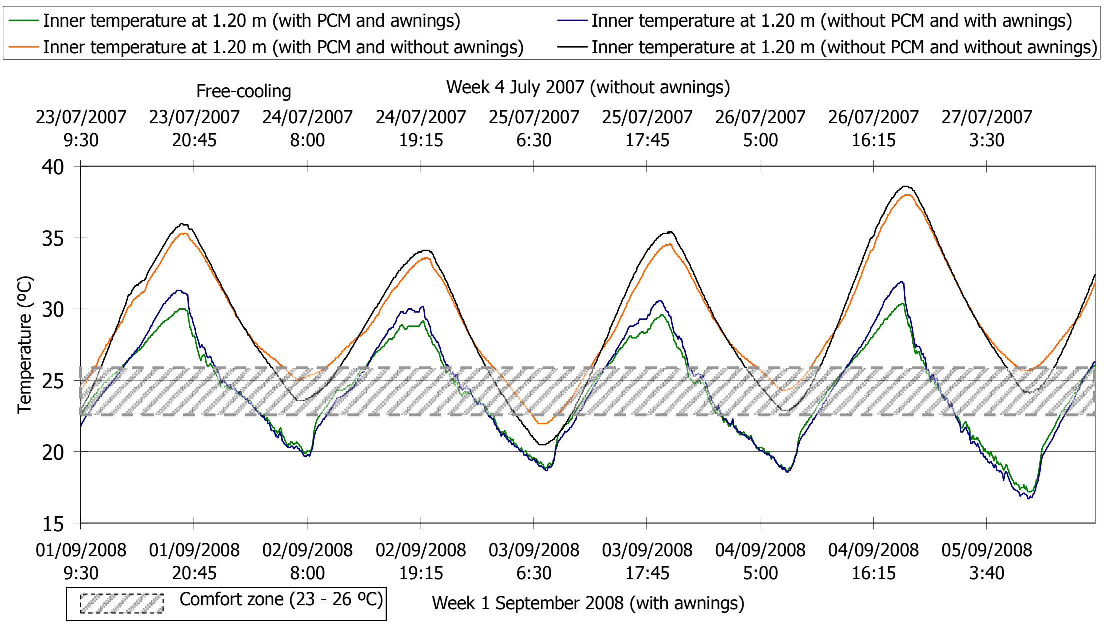


Figure 75. Cubicle inner temperature at 1.2 m height for cubicles with and without awnings during free-cooling experiments.

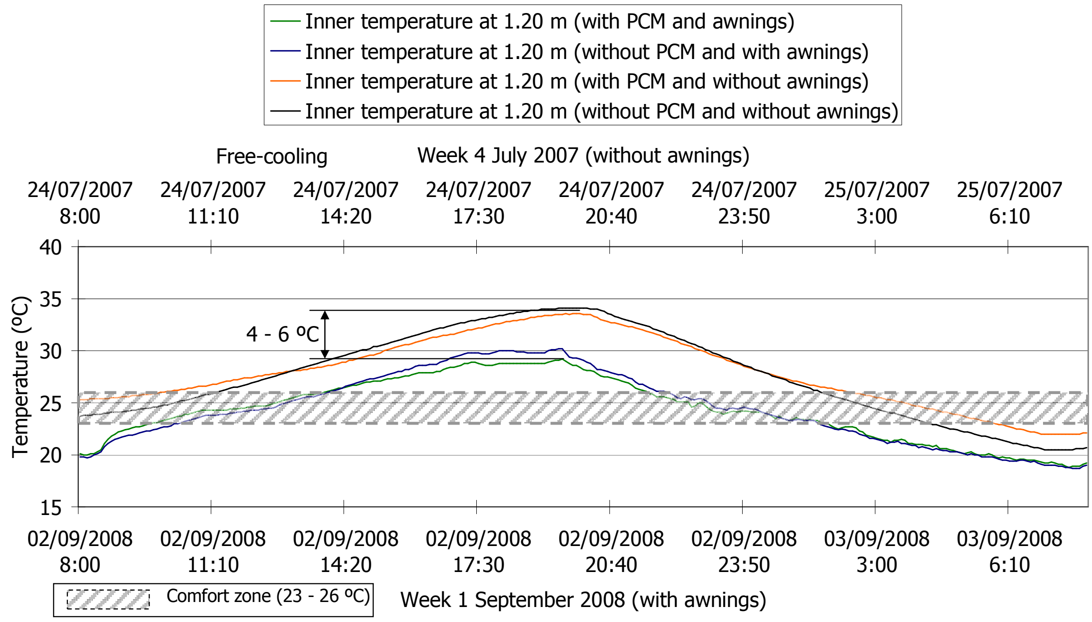


Figure 76. Detail of the cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature differences during free-cooling experiments.

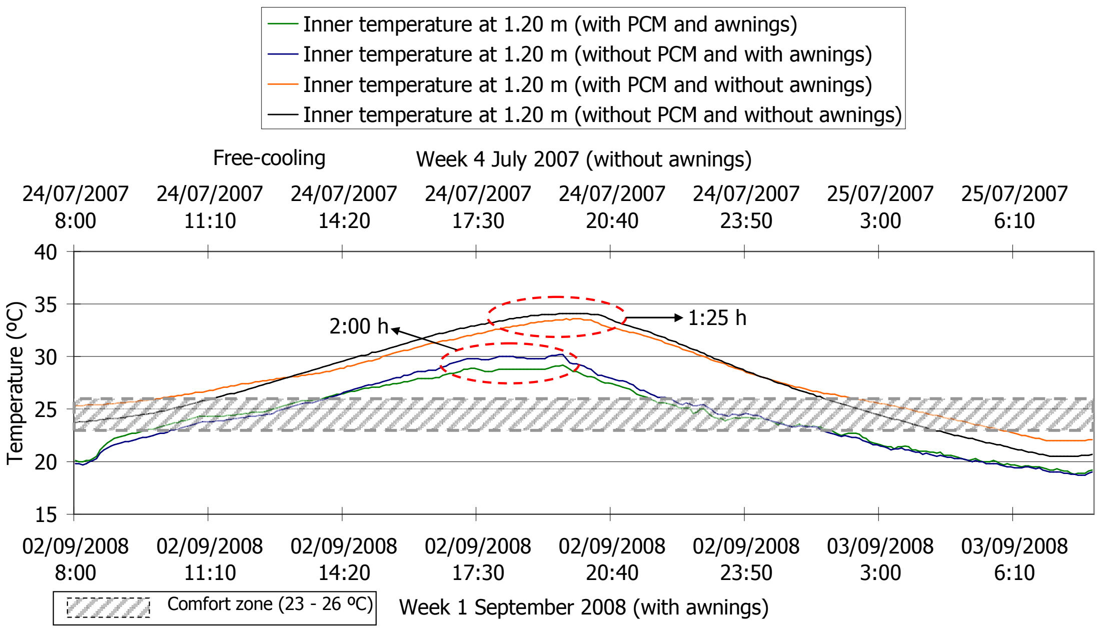


Figure 77. Detail of the cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature delays during free-cooling experiments.

As for inner temperatures at 2.0 m, they are shown in Figure 78. As seen, these values follow a similar variation pattern as the one described for temperatures at 1.2 m, however, values are a bit different.

Regarding higher temperature values, cubicles with awnings and PCM have values 1 ºC lower than those of cubicles without PCM, while cubicles without awnings and no PCM exhibit values 0.3 ºC higher than those in cubicles with PCM. Cubicles without awnings have peak values up to 6 ºC higher than those with awnings (Figure 79). Peak values in cubicles with awnings are then an 18% lower than those in cubicles without awnings.

It is also observed that inner temperatures at 2.0 m in cubicles with awnings and PCM reach their peak value 2:15 hours later than those without PCM; on the other hand, the same phenomenon in cubicles without awnings occurs, but only 1:05 hours later (Figure 80). The time delay has been increased in 1:10 hours (108%).

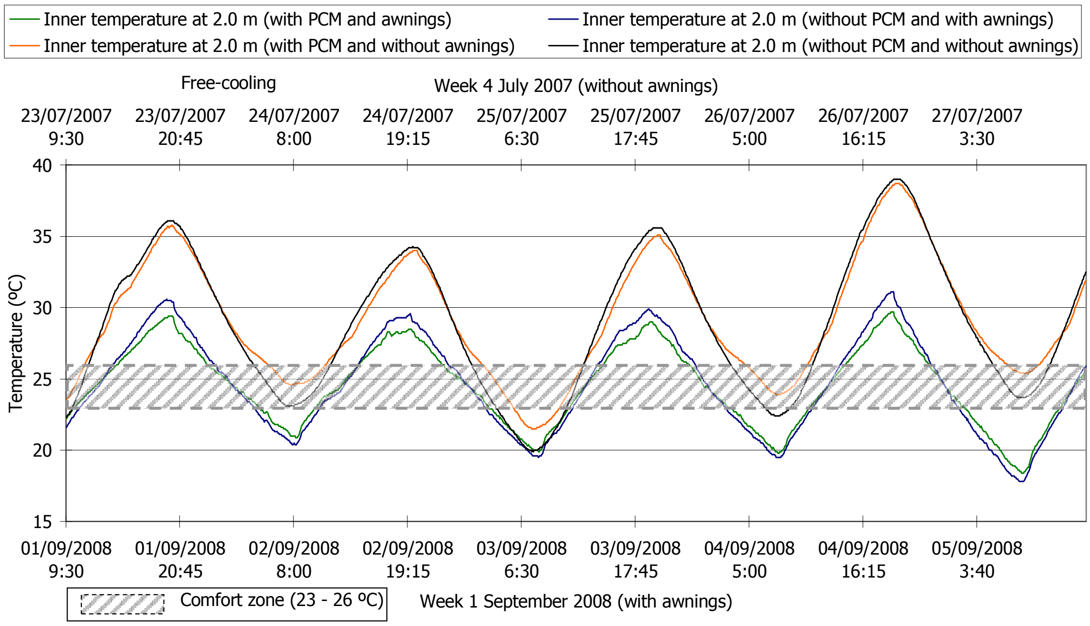


Figure 78. Cubicle inner temperature at 2.0 m height for cubicles with and without awnings during free-cooling experiments.

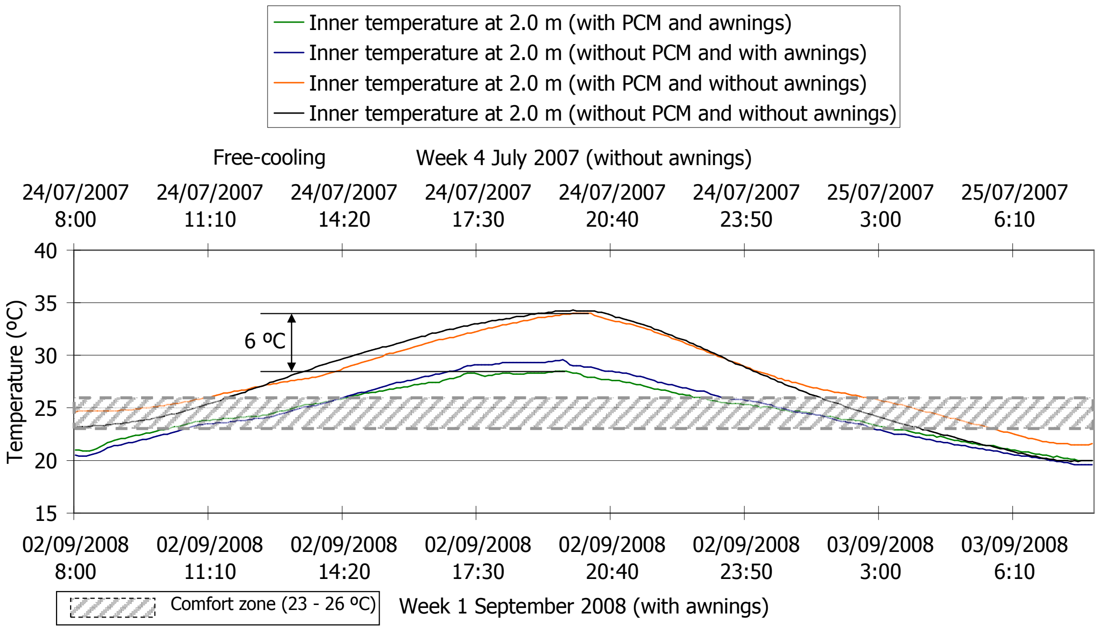


Figure 79. Detail of the cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature differences during free-cooling experiments.

As seen at Figure 78 and Figure 79, in both cases the cubicles have reached comfort conditions at the inside for some hours during the daytime, however, this aspect is to be analyzed from the point of view of the operative comfort temperature as stated at the methodology section, and is explained next.

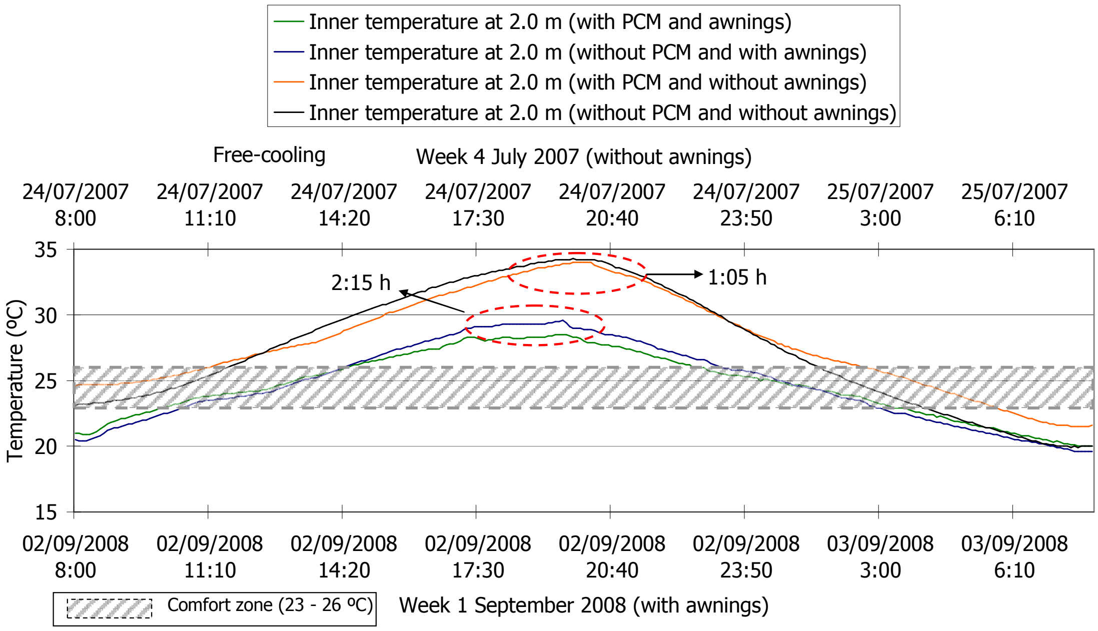


Figure 80. Detail of the cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature delays during free-cooling experiments.

3.4.2.4 Operative comfort temperature (T_0)

The operative comfort temperature has already been defined in section 3.3.4. Figure 81 shows the evolution of this parameter along the considered weeks for the studied cubicle types.

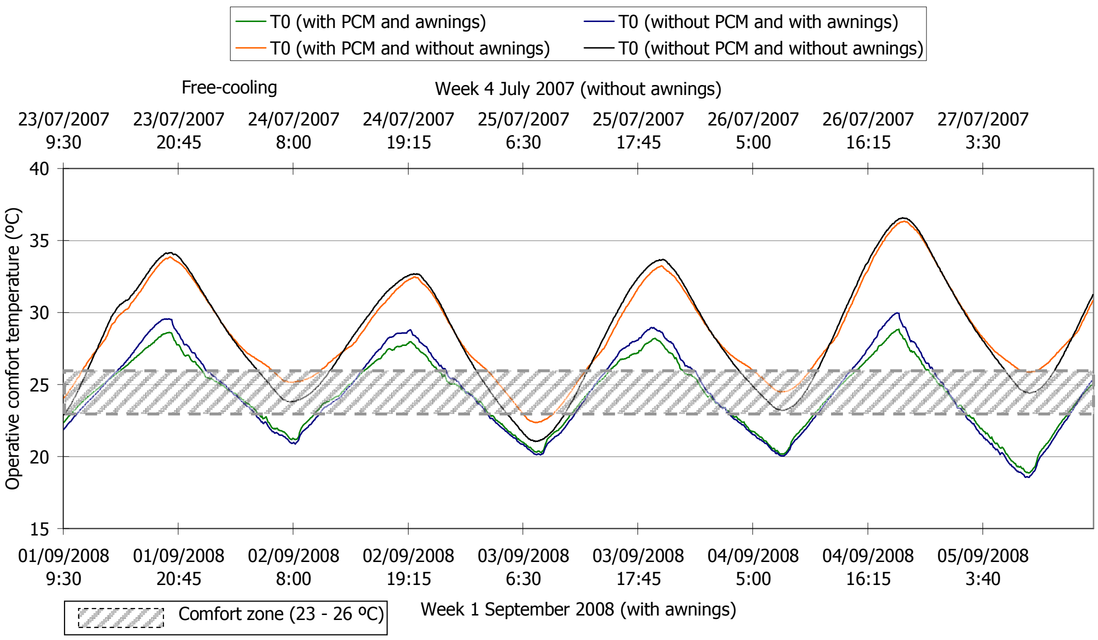


Figure 81. Operative comfort temperature for cubicles with and without awnings during free-cooling experiments.

It is seen at the upper temperature limits that there is a 1 ºC difference in cubicles with awnings, those with PCM with the lowest values; while cubicles with PCM and no awnings exhibit only a 0.2 ºC lower value than those without PCM and no awnings. T_0

peak values in cubicles with awnings and PCM are up to 4 ºC (12%) lower than those of cubicles with PCM and without awnings (Figure 82).

It is observed that T_0 in cubicles with PCM and awnings reach their peak values 2:10 hours later than those with awnings and no PCM, while in cubicles without awnings, those with PCM show a delay of only 45 minutes respect from those with no PCM (Figure 83). The time delay has been increased in 189%.

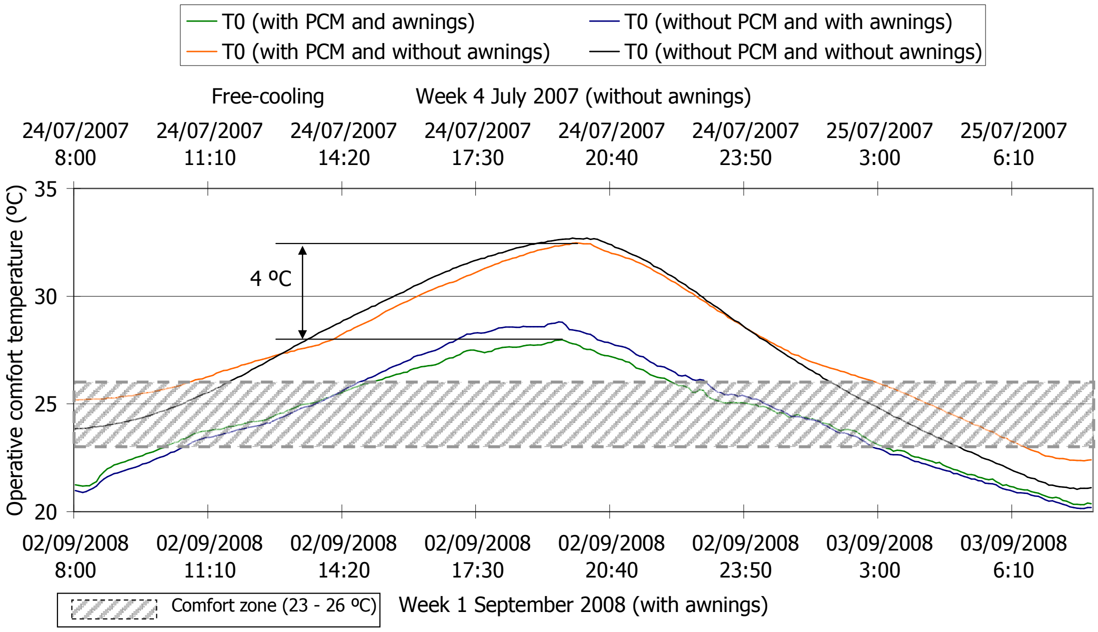


Figure 82. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature differences during free-cooling experiments.

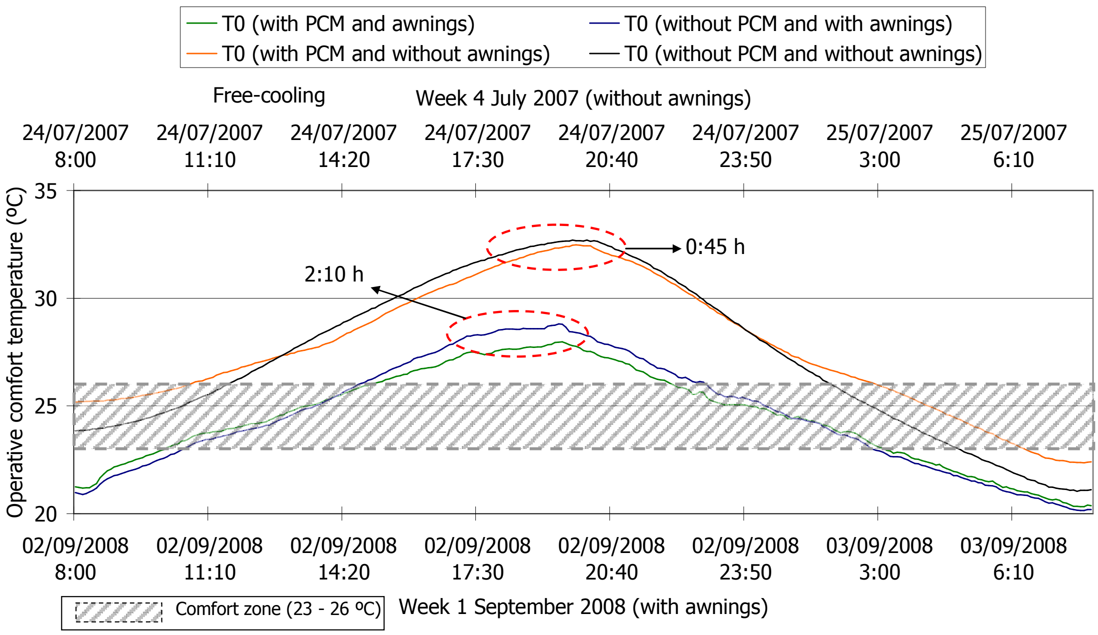


Figure 83. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature delays during free-cooling experiments.

The influence that PCM and awnings exert over the operative comfort temperature is clear, as they narrow the amplitude within this parameter changes and delay its arrival at peak values. These effects were expected since there is again a direct proportionality between the operative comfort temperature and the inner temperature, directly influenced by the wall temperature. The combination of the mentioned effects causes cubicles with awnings to achieve more weekly hours in comfort conditions. This is better appreciated in Figure 84 (elaborated in a similar manner to that of the PCM activation hours percentage), which shows the weekly hours percentage each cubicle type has remained under comfort conditions, based on the T_0 parameter.

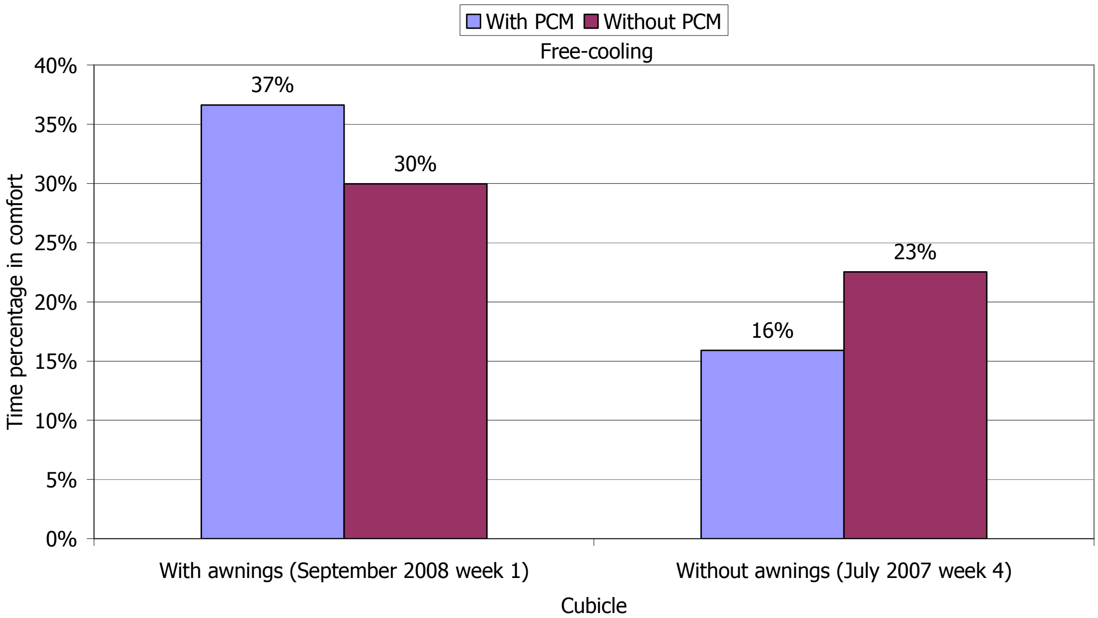


Figure 84. Comparison of the weekly hours percentage under comfort for cubicles with and without awnings during free-cooling experiments.

It may be seen that the combined use of PCM and awnings in the cubicles may increase the time under comfort conditions in 7% regarding cubicles not including PCM. This phenomenon does not take place in cubicles without awnings, where those without PCM exhibit more hours in comfort than those with PCM (again a 7% difference); this may be attributed to the fact that the PCM did not get to complete full phase change cycles in this cubicle type, and as the operative comfort temperature is directly proportional to the wall temperature. Moreover, since PCM acted as an insulator, it could slow down the natural cooling of the cubicle at night so minimum temperatures were not as low as they could be, leading to more hours in discomfort conditions.

3.4.2.5 Conclusions to free-cooling experiments

- Wall inner temperature peak values in cubicles with PCM and awnings are 3 to 4 ºC lower (6%) than those of cubicles without awnings.
- Awnings make it easier for PCM to complete full phase change cycles despite the influence of high ambient temperatures, leading to a 4% more hours of PCM activation per week.
- The insulation effect by PCM as it melts (enhanced by the use of awnings) increases in 50 minutes (36%) the time it takes for the wall temperature to reach its peak values when compared to that of the wall temperatures in cubicles without PCM and with awnings.

- Wall heat flux in cubicles with awnings presents a more steady variation along the week thanks to a higher thermal inertia by means of PCM.
- Wall heat flux peak values in cubicles with awnings are 17.5 W/m^2 (146%) higher than that in cubicles without awnings, and the flux peak values in cubicles with awnings are attained 8:12 hours (62%) before those of cubicles without awnings.
- As inner temperatures and the operative comfort temperature are both directly proportional to wall temperatures, the effects of storing energy and enhancing the thermal inertia by the PCM (improved by the awnings when it corresponds) are also observed with these variables, and translate into a peak value reduction and a longer time to reach those values (a time delay).
- The temperature peak values reduction for the previous variables is of 4-6 ºC (~18%), 6 ºC (18%), and 4 ºC (12%) for the inner temperatures at 1.2 m, 2.0 m, and the operative comfort temperature respectively for cubicles with awnings respect of those without awnings.
- Likewise, the time delay for the same variables was increased in 35 minutes (41%), 1:10 hours (108%), and 1:25 hours (189%), respectively.
- The operative comfort temperature presents a narrower range of variation thanks to the use of awnings.
- The use of awnings has increased in 7% the weekly hours during which cubicles with PCM have remained under comfort conditions.

3.4.3 Open windows

3.4.3.1 Climatic data

A graphical comparison between the outside temperatures and solar radiation respectively is shown in Figure 85 and Figure 86 for the correspondent weeks.

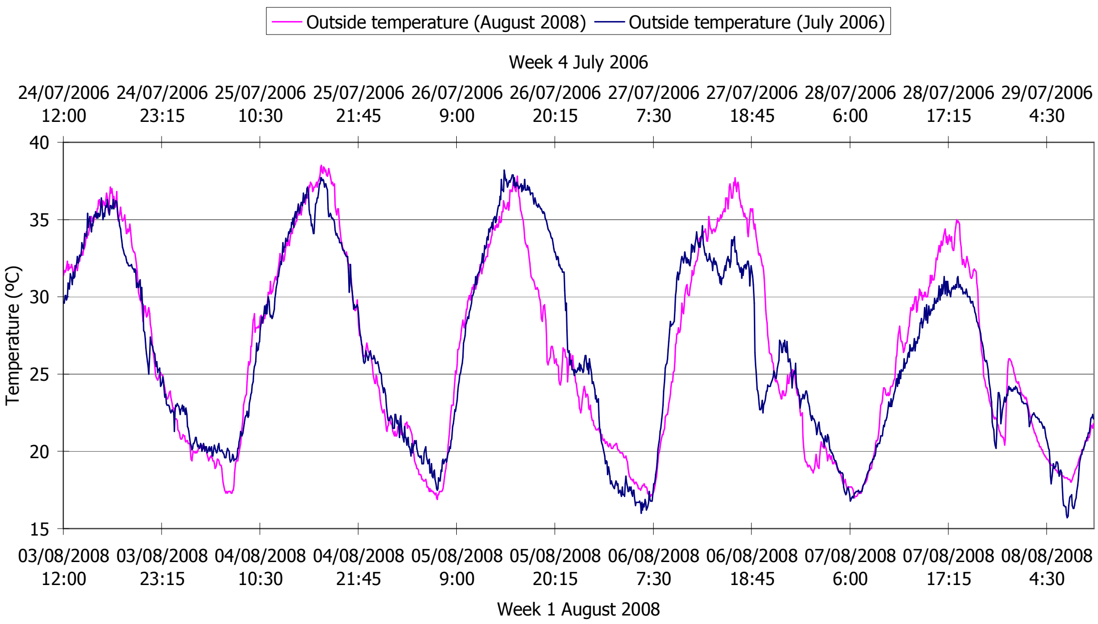


Figure 85. Comparison of the selected weeks outside temperature (open windows experiments).

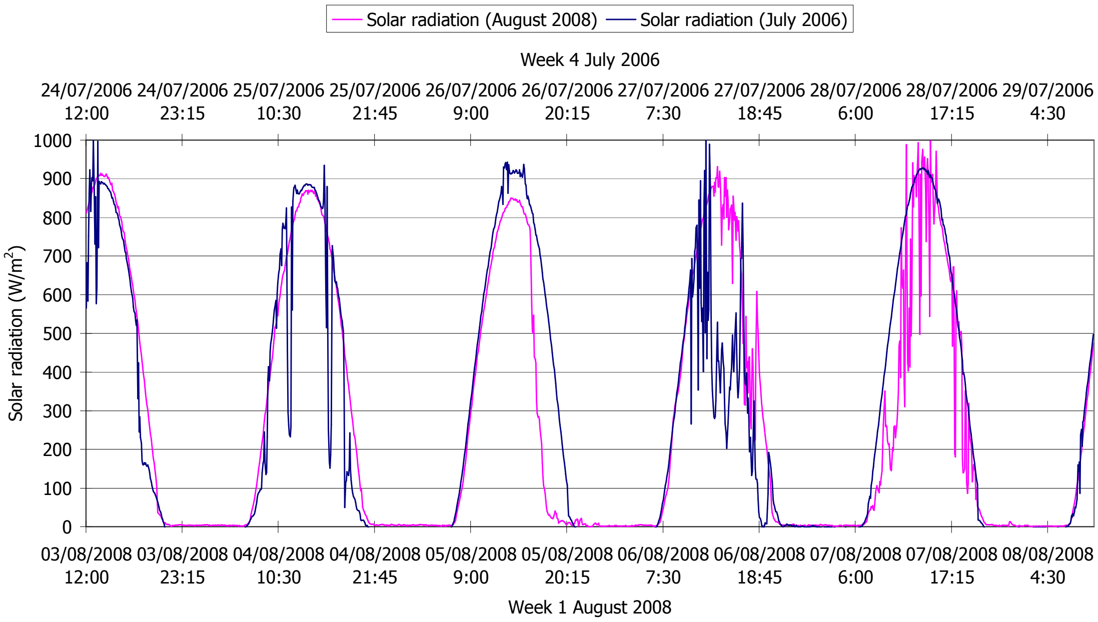


Figure 86. Comparison of the selected weeks solar radiation (open windows experiments).

3.4.3.2 Wall temperature and heat flux

Figure 87 shows a comparison of the respective temperatures for cubicles with and without awnings respectively.

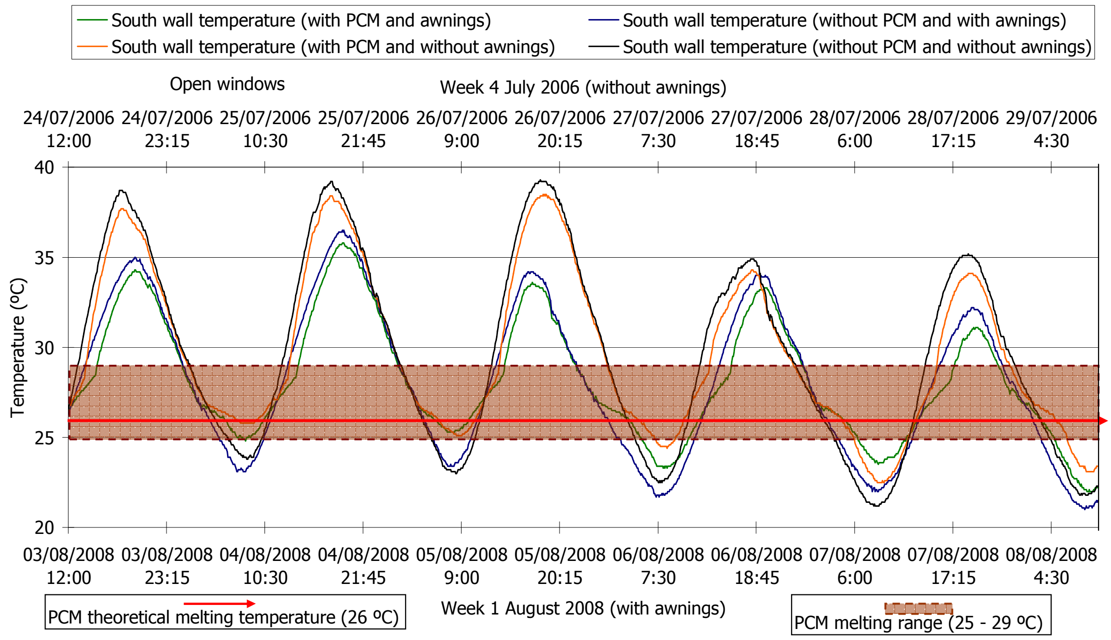


Figure 87. South wall temperature for cubicles with and without awnings during open windows experiments.

It is first appreciated that the wall temperature peaks were up to 3 ºC (7%) lower in cubicles with awnings than in those without them (Figure 88), this effect had also been observed and explained with the free-cooling experiments (refer to section 3.4.2 for further details). Regarding the PCM activation, it is observed that in both cubicle types the material did not get to solidify completely on all days, probably due to high outdoors temperatures and as the windows were now open. This means that despite the PCM was active, it mostly did not release all the stored heat.

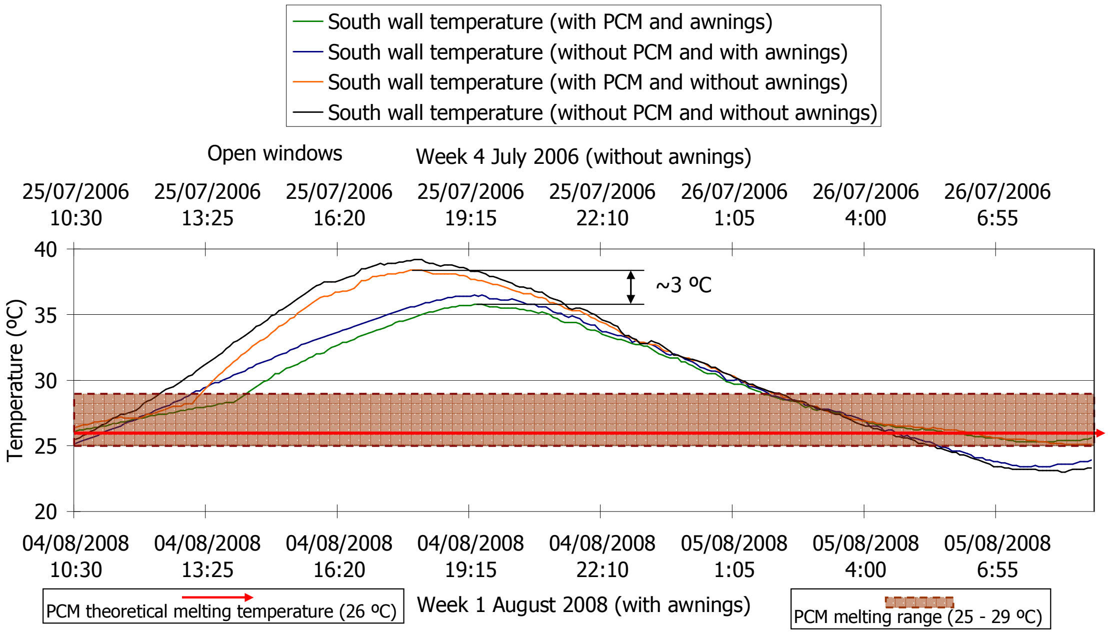


Figure 88. Detail of the south wall temperature for cubicles with and without awnings showing temperature differences during open windows experiments.

It is observed that walls containing PCM in cubicles with awnings reached their peak value around 1:30 h later than those not containing PCM; while PCM in cubicles without awnings took about 1:45 more hours to reach their peak value, that is, this time delay decreased in 15 minutes (-14%) (Figure 89). Regarding the weekly time percentage the PCM was active in the cubicle types (Figure 90), it is appreciated that in cubicles with awnings PCM was active for 10% more hours during the week, and thus for a bit more than half the considered period of time.

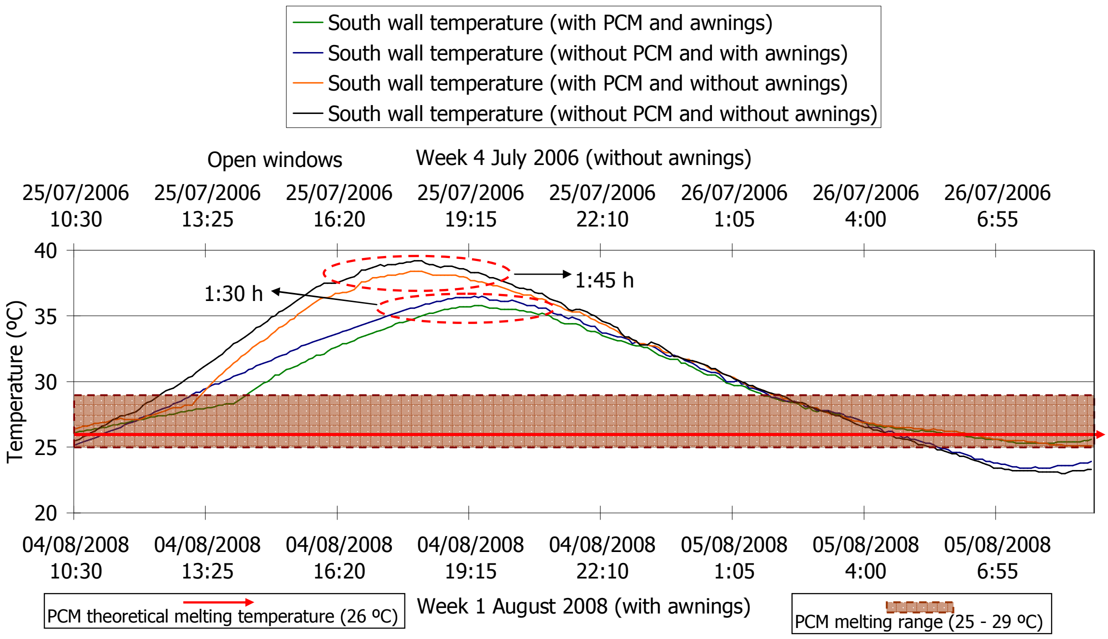


Figure 89. Detail of the south wall temperature for cubicles with and without awnings showing temperature delays during open windows experiments.

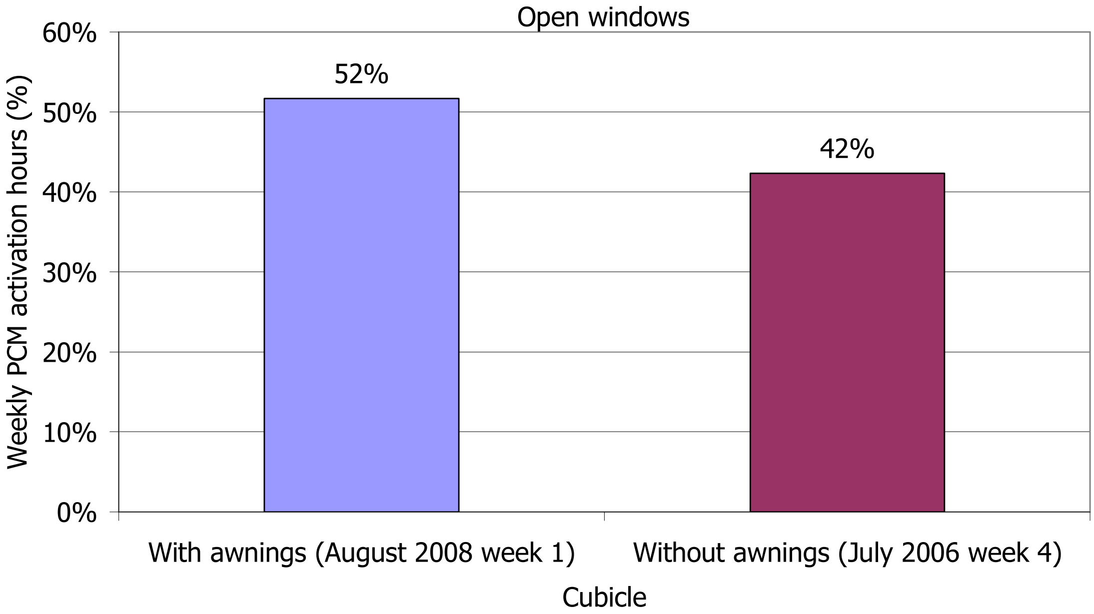


Figure 90. Comparison of the PCM active hours percentage for cubicles with and without awnings during open windows experiments.

The fact that windows remained open the whole time means that climatic conditions influenced more strongly the studied parameters. In this case, the PCM-awnings effect over the thermal inertia could not be the same as with the free-cooling experiments (where windows were open only at night). As outside temperatures were relatively high, the thermal inertia could not be improved (despite the presence of awnings); however, the experienced 14% decrease in the time delay would have probably been larger had awnings not been installed.

Figure 91 shows the heat flux behaviour through the south wall during the considered period. It is seen that the flux in cubicles without awnings, both with and without PCM, exhibited greater values (3 W/m^2) than those in cubicles with awnings (Figure 92), that is, fluxes in cubicles with awnings were a 10% lower; however, fluxes in both cubicle types presented a more similar behaviour to that of the other. On the other hand, it is observed that the flux in cubicles with awnings remained more stable when the wall temperature reached its peak values.

It has also been noticed that fluxes in both cubicles followed the same pattern when the wall temperature lied within the PCM melting range, however the flux in cubicles without awnings did increase much faster during this situation. It is also noticed that, while flux peak values in cubicles without awnings were attained at the same time, there was a delay of 6:40 hours in cubicles with awnings (Figure 93). The effect of the outside climatic conditions over the wall flux and the thermal inertia is once more evidenced in cubicles without awnings, while thanks to the awnings in the respective cubicles, a time delay was detected. These effects have been explained more in detail when analyzing the free-cooling experiments.

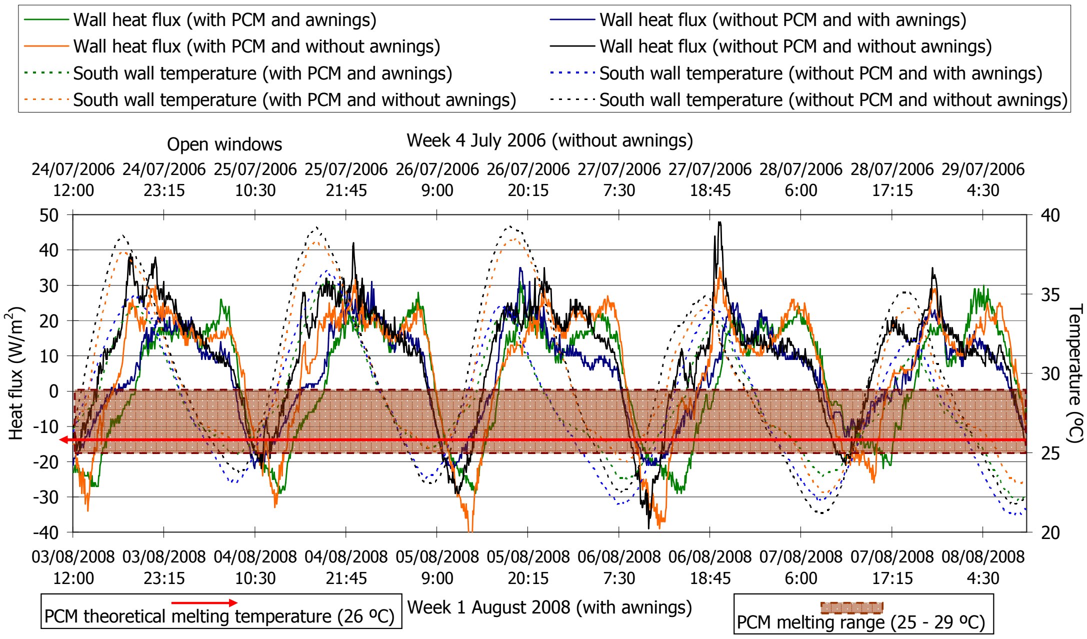


Figure 91. Measured heat flux through the south wall in cubicles with and without awnings during open windows experiments.

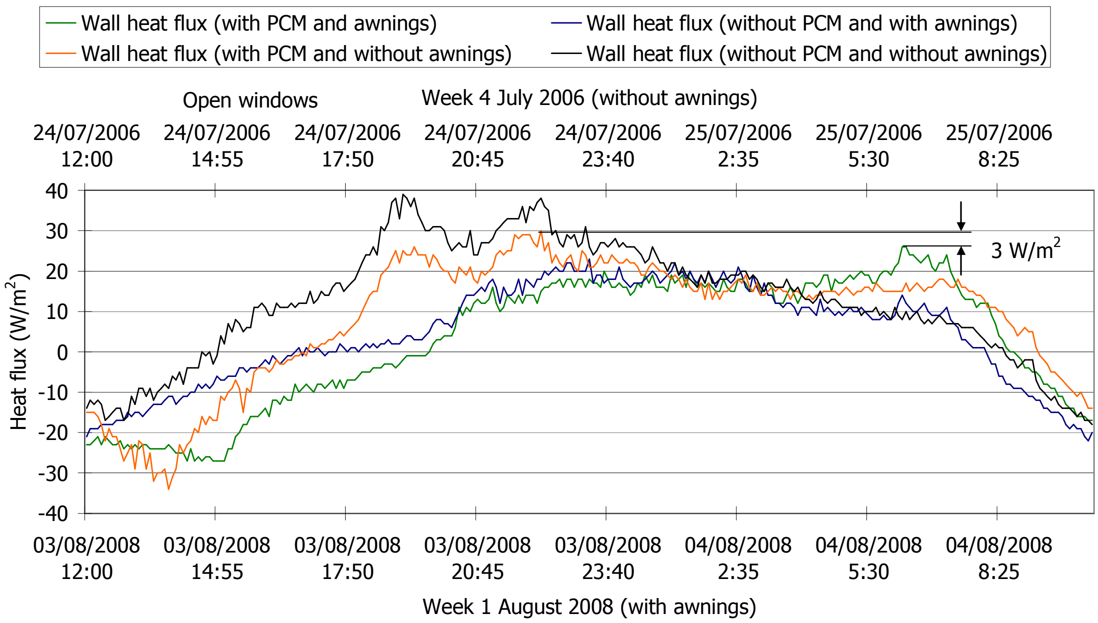


Figure 92. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux differences during open windows experiments.

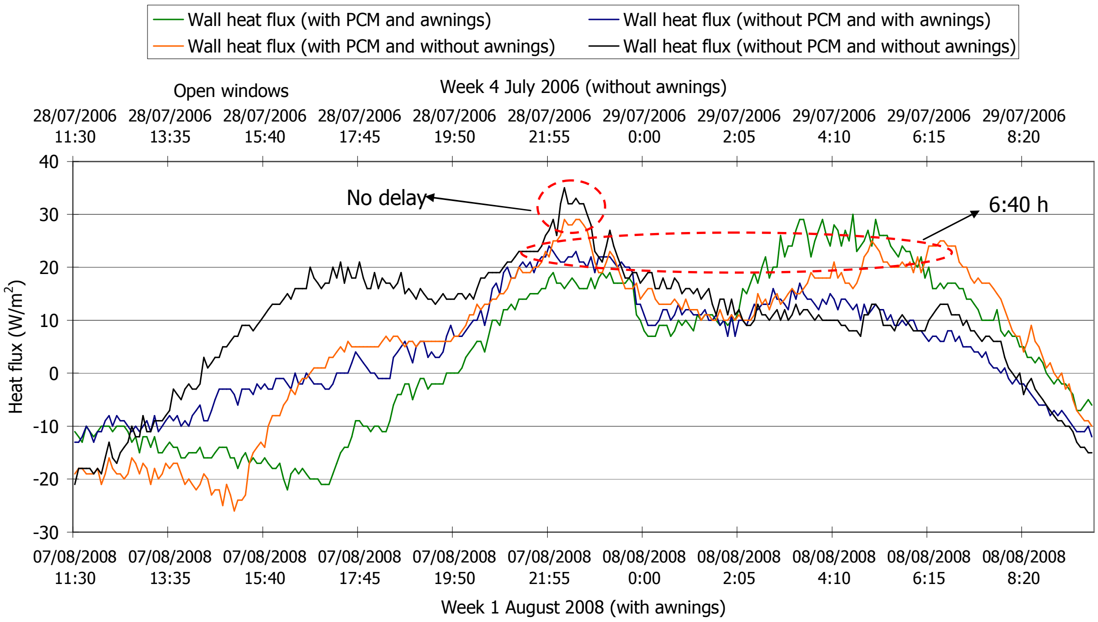


Figure 93. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux delays during open windows experiments.

3.4.3.3 Cubicle inner temperature

As with the previous experiment, this parameter is analyzed at 1.2 and 2.0 m heights. First, the 1.2 m values are reviewed (Figure 94).

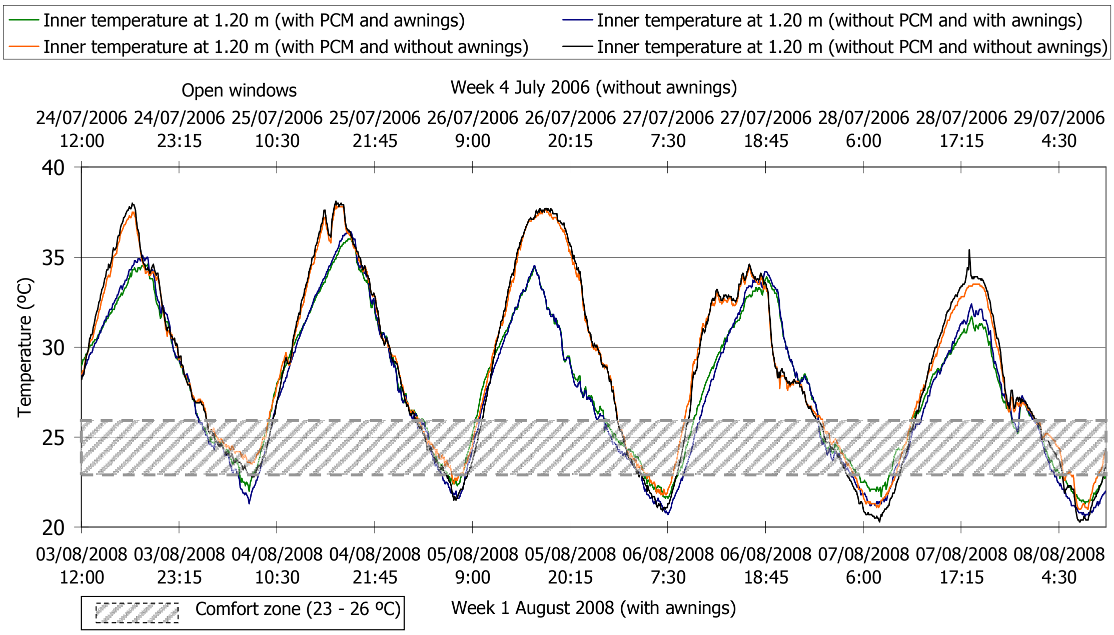


Figure 94. Cubicle inner temperature at 1.2 m height for cubicles with and without awnings during open windows experiments.

It is seen that peak values were even 6 ºC (16%) lower in cubicles with awnings (Figure 95). It is also observed that in cubicles with PCM and awnings, the inner temperature at 1.2 m reached its peak values 50 minutes later or less than in cubicles without PCM; in cubicles without awnings, a similar phenomenon occured in those with PCM (around 40 minutes or less), though on some days no appreciable delay could be observed for both cases, from which it is seen that as windows were open, awnings almost did not exert any effect over inner temperatures as only the influence of PCM and the outdoors temperature is appreciated (Figure 96). The mentioned time delay was increased in 25% at best. Similar effects were observed when analyzing the cubicle inner temperatures during free-cooling experiments, and they were explained more in detail when discussing those experiments.

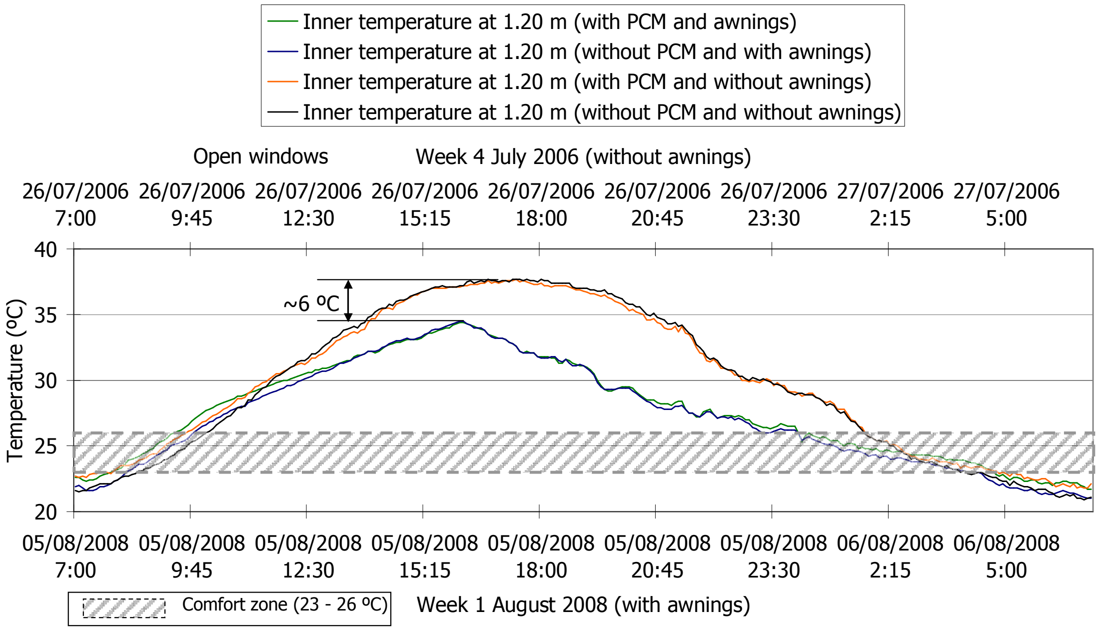


Figure 95. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature differences during open windows experiments.

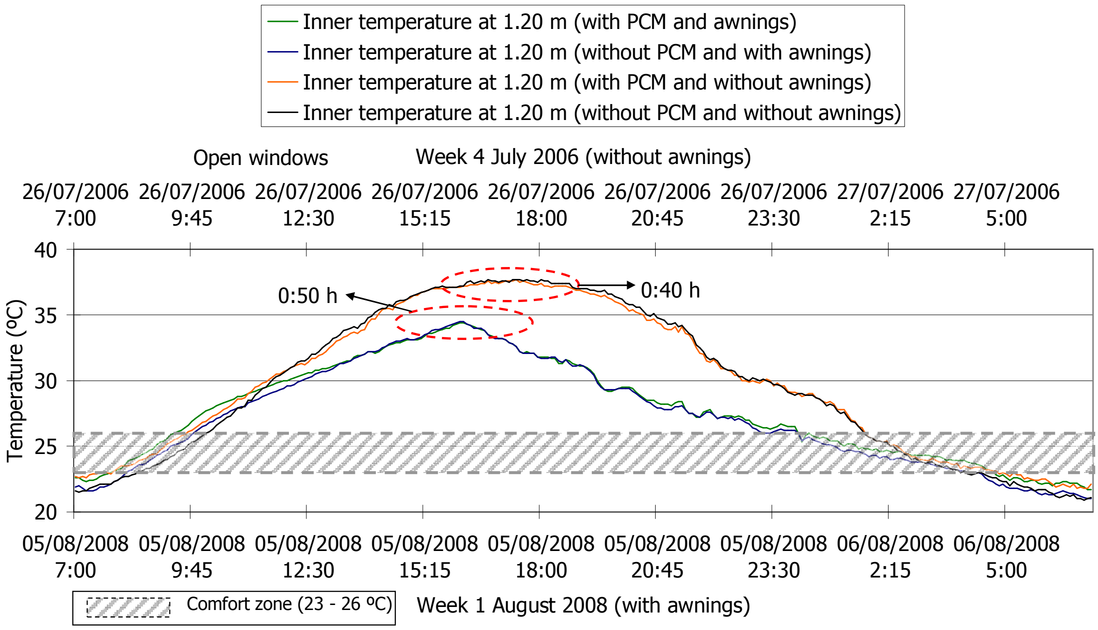


Figure 96. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature delays during open windows experiments.

Inner temperatures measured at 2.0 m in both cubicle types are shown in Figure 97. In this case, the behaviour of this parameter was quite similar to that measured at 1.2 m; so therefore, same commentaries may be applied on this case.

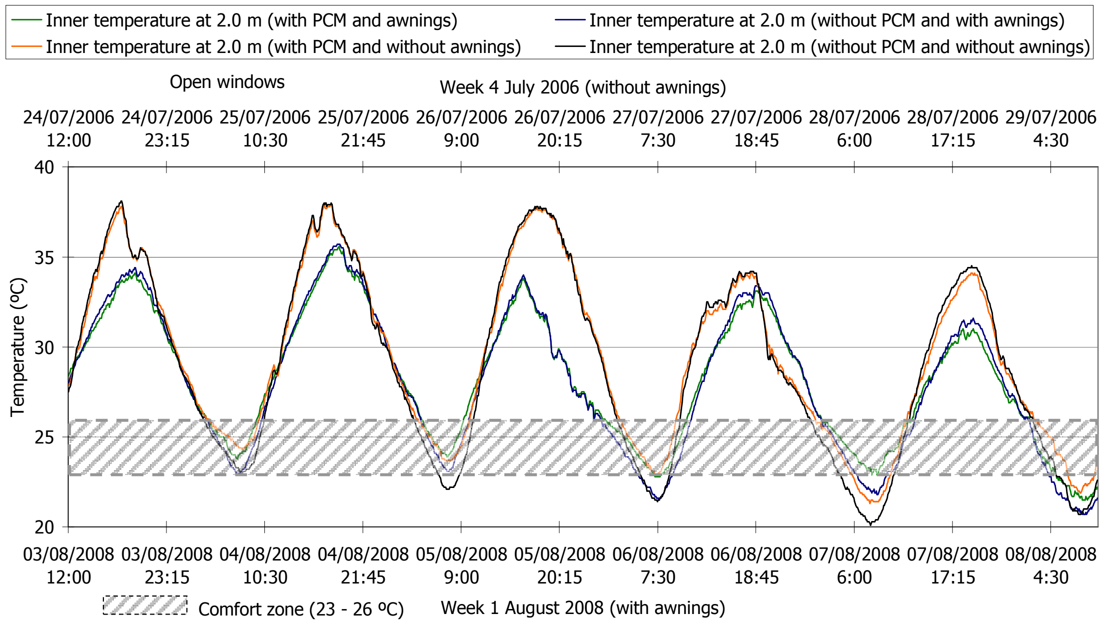


Figure 97. Cubicle inner temperature at 2.0 m height for cubicles with and without awnings during open windows experiments.

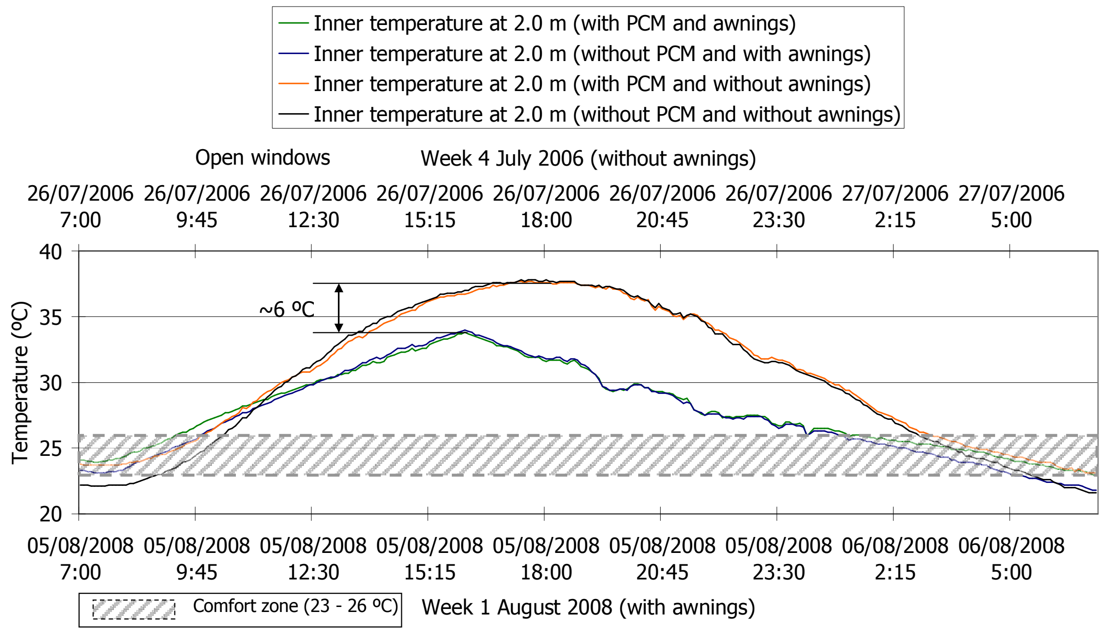


Figure 98. Detail of the Cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature differences during open windows experiments.

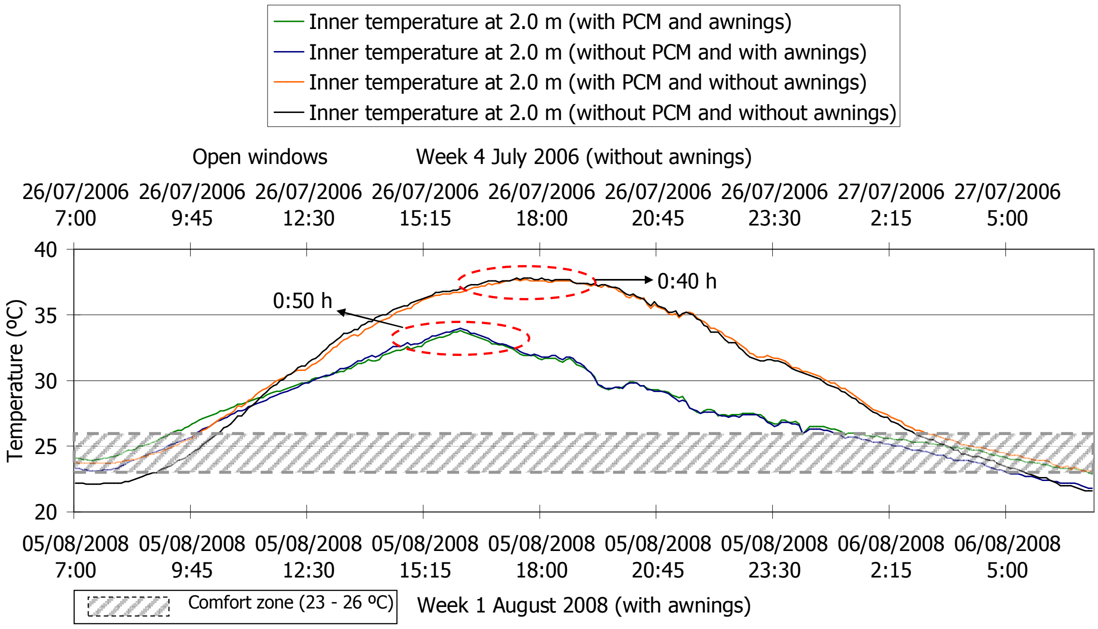


Figure 99. Detail of the Cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature delays during open windows experiments.

3.4.3.4 Operative comfort temperature (T_0)

The evolution of the T_0 parameter in both cubicle types is presented in Figure 100. It is seen that peak values were 4 ºC (11%) lower in cubicles with awnings than in those without awnings (Figure 101). T_0 peak values in cubicles with awnings and PCM were reached about 1 hour later than in cubicles without PCM, while in cubicles without awnings this delay was of 40 minutes (Figure 102), that is, the operative comfort temperature reached its peak values 20 minutes later (a 50% increase) in cubicles with awnings.

It should be noticed that these peak values lied outside the considered comfort zone at the inside of the cubicles, as they were way up higher than the upper comfort limit. The effect of the use of awnings though, is still beneficial as it has narrowed the amplitude range within the T_0 parameter varies (by reducing the peaks), thus increasing the amount of time during which comfort conditions were attained inside the cubicles. This may be better appreciated in comparing the percentage of hours each cubicle has remained under comfort during a week (Figure 103). As it may be observed, awnings increased the time under comfort conditions in both cubicle types, both with and without PCM. A 4% more hours under comfort was achieved in cubicles with PCM, while a 1% in cubicles without PCM.

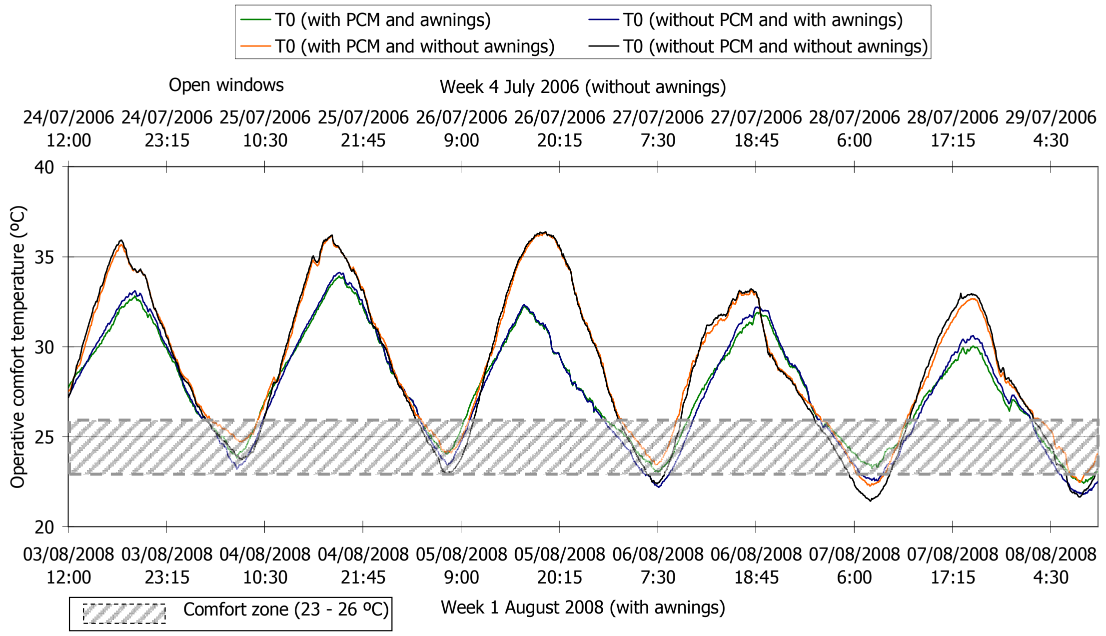


Figure 100. Operative comfort temperature for cubicles with and without awnings during open windows experiments.

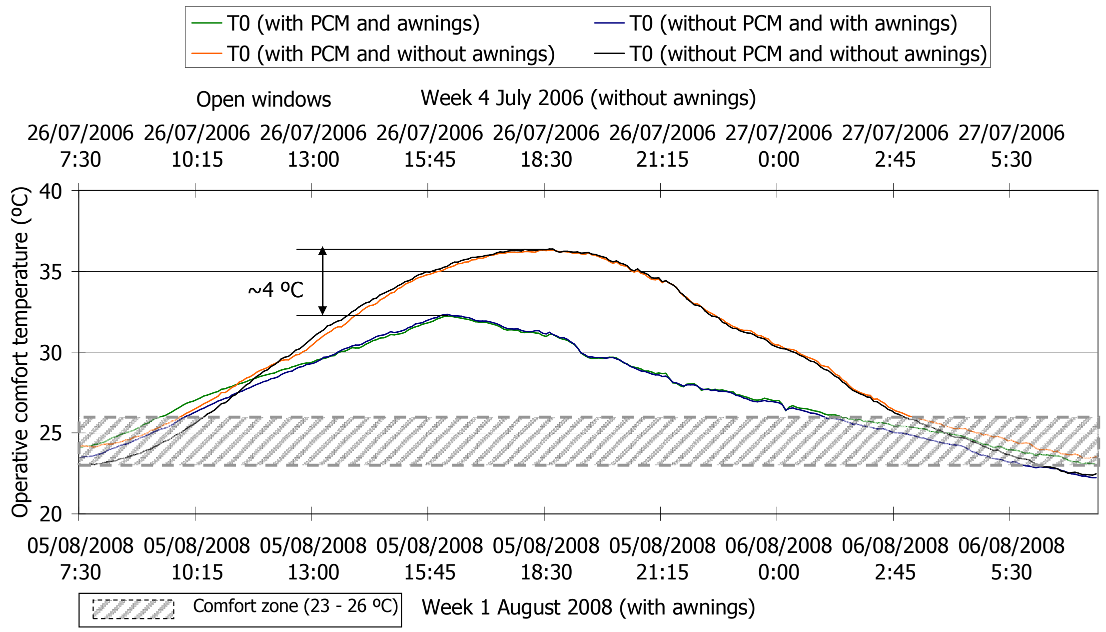


Figure 101. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature differences during open windows experiments.

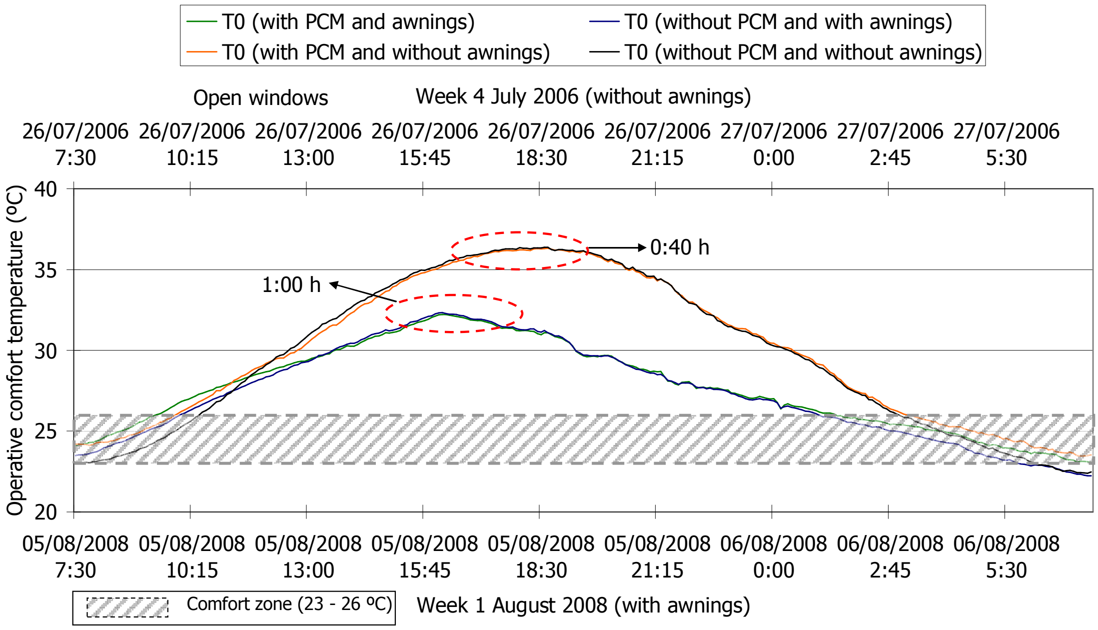


Figure 102. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature delays during open windows experiments.

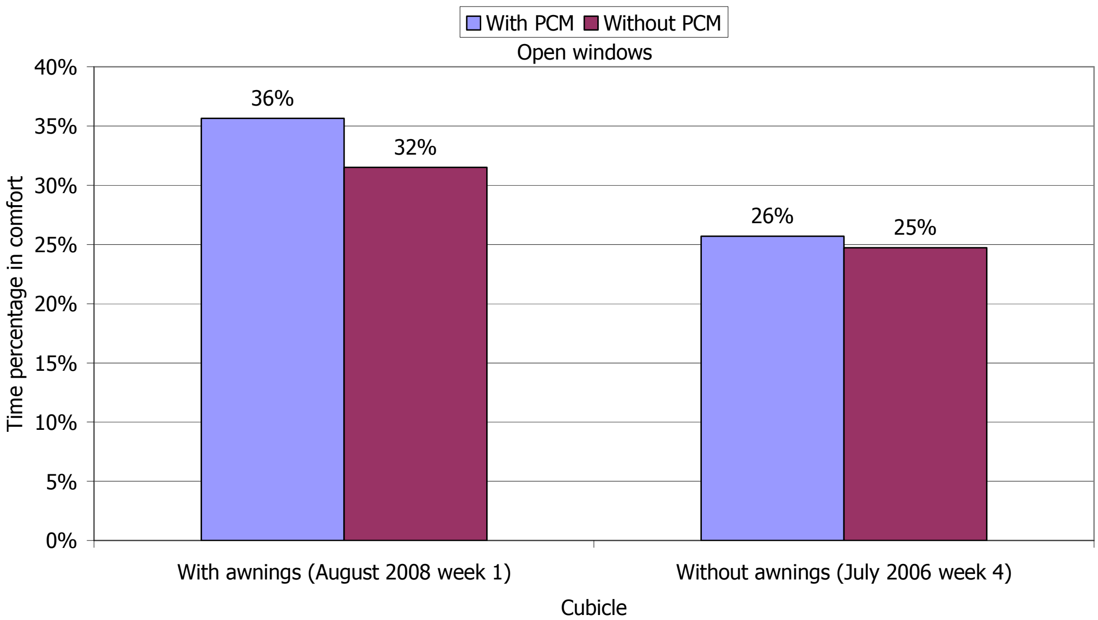


Figure 103. Comparison of the weekly hours percentage under comfort for cubicles with and without awnings during open windows experiments.

3.4.3.5 Conclusions to open windows experiments

In this case conclusions are mostly common to all three parameters (except for the wall heat flux), and are summarized next:

- The use of PCM-awnings lowered the temperature peaks in 3 ºC (7%), 6 ºC (16%) and 4 ºC (11%) for the wall temperature, cubicle inner temperature and operative comfort temperature respectively.

- As outdoors temperatures were relatively high, the PCM did not get to complete full phase change cycles since it was not able to solidify completely (both in cubicles with and without awnings), thus not releasing all the heat it was expected to.
- Awnings have increased the PCM active hours in 10% respect the one in cubicles without awnings.
- The operative comfort temperature and cubicle inner temperatures in cubicles with awnings showed a time delay increase of 20 minutes (50%) and 10 minutes (25%) in reaching their peak values, respect of the same parameters measured in cubicles without awnings, as a result of the thermal inertia enhancement. The wall temperature however, experienced a 15-minute decrease (-14%) because of the influence of the high outside temperatures.
- The use of awnings allowed increasing the weekly hours under comfort in 4% in cubicles with PCM and in 1% in cubicles without PCM.
- Heat flux in cubicles with awnings presented lower values than those in cubicles without awnings (3 W/m^2, a 10%), and tended to remain more stable while peak values were attained.
- The fluxes variation in both cubicle types was similar while the wall temperature lied within the PCM melting range, but the flux in cubicles without awnings showed a bigger increase tendency in this case.
- The flux in cubicles with PCM and awnings reached its peak value 6:40 hours later than that of cubicles without PCM and with awnings; no time delay was detected in cubicles without awnings.

3.4.4 Closed windows

3.4.4.1 Climatic data

The comparison of climatic data for the considered weeks is shown in Figure 104 and Figure 105.

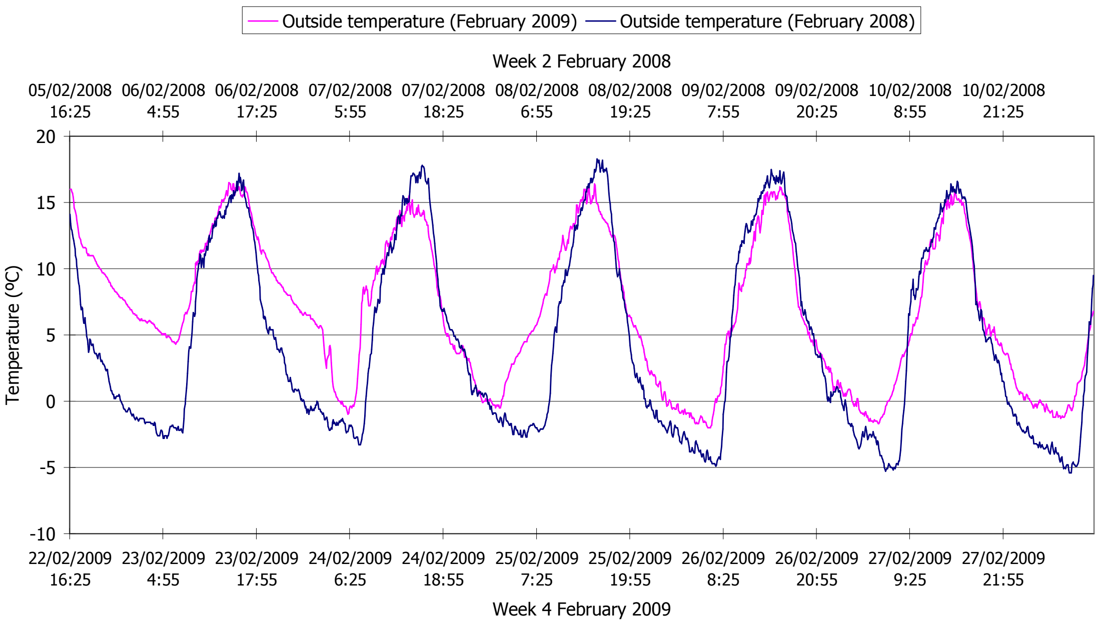


Figure 104. Comparison of the selected weeks outside temperature (closed windows experiments).

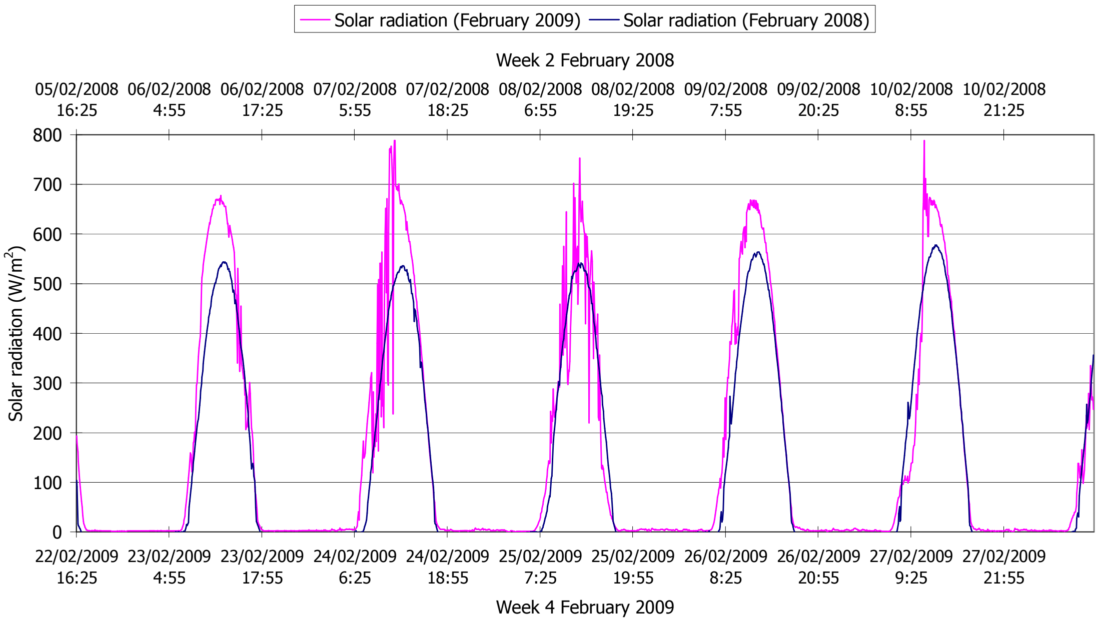


Figure 105. Comparison of the selected weeks solar radiation (closed windows experiments).

3.4.4.2 Wall temperature and heat flux

Figure 106 shows the respective comparison between the wall temperatures in both cubicle types. Unfortunately, much likely because of the low outdoors temperatures, PCM did not activate during the considered weeks as they both correspond to the winter season of their respective years. Since there is no PCM work for the considered experiment, no analysis about the PCM effect over the cubicles and the operative comfort temperature is able to be done with these data sets. Remaining aspects are still analyzed however.

It is observed that wall peak temperatures in cubicles with awnings were 1.1 ºC lower (5.6%) than those of cubicles without awnings (Figure 107). As PCM did not store energy and/or activate, and the windows were closed (climatic conditions did not exert a much large influence), this effect is attributed to the awnings, which reduced the solar radiation that reached the walls.

It is also seen that temperatures in cubicles with awnings and PCM arrived at their peak values 2:25 hours later than those of cubicles with awnings and no PCM, while this delay was of 2:10 hours in cubicles without awnings for each cubicle type respectively (Figure 108), that is, there was a 12% increase. This small improvement in the cubicle thermal inertia is again due to the shadows produced by the awnings, but also to the thermal inertia of PCM, whose effect is noticed when temperatures approached the melting range.

Regarding the wall heat flux, Figure 109 shows the comparison of fluxes through the south wall. It is appreciated that the heat flux presented a daily behaviour pattern much similar to that of the wall temperature, that is, very uniform throughout the day with maximum and minimum peaks appearing at the same time as those of wall temperature. However, because of the awnings, the flux in cubicles with awnings and PCM was about 10 W/m^2 (26%) lower than that of cubicles with PCM and no awnings (Figure 110). On the other hand, it is observed that the flux in cubicles without awnings increased much quicker than that of cubicles with awnings. A delay in reaching peak values is also observed in fluxes of both cubicle types, 1:50 hours in cubicles with awnings, and 1:25 hours in cubicles without awnings. Therefore, there was a 25-minute increase (29%) in this delay in cubicles with awnings (Figure 111).

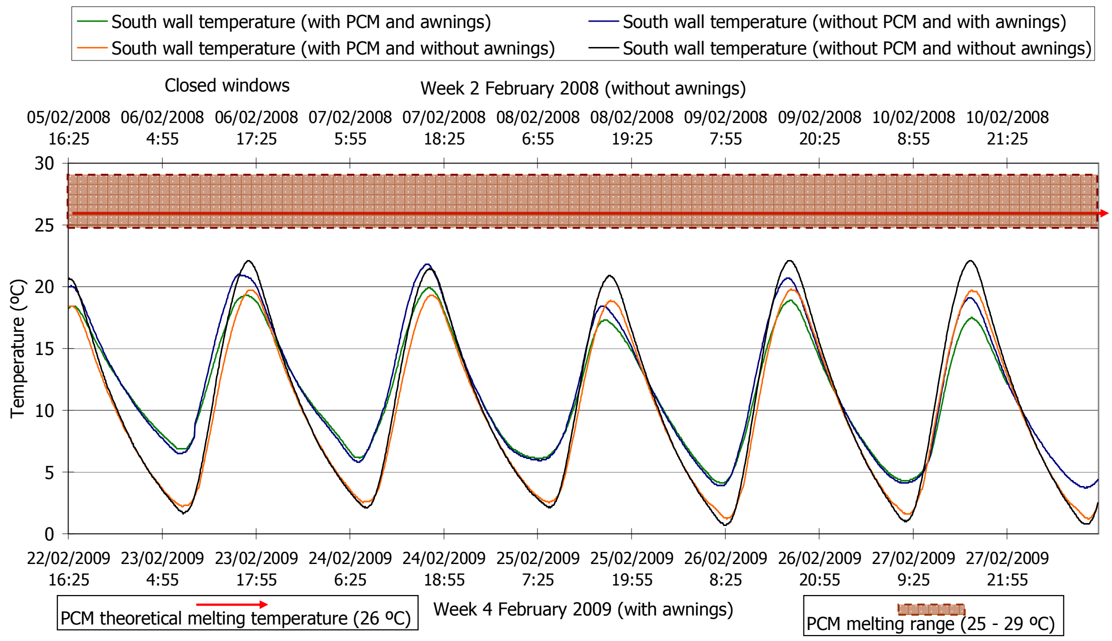


Figure 106. South wall temperature for cubicles with and without awnings during closed windows experiments.

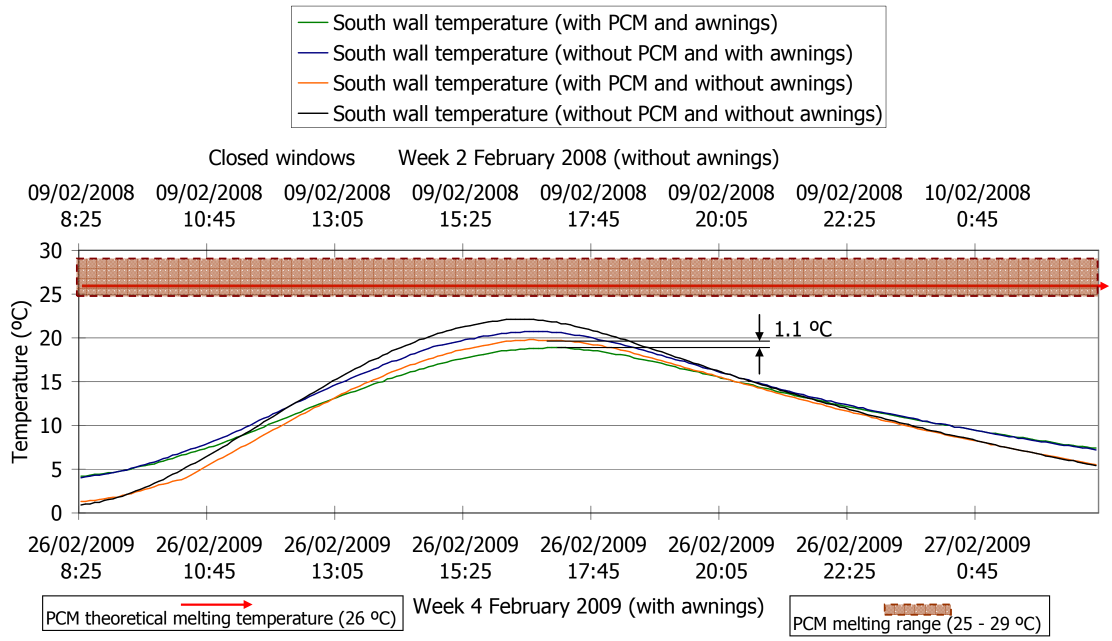


Figure 107. Detail of the south wall temperature for cubicles with and without awnings showing temperature differences during closed windows experiments.

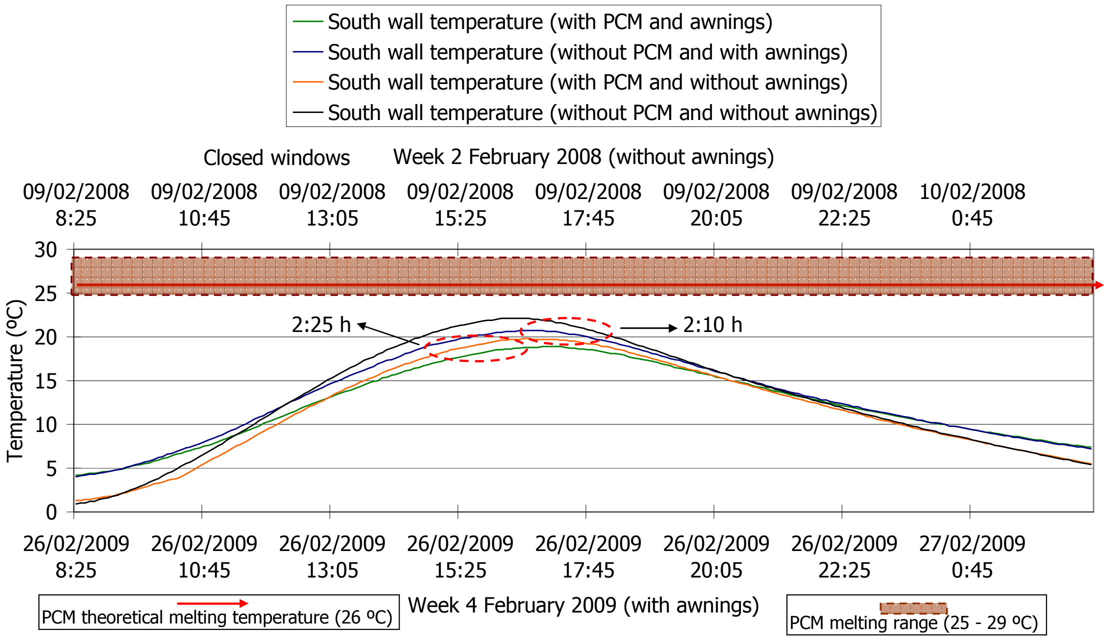


Figure 108. Detail of the south wall temperature for cubicles with and without awnings showing temperature delays during closed windows experiments.

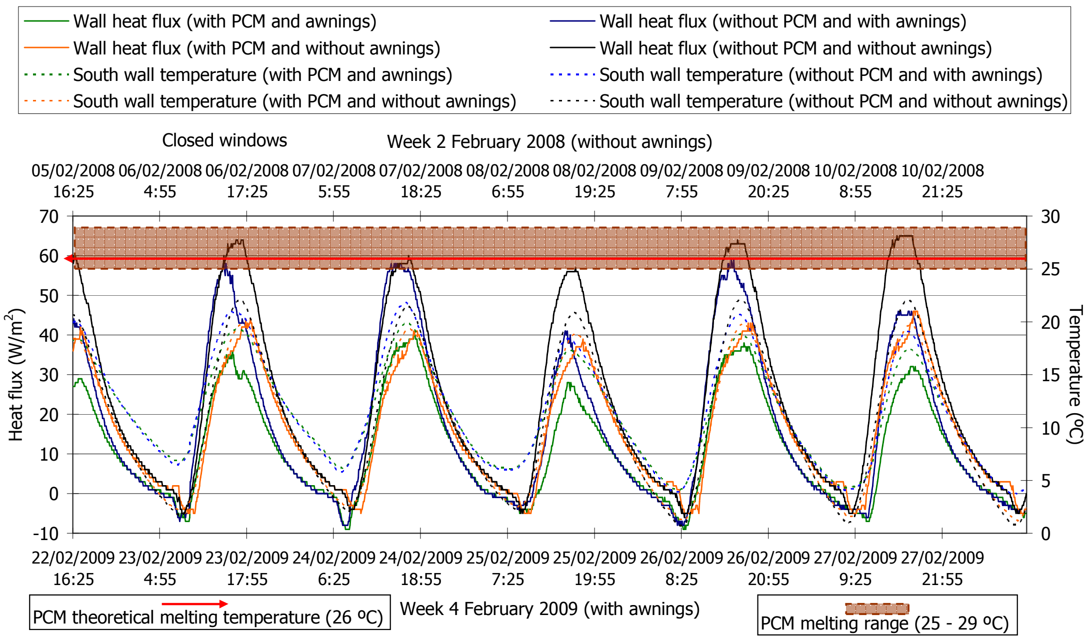


Figure 109. Measured heat flux through the south wall in cubicles with and without awnings during closed windows experiments.

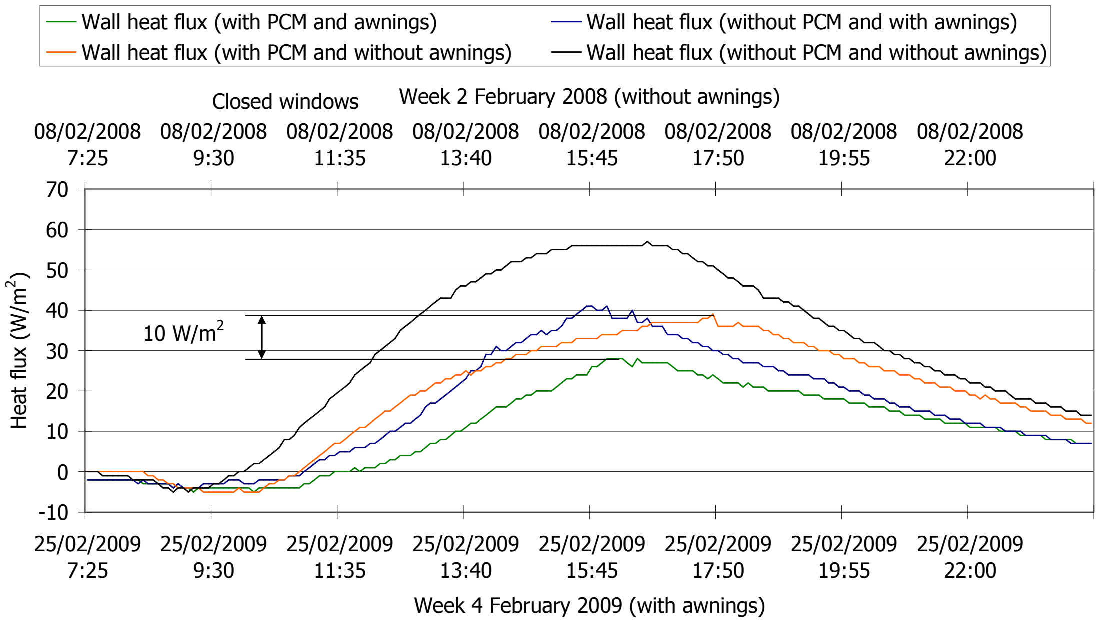


Figure 110. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing temperature differences during closed windows experiments.

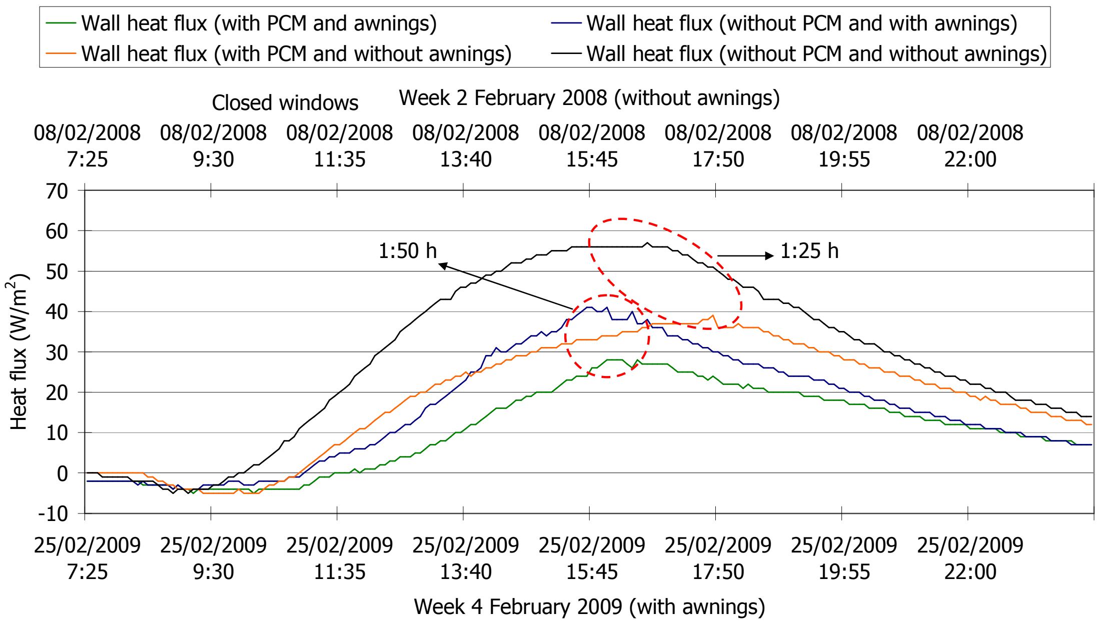


Figure 111. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux delays during closed windows experiments.

3.4.4.3 Cubicle inner temperature

The cubicles inner temperature at 1.2 and 2.0 m are shown in Figure 112 and Figure 115 respectively. As seen, both parameters behaved similarly to one another and values were almost the same, as PCM was not active; however, there were small effects over inner temperatures regarding the difference between peak values and the time it took to the parameters to reach them.

It is observed that temperatures at 1.2 m in cubicles with awnings were 1 ºC (7%) lower than those in cubicles without awnings (Figure 113), and that peak values in cubicles with PCM and awnings were attained 1:30 hours later than in those without PCM, while this delay was of 1:10 hours respectively in cubicles without awnings, that is, a 20-minute delay increase (29%) was produced by the use of awnings (Figure 114).

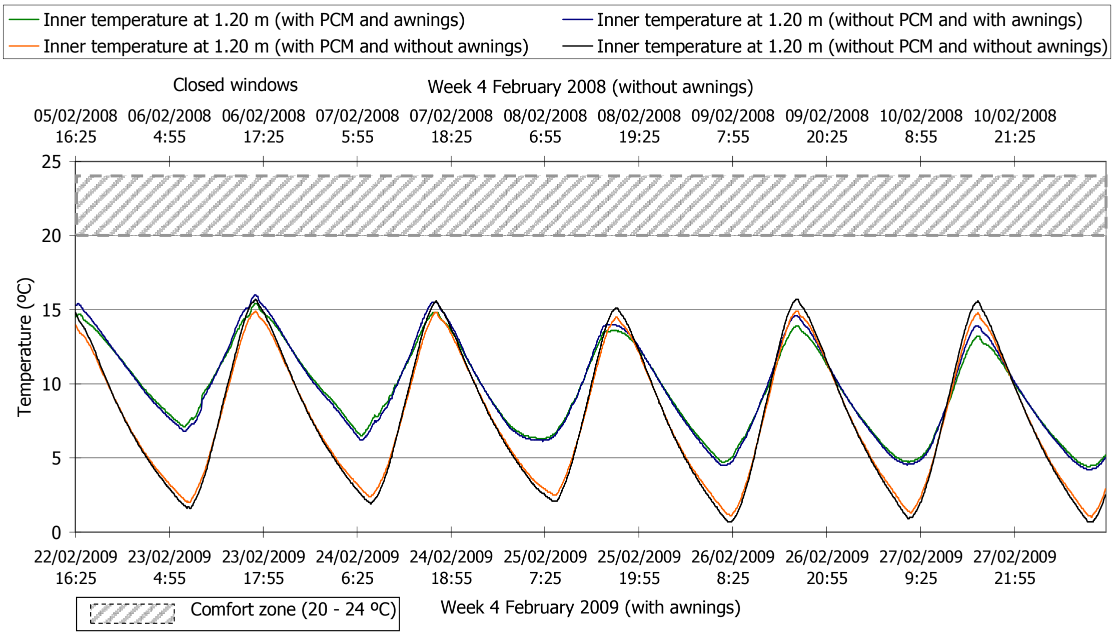


Figure 112. Cubicle inner temperature at 1.2 m height for cubicles with and without awnings during closed windows experiments.

Regarding temperatures at 2.0 m, those in cubicles with awnings were 1.3 ºC (9%) lower than those in cubicles without awnings (Figure 116), and peak values in cubicles with PCM and awnings were reached 1:05 hours later than in those without PCM, an amount of time which is also observed in cubicles without awnings, that is, no time delay in reaching peak values was generated in this case (Figure 117).

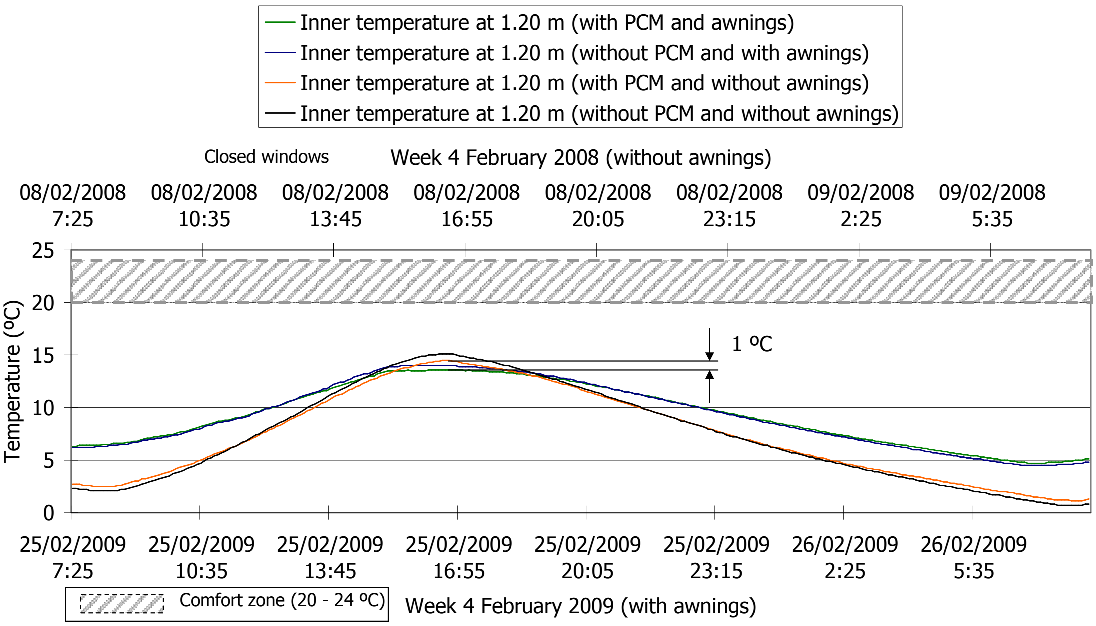


Figure 113. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature differences during closed windows experiments.

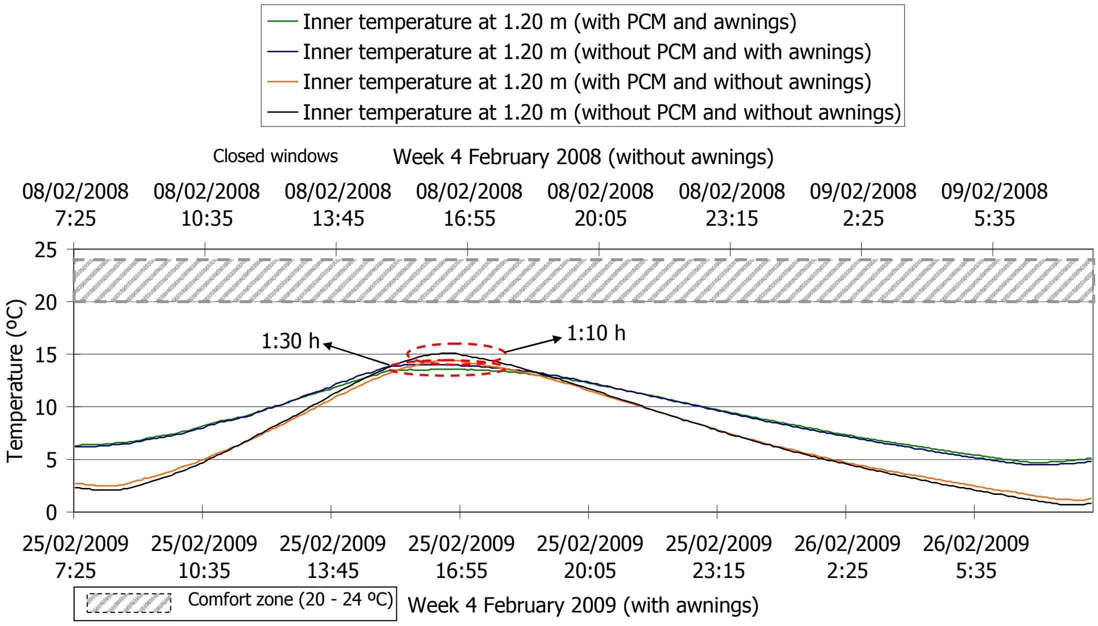


Figure 114. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature delays during closed windows experiments.

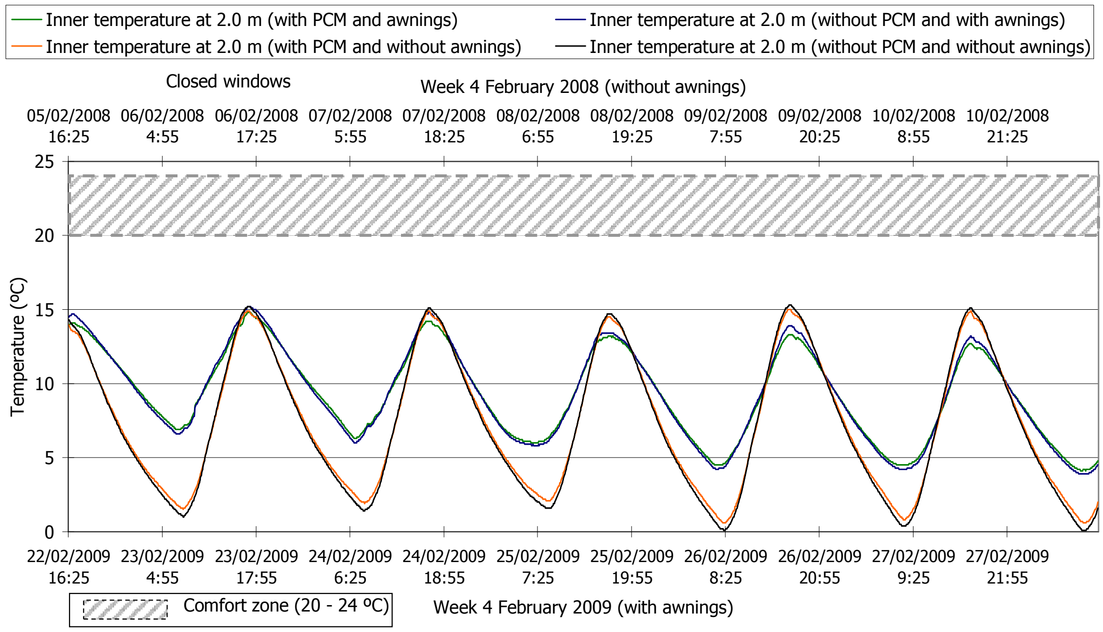


Figure 115. Cubicle inner temperature at 2.0 m height for cubicles with and without awnings during closed windows experiments.

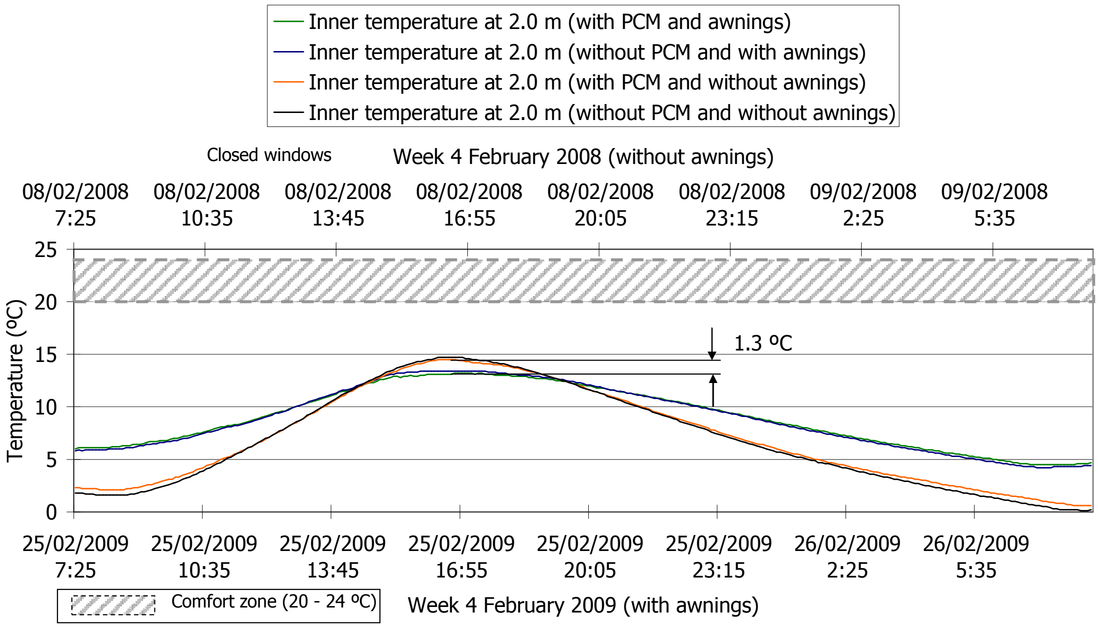


Figure 116. Detail of the Cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature differences during closed windows experiments.

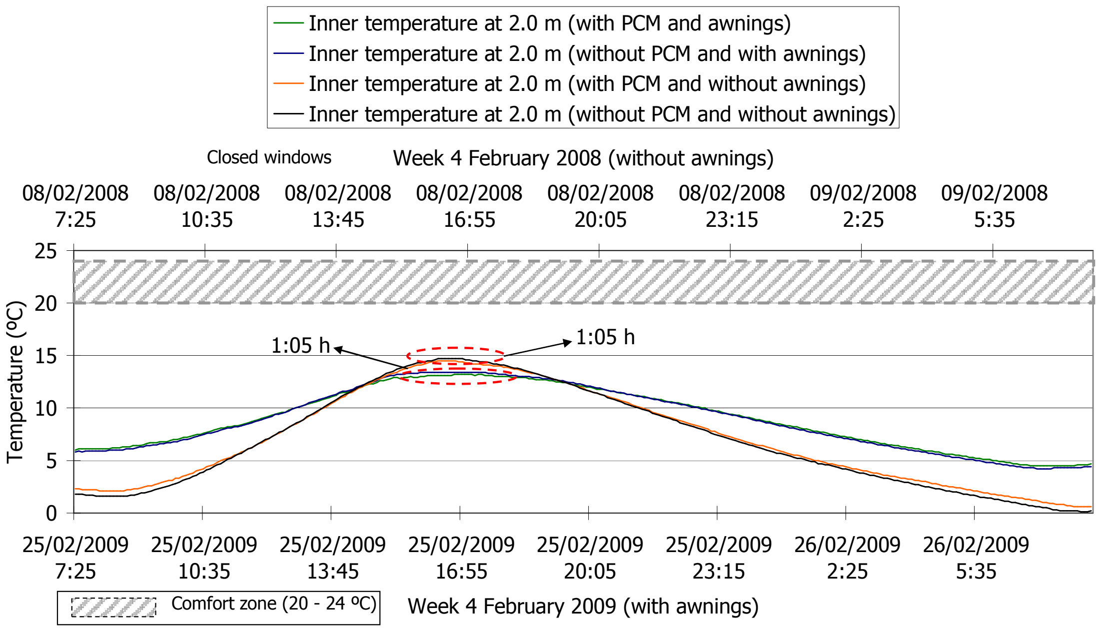


Figure 117. Detail of the cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature delays during closed windows experiments.

3.4.4.4 Conclusions to closed windows experiments

- Observed effects are mostly produced by the awnings, the thermal inertia of the PCM itself (which did not activate), and the climatic conditions.
- Peak values of wall temperatures and inner temperatures at 1.2 m and 2.0 m in cubicles with awnings were lower in 1.1 ºC (5.6%), 1 ºC (7%) at 1.2 m, and 1.3 ºC (9%) at 2.0 m respect of those of cubicles without awnings.
- Awnings increased the delay these temperatures experienced in reaching their peak values in 15 minutes (12%) and 20 minutes (29%) respectively. Temperatures at 2.0 m did not experience such time delay.

- The wall heat flux behaved in a similar manner to the wall temperature as their maximum and minimum values took place at the same time, and presented a very uniform variation pattern along the week.
- Heat flux peak values in cubicles with awnings were 10 W/m^2 (26%) lower than those in cubicles without awnings, which had a tendency to increase much faster than those in cubicles with awnings though.
- Also, a delay in reaching the flux peak values was observed; this delay was increased in 25 minutes (29%) in cubicles with awnings.

3.4.5 Closed windows with radiator

3.4.5.1 Climatic data

The respective comparisons of climatic data for the correspondent weeks are shown next (Figure 118 and Figure 119).

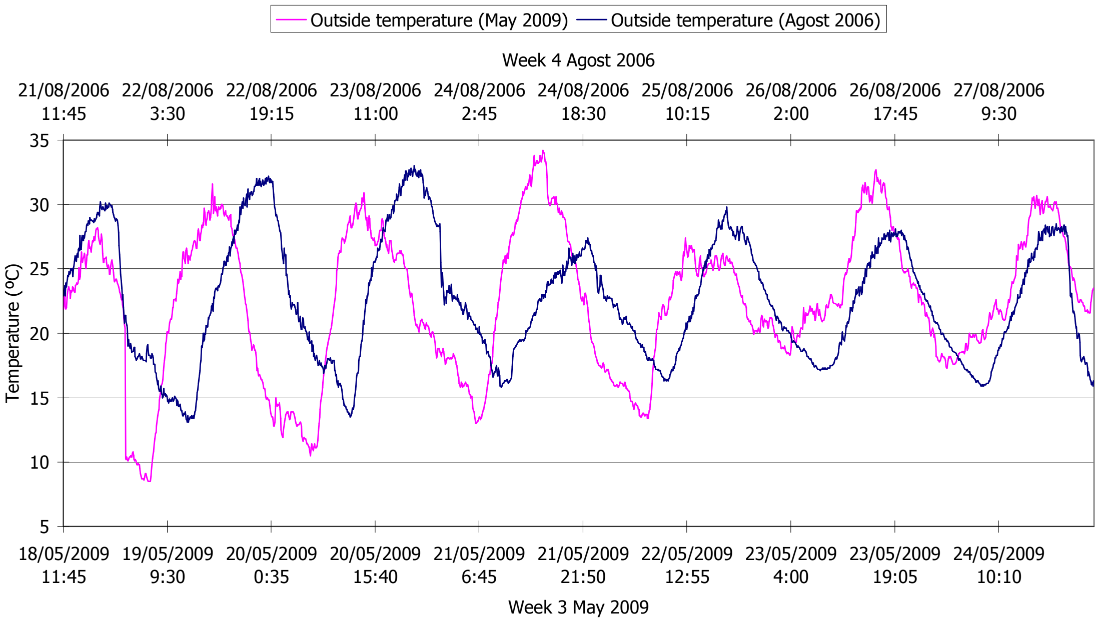


Figure 118. Comparison of the selected weeks outside temperature (closed windows with radiator experiments).

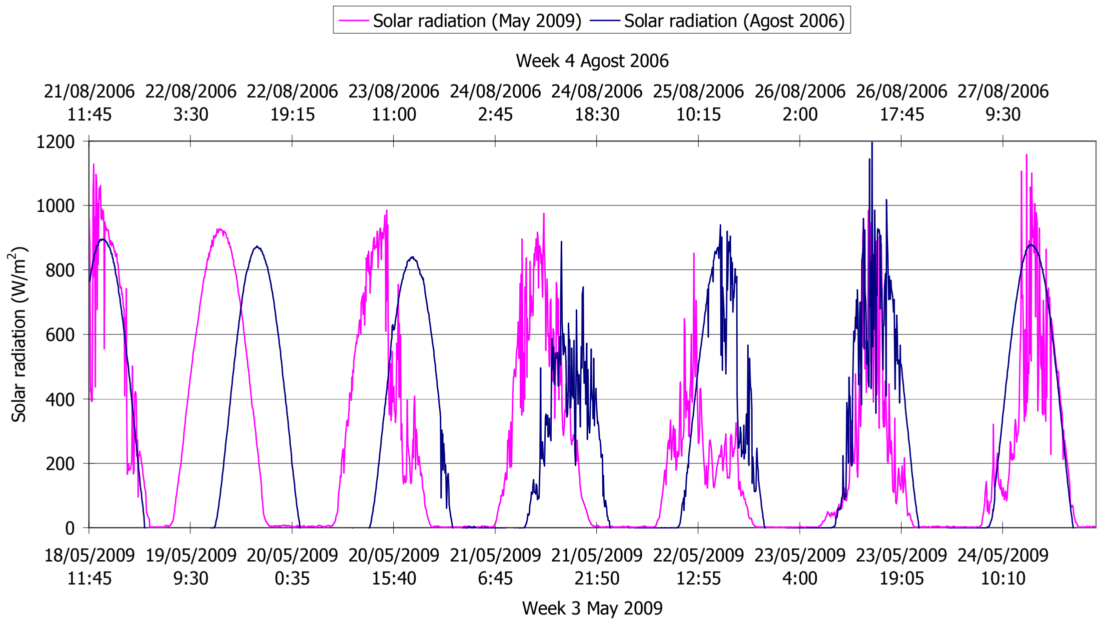


Figure 119. Comparison of the selected weeks solar radiation (closed windows with radiator experiments).

3.4.5.2 Wall temperature and heat flux

The wall temperature comparison for the considered weeks for this experiment is shown in Figure 120.

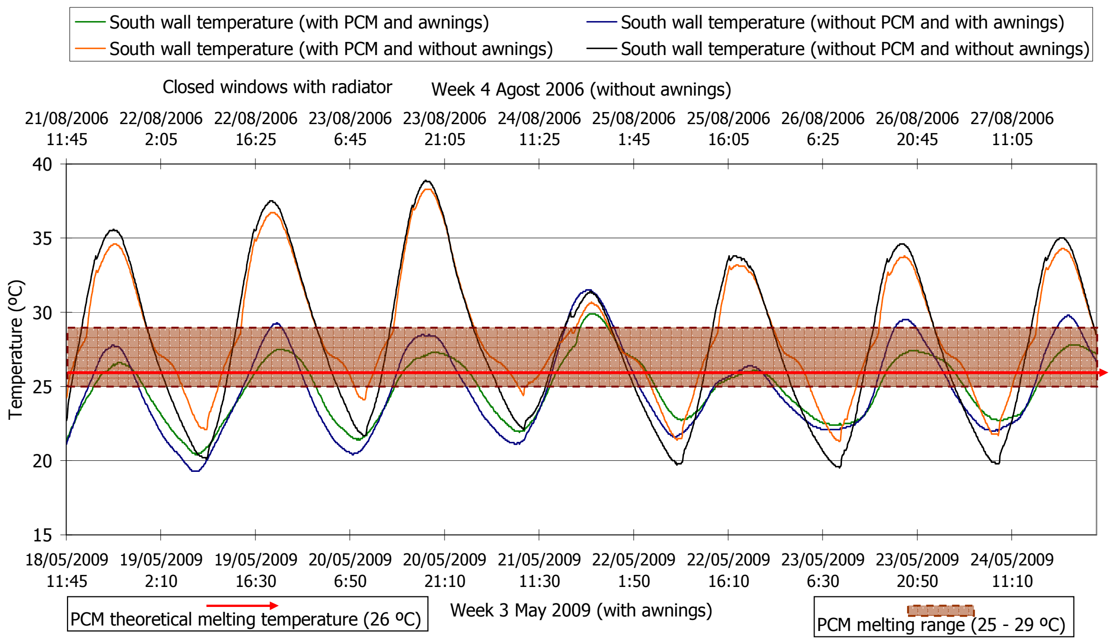


Figure 120. South wall temperature for cubicles with and without awnings during closed windows with radiator experiments.

Wall temperatures did not remain constant at the set-point of 25 ºC, but they did oscillate between around 20 ºC and 35 ºC approximately. When outside temperatures were increasing during the day and inner temperatures reached 25 ºC, the radiators switched off automatically, and therefore, temperatures above 25 ºC could not be controlled and depended on the outside temperatures. At night, when outdoors temperature cooled down the radiators switched on at 25 ºC (inner temperature). But, as it can be seen, inner wall temperatures decreased below this value. This is attributed to the lack of thermal insulation in the cubicles, which translated into high energy losses not compensated by the radiator.

It may be seen that in cubicles with awnings, regarding peak values, those of cubicles with awnings were at least 5 ºC (15%) lower than those of cubicles without awnings (Figure 121). As for PCM activation, it is observed that PCM did get to complete full phase change cycles in cubicles without awnings; this phenomenon did not occur the whole time in cubicles with awnings given that on some days, PCM did not get to melt completely, thus not storing all the expected heat.

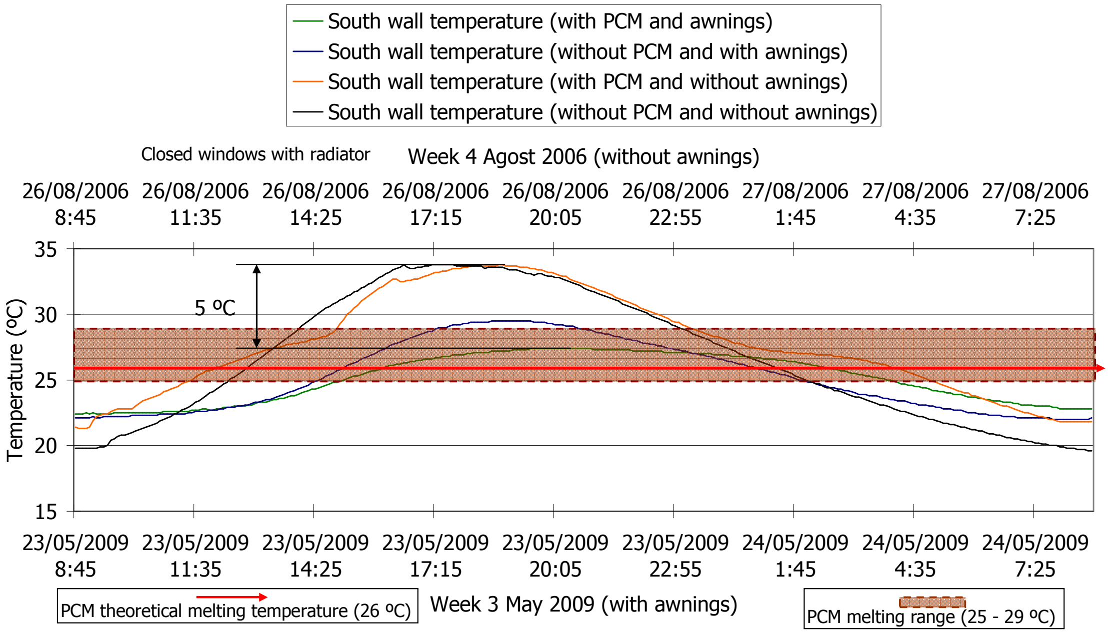


Figure 121. Detail of the south wall temperature for cubicles with and without awnings showing temperature differences during closed windows with radiator experiments.

Aside from the effects of PCM, the influence of the awnings over the respective cubicles is clear. On the one hand, awnings kept PCM from reaching its melting range top value most of the days. On the other hand, wall temperature lower values were mostly equal or higher than 20 ºC. Both factors led the wall temperature to oscillate within a narrower margin. This was benefitial as in this case wall temperatures did not reach very high values, and PCM did solidify every day, being "ready" to work the following day.

In cubicles without awnings, this margin was higher. Lower values were similar to those for cubicles with awnings (reaching an average of 35 ºC); however, peak values were much higher as solar radiation was not contained as with the awnings. As a result of this, PCM did get to activate, but because of the climatic conditions, temperature changes took place very fast, thus the wall temperatures remained for a shorter time within the PCM melting range. When temperatures went down, the "cooling" process was not as fast, and a clearer phase change pattern is appreciated at the wall temperature of cubicles with PCM. Also, lower values did not go down as low as those of the wall without PCM and no awnings.

Another observed effect is that walls with PCM in cubicles with awnings reached their peak value around 4 hours later than those without PCM, while in cubicles without awnings, walls with PCM reached their peak values around 2 hours later than those without PCM, that is, awnings increased this delay in 2 hours (100%). The influence awnings have exerted over PCM activation in both cubicles with and without them has just been mentioned, but is better appreciated in comparing the weekly hours during which PCM was active (Figure 123). It is observed that the weekly PCM active hours increased in 2% respect of the one of cubicles without awnings.

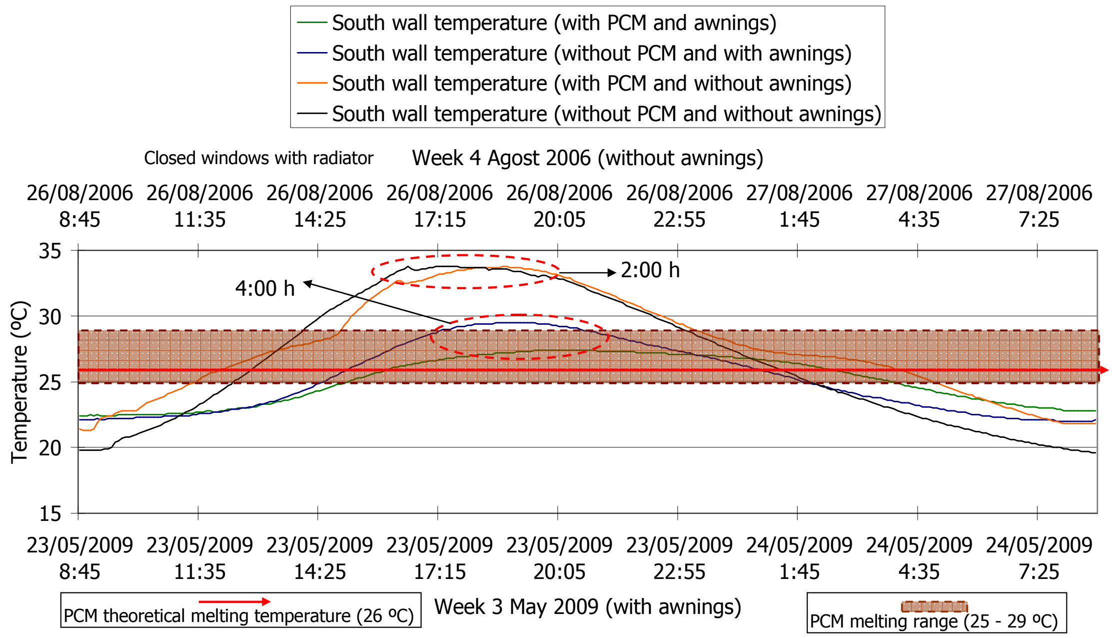


Figure 122. Detail of the south wall temperature for cubicles with and without awnings showing temperature delays during closed windows with radiator experiments.

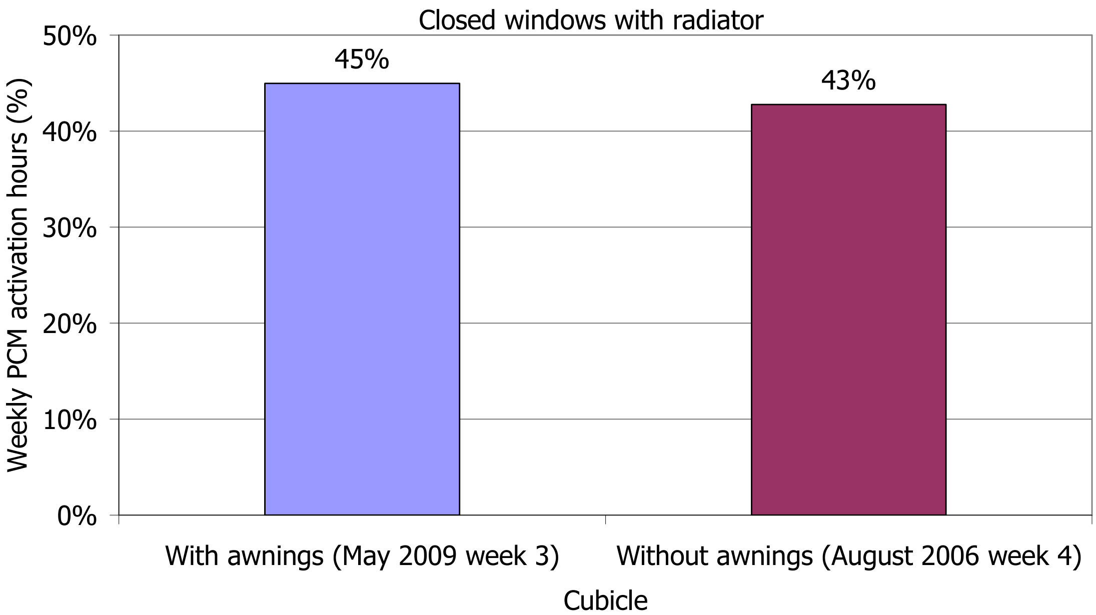


Figure 123. Comparison of the PCM active hours percentage for cubicles with and without awnings during closed windows with radiator experiments.

As for the wall heat flux, experimental measurements are shown in Figure 124. It is seen that the heat flux followed the same pattern as wall temperatures, that is, it increased and decreased along with them, however, it is also seen that the flux in cubicles with awnings mostly oscillated among narrower upper and lower limits than those measured in cubicles without awnings, and that the flux in cubicles with awnings did not increase as much as the one in cubicles without awnings when the wall temperature was increasing. The flux peak values in cubicles with awnings and PCM was 4.5 W/m^2 (30%) lower than that of cubicles with PCM and without awnings (Figure 125).

On the other hand, it is appreciated that flux peak values in cubicles with PCM and awnings were reached 7:25 hours later than in those without PCM and with awnings; while this delay was of 10:12 hours in cubicles without awnings respectively. There was a decrease of 2:47 hours (-27%) of the mentioned time delay in cubicles with awnings, much likely because PCM could not melt and complete full phase change cycles.

As explained in previous sections, the heat flux is conditioned by the temperature difference between that of the wall, and either the outside temperature or the cubicle inner temperature (which in this case was affected by the radiator). In applying shadows to the walls, higher temperature differences were attained before (as wall temperatures were lower), and consequently, flux peak values were reached before in cubicles with awnings than in those without awnings.

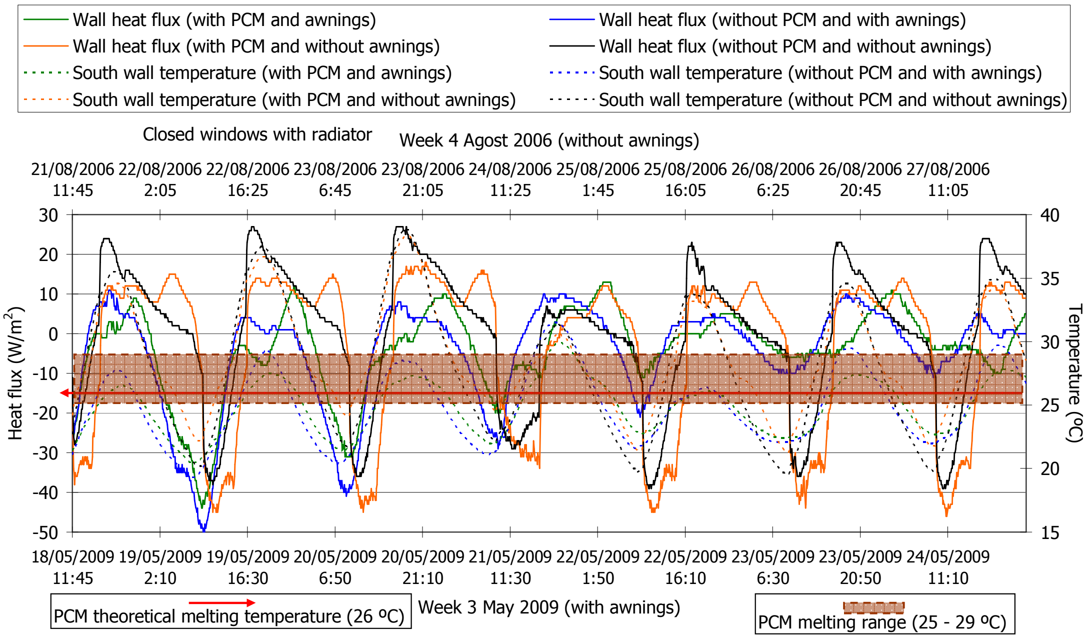


Figure 124. Measured heat flux through the south wall in cubicles with and without awnings during closed windows with radiator experiments.

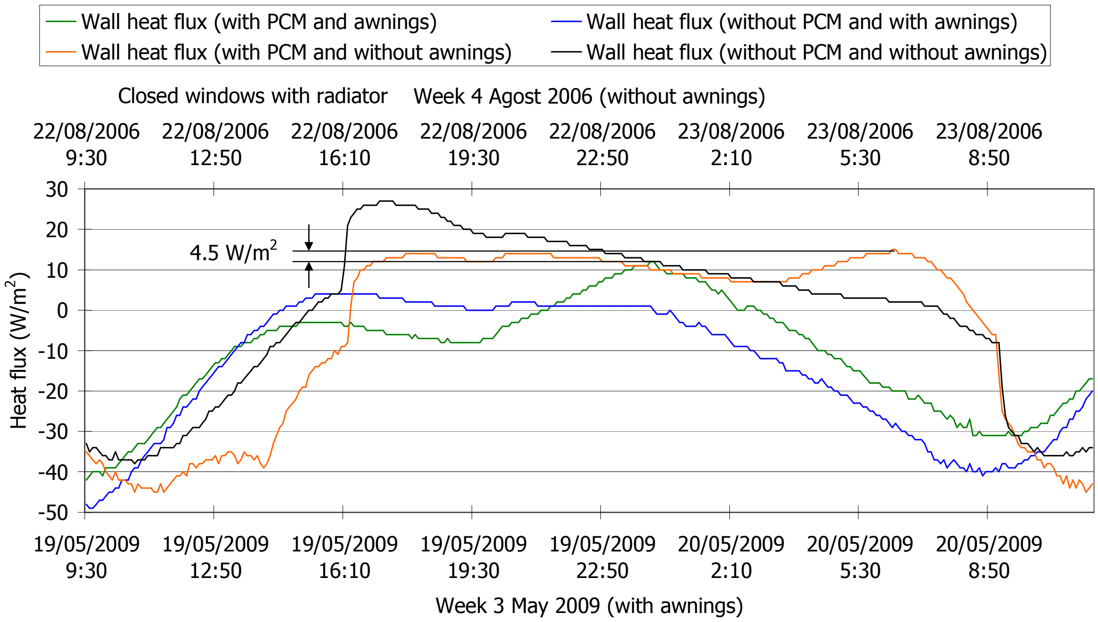


Figure 125. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing temperature differences during closed windows with radiator experiments.

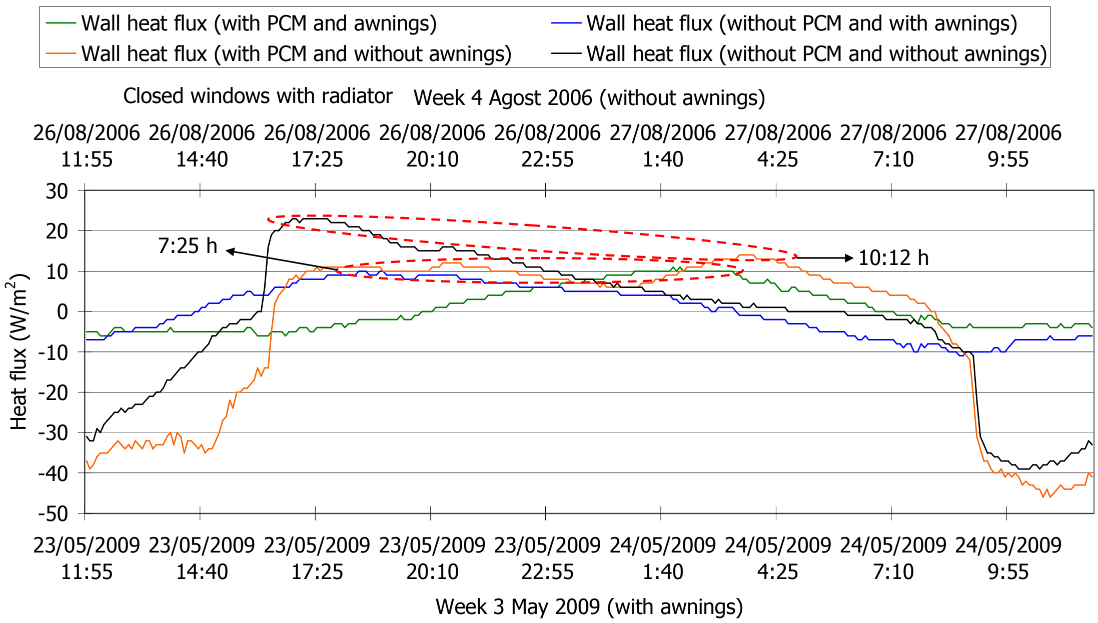


Figure 126. Detail of the measured heat flux through the south wall in cubicles with and without awnings showing flux delays during closed windows with radiator experiments.

3.4.5.3 Cubicle inner temperature

First, the inner temperature at 1.2 m (Figure 127) is analyzed.

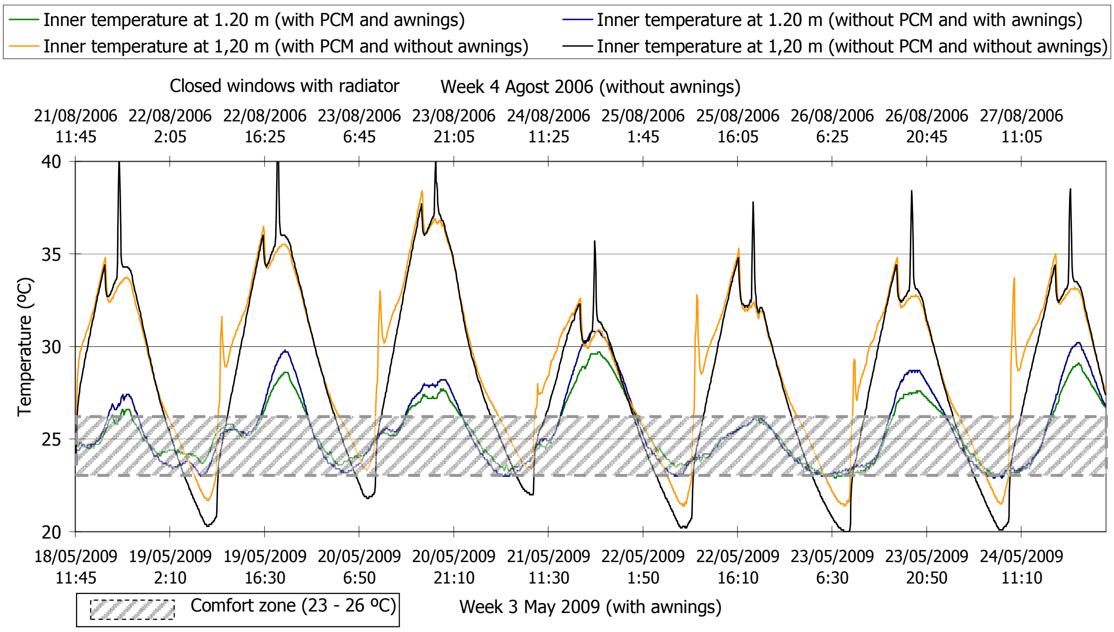


Figure 127. Cubicle inner temperature at 1.2 m height for cubicles with and without awnings during closed windows with radiator experiments.

In observing Figure 118 and Figure 127, it is appreciated that lowest outside temperatures at night oscillated between around 10 ºC and 18 ºC during the considered week for experiments with awnings, while inner cubicle temperatures at 1.2 m lowest values were of around 23 ºC. Likewise, during experiments without awnings, lowest outside temperatures were between around 13 ºC and 17 ºC, and inner cubicle temperatures at 1.2 m were of around 20 ºC. The heating effect of the radiator is not seen directly, as inner temperatures should have been constant and close to the set-point of 25 ºC in all cubicles.

As mentioned when analyzing wall temperatures, the lack of thermal insulation in the cubicles led to heat losses that the radiator could not compensate. In the case of inner temperatures, as they are directly proportional to wall temperatures, similar commentaries may be applied. In cubicles containing PCM and awnings, the combined insulation effect of both did not allow inner temperatures to go down beyond 23 ºC (still within the comfort zone), and then the radiators switched on and temperatures started increasing. In cubicles with PCM and without awnings, the effect by PCM alone was not enough to keep temperatures inside the comfort zone, as they decreased a bit more before the radiators could start heating the cubicle.

Inner temperatures in cubicles without PCM, both with and without awnings, decreased more; however, lowest values of temperatures in cubicles with awnings did not feature appreciable differences respect to those of cubicles with PCM and awnings (Figure 127), unlike the case of temperatures in cubicles without awnings, which did show visible differences with those of cubicles with PCM.

Regarding other aspects, as observed, awnings lowered temperature peaks in cubicles with awnings in up to 7 ºC (20%) respect of those of cubicles without awnings (Figure 128). As it may be seen in Figure 127, the cubicles without awnings presented small temperature peaks which reproduced every day at similar hours; this was probably attributed to solar radiation coming from the outside through the windows, thus getting in contact with the sensor, as probably the blinds at the windows were out of place. It is observed that there was a delay of 2:25 hours at inner temperature in cubicles with awnings and PCM in reaching their peak values respect of those without PCM, while there was only a delay of 1:05 hours in cubicles with PCM and no awnings respect of those without PCM. The delay was increased in 1:20 hours (123%) (Figure 129).

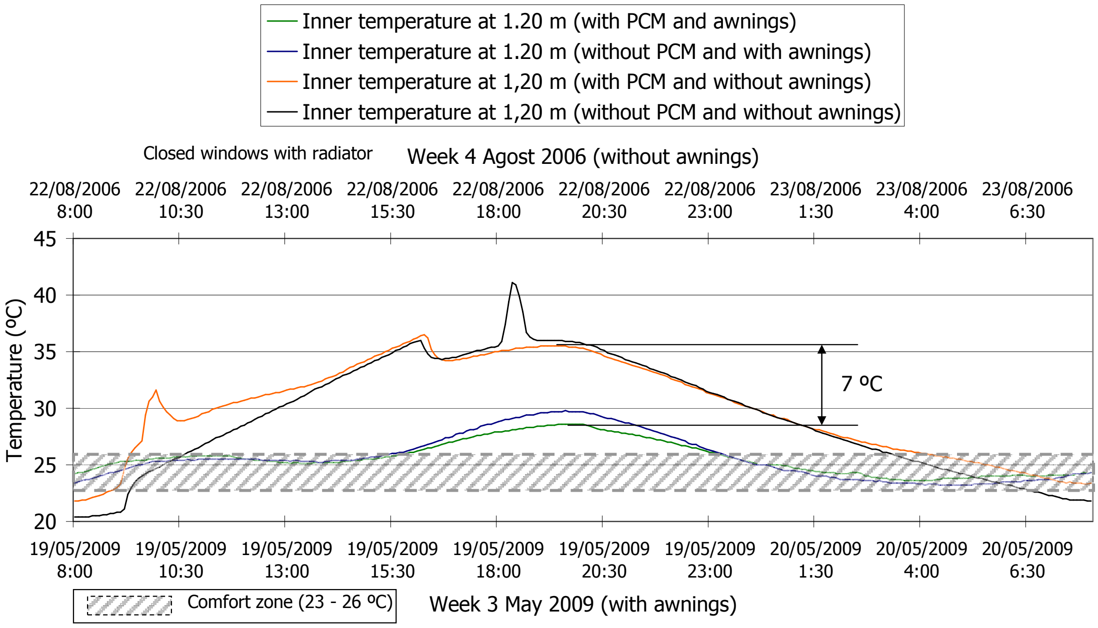


Figure 128. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature differences during closed windows with radiator experiments.

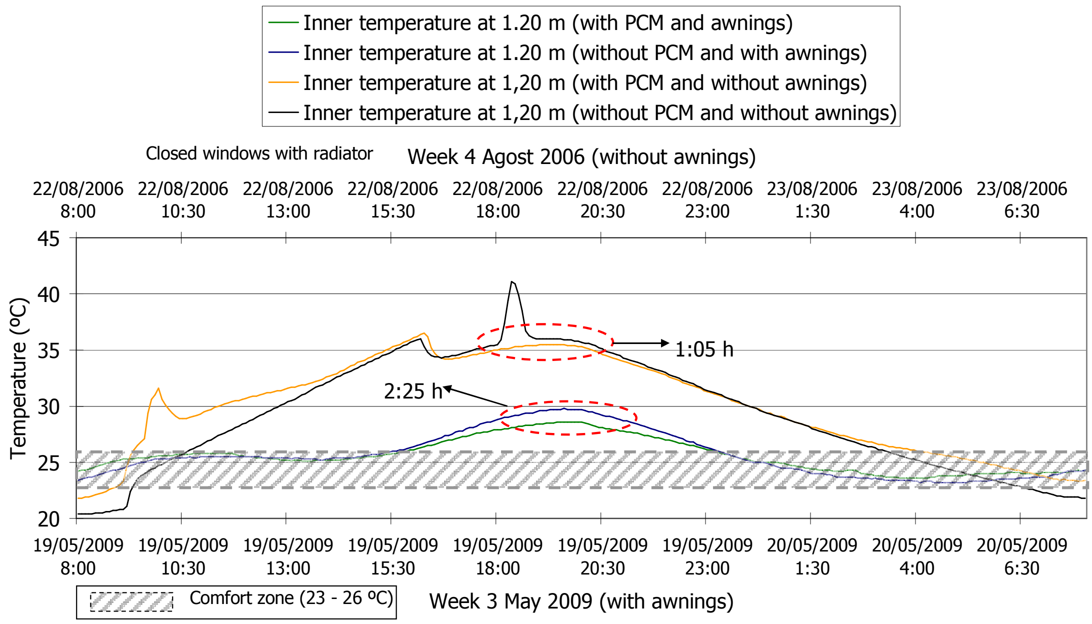


Figure 129. Detail of the Cubicle inner temperature at 1.2 m height for cubicles with and without awnings showing temperature delays during closed windows with radiator experiments.

The comparison for inner temperatures at 2.0 m is shown in Figure 130. As observed, the behaviour of this temperature was quite similar to that of the inner temperature at 1.2 m, so therefore same commentaries are valid in this case. Regarding the peaks reduction, in this case, the peak values reduction was of 19% (Figure 131). However, the time delays were different: 2:10 hours in cubicles with awnings, and 1:30 hours in cubicles without awnings, that is, an increase of 40 minutes (44%) in the delay. It should be mentioned that this parameter also exhibited small temperature peaks which repeated every day, though not as high as those observed with temperatures at 1.2 m, as in this case sensors were located at a greater height and therefore could not receive the same amount of solar radiation from the outside as those at 2.0 m.

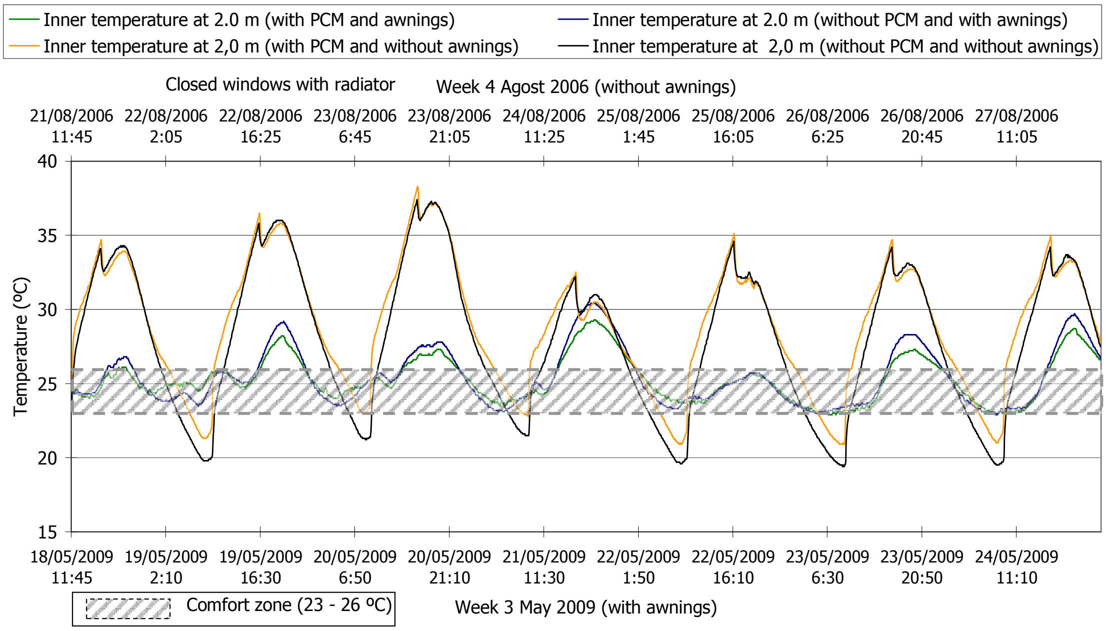


Figure 130. Cubicle inner temperature at 2.0 m height for cubicles with and without awnings during closed windows with radiator experiments.

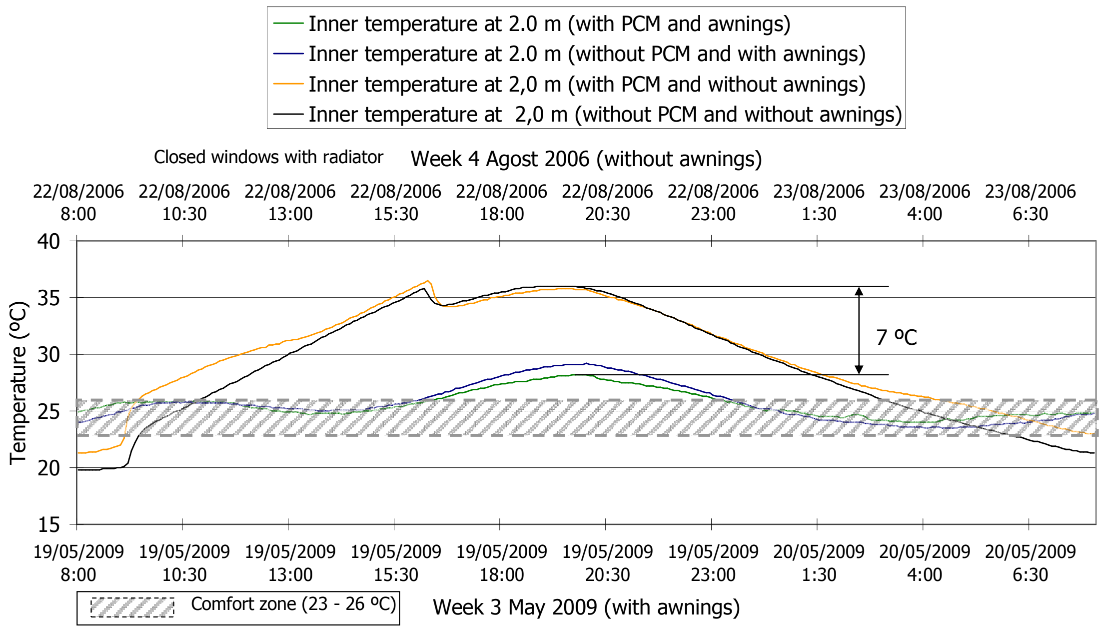


Figure 131. Detail of the Cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature differences during closed windows with radiator experiments.

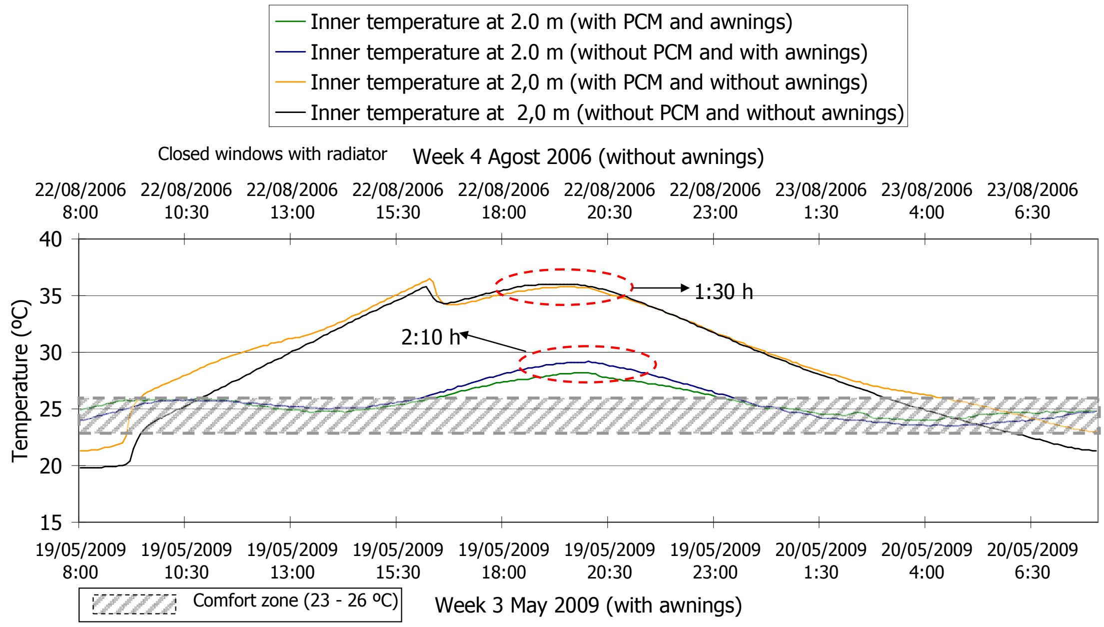


Figure 132. Detail of the Cubicle inner temperature at 2.0 m height for cubicles with and without awnings showing temperature delays during closed windows with radiator experiments.

3.4.5.4 Operative comfort temperature (T_0)

The operative comfort temperatures for the considered cubicle types are shown in Figure 133.

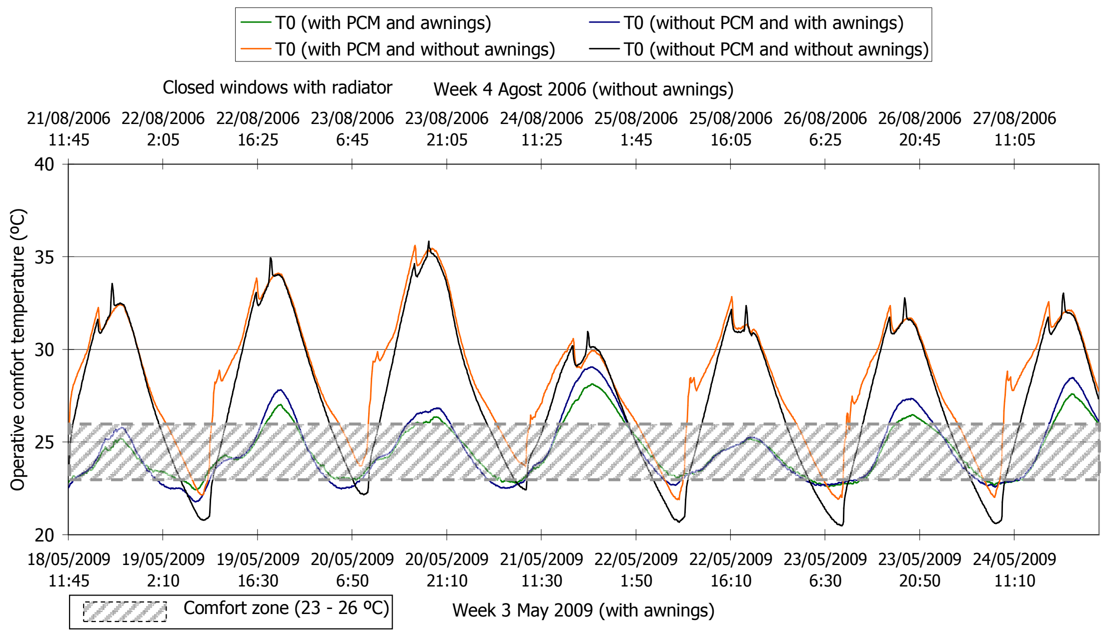


Figure 133. Operative comfort temperature for cubicles with and without awnings during closed windows with radiator experiments.

Awnings and PCM diminished the peak values of T_0 up to 7 ºC (21%) (Figure 134) and stabilized lowest values almost matching the comfort zone low limit, mostly staying inside the comfort zone during the week; in addition to this, it is seen that T_0 followed a very regular pattern of variation.

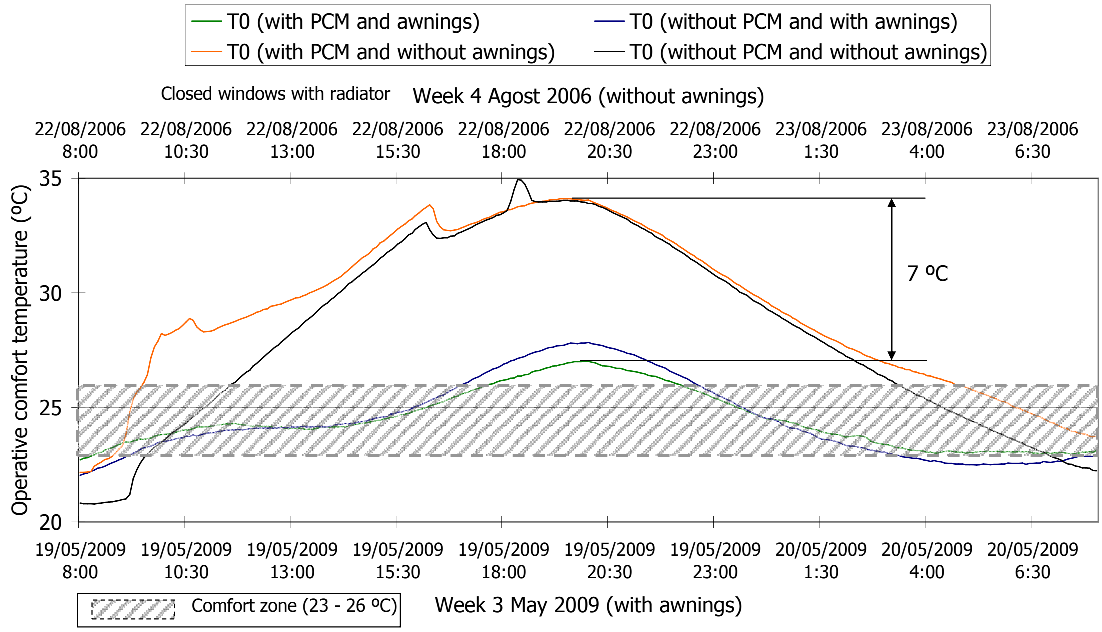


Figure 134. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature differences during closed windows with radiator experiments.

In cubicles with awnings, those with PCM took around 2:40 hours to arrive to their peak values respect to those without PCM; while in cubicles without awnings this delay was of 50 minutes, or less on some days (Figure 135). The use of PCM and awnings increased in 1:10 hours (140%) the mentioned time delay.

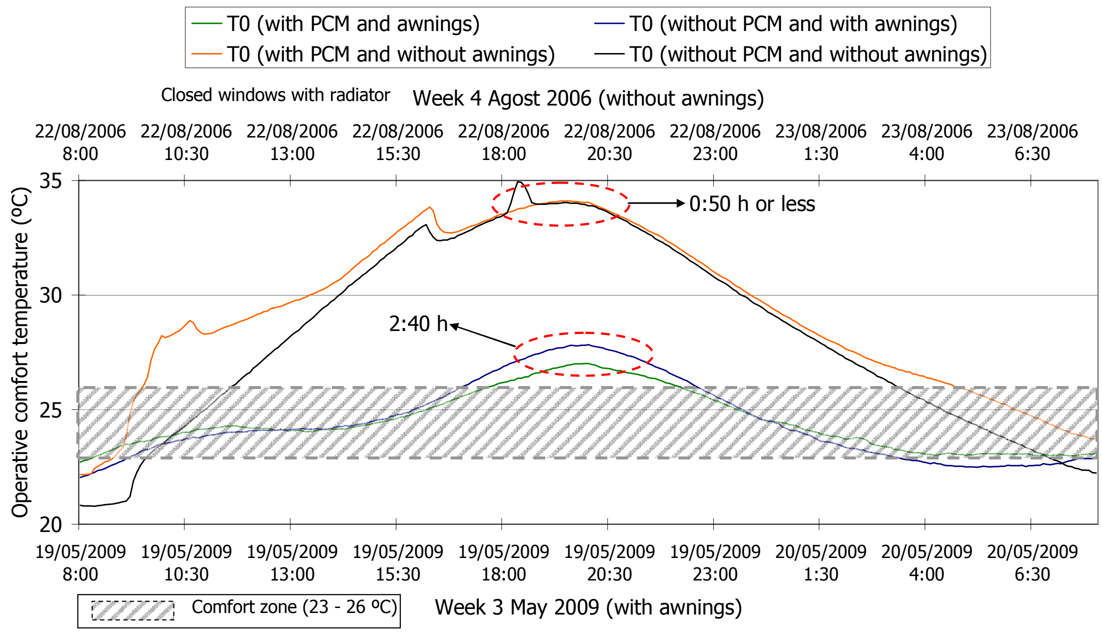


Figure 135. Detail of the operative comfort temperature for cubicles with and without awnings showing temperature delays during closed windows with radiator experiments.

The effect that PCM and awnings exerted over the weekly hours in comfort may be observed in Figure 136. As expected, the mentioned value was largely increased, as there are 42% more hours per week under comfort conditions in cubicles with PCM, and 25% more hours in cubicles without PCM. The influence of the radiator over this increase is to be mentioned, as it prevented temperatures from decreasing excesively at night when outside temperatures were relatively low, particularly in cubicles with awnings where temperatures were hardly lower than the comfort zone low limit. However the heating effect of the device was hard to appreciate because of the lack of thermal insulation in all cubicles.

On the other hand, it is seen that there was a 4% reduction of the hours under comfort in cubicles with PCM and without awnings respect of those in cubicles without PCM and without awnings. This phenomenon is similar to that occurred during free-cooling experiments, where due to the PCM acting as an insulator and it did not allow temperatures to go down enough at night, so there were more hours under discomfort.

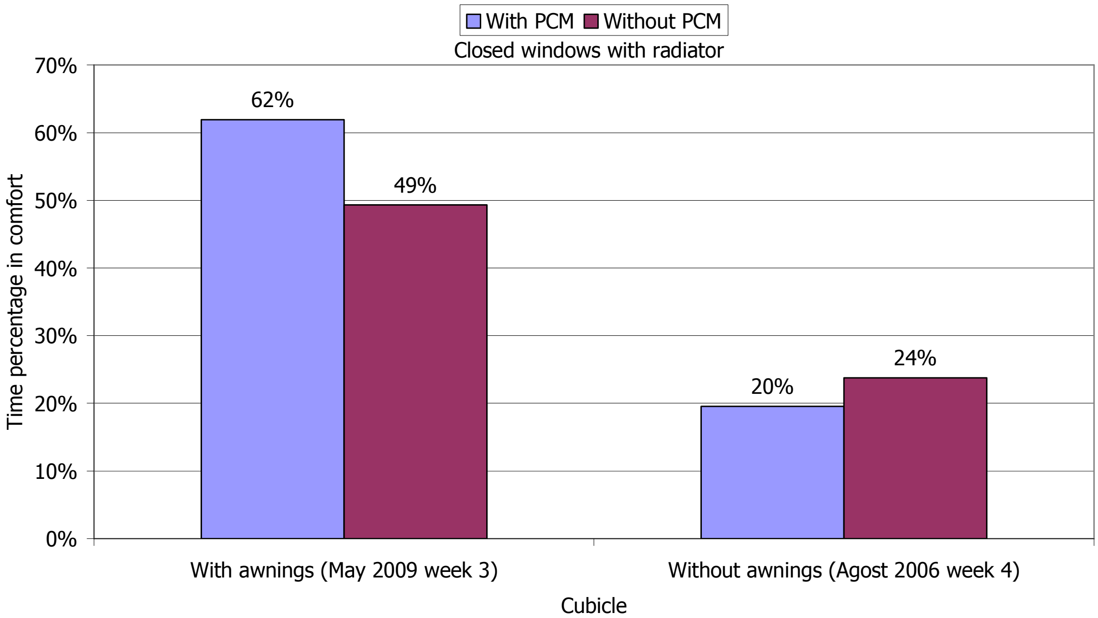


Figure 136. Comparison of the weekly hours percentage under comfort for cubicles with and without awnings during closed windows with radiator experiments.

3.4.5.5 Energy consumption and CO_2 emissions

The importance of the energy consumption was mentioned in section 3.2.5. As done with other measured parameters, the goal was to perform a comparison of the consumptions in cubicles in a similar manner; unfortunately, during the first experimental stage (up until 2008), the energy consumption was not measured in the studied cubicles, so the effect of PCM and awnings over this parameter could not be analyzed. However, as there are available data for cubicles with awnings, those results are presented next.

Figure 137 shows the daily electrical energy consumption for cubicles with awnings, Figure 138 presents the consumption reduction thanks to the use of PCM in the respective cubicle, and Figure 139 shows the correspondent daily energy consumption reduction percentage. The weekly energy consumption in cubicles without PCM and awnings totalized 31,385 Wh_e (around 31.4 kWh_e), while the consumed energy in cubicles with PCM and awnings resulted in 25,298 Wh_e (around 25.3 kWh_e) per week. Therefore, final energy weekly savings accounted for 6,087 Wh_e (around 6.1 kWh_e) between cubicles with awnings, that is, a 19.4 % weekly consumption reduction.

Parameters related to the energy consumption are the CO_2 emissions. They are linearly related to one another as seen with the following equation:

$$CO_2 = f_e \cdot Energy$$

Eq. 18

where: CO_2 = CO_2 equivalent emission (g CO_2)
f_e = CO_2 emissions conversion factor (g CO_2/kWh$_e$)
Energy = electrical energy consumption (kWh$_e$)

The electrical CO_2 emissions reduction factor is given directly by the bibliography, and is of 649 g CO_2/kWh$_e$ for Spain [307]. Based on this, the equivalent CO_2 emissions and the correspondent emissions reduction have been calculated (Figure 140 and Figure 141), and as these ones are proportional to the consumption, so are the daily emissions reduction (Figure 142). Weekly emissions in cubicles with PCM and awnings totalized 16,418.402 g CO_2 (around 16.4 kg CO_2), while in cubicles without PCM and with awnings emissions were of 20,368.865 g CO_2 (around 20.4 kg CO_2) per week. The emission reduction was then of 3,950.463 g CO_2 (around 3.9 kg CO_2) per week, a 19.4% reduction was achieved again as the dependence between variables is linear.

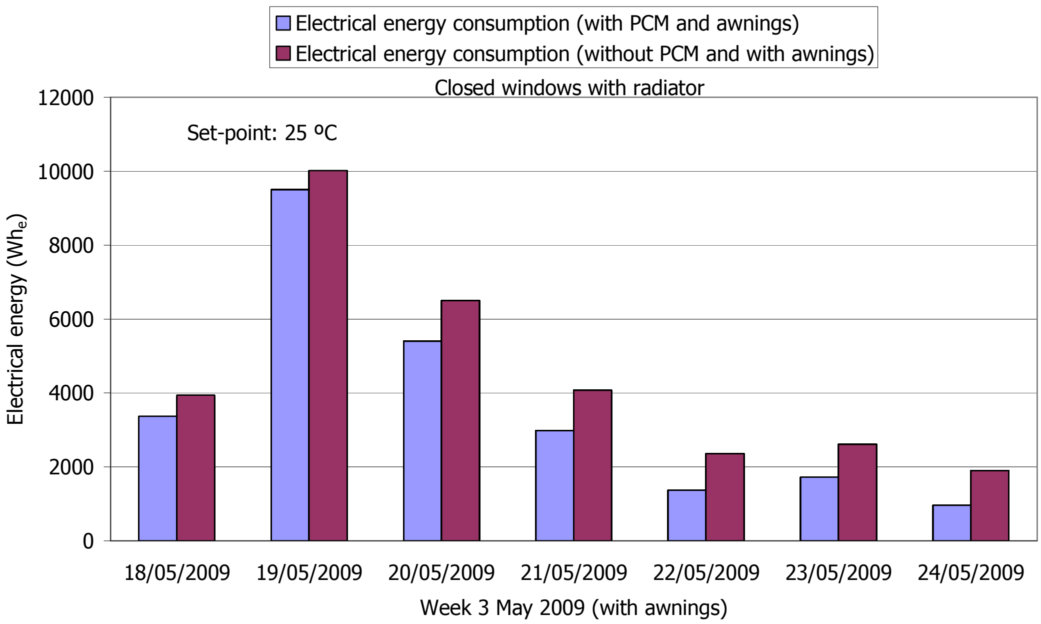


Figure 137. Daily electrical energy consumption in cubicles with awnings.

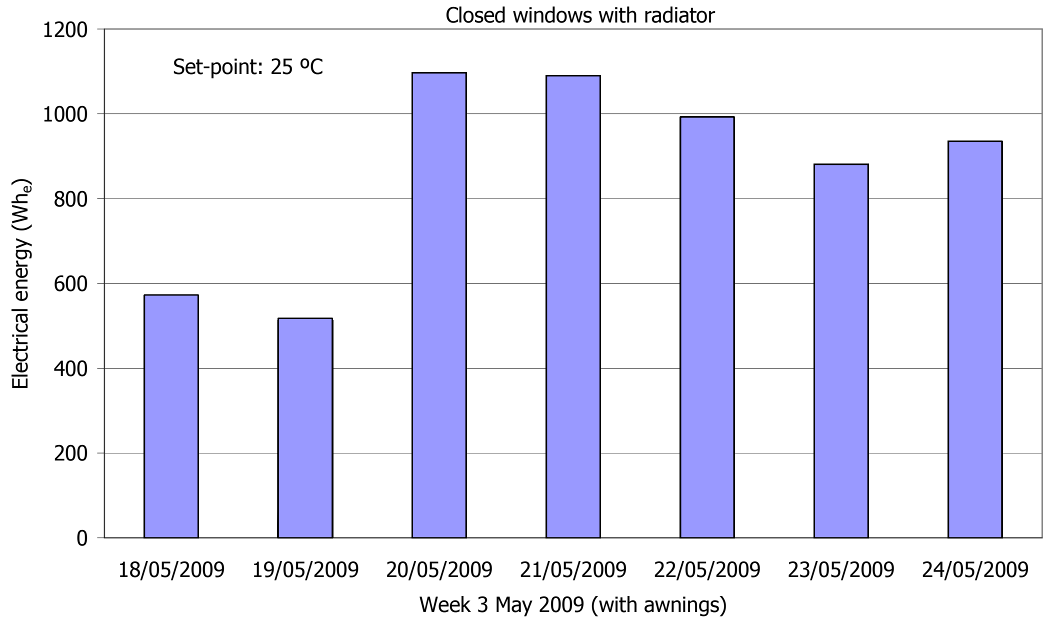


Figure 138. Daily electrical energy consumption reduction by usage of PCM in cubicles with awnings.

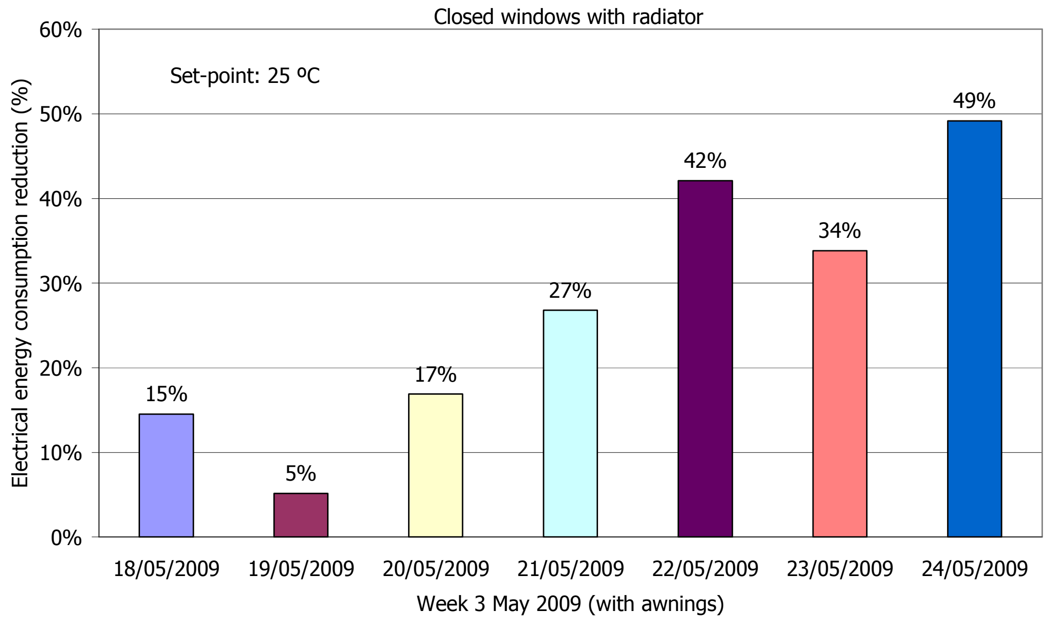


Figure 139. Electrical energy consumption reduction percentage by usage of PCM in cubicles with awnings.

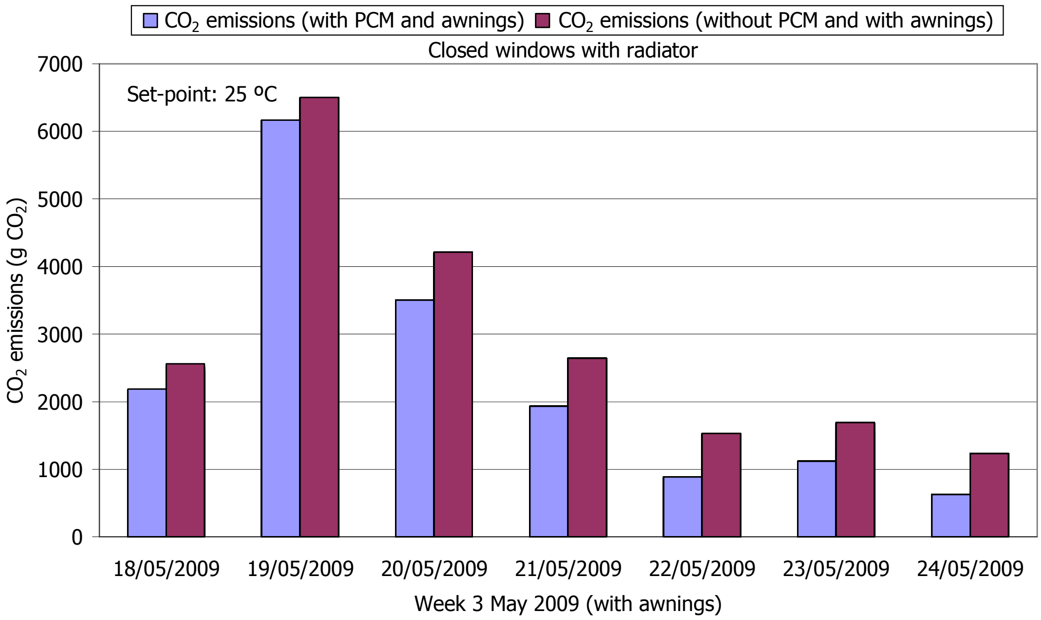


Figure 140. Daily CO_2 emissions in cubicles with awnings.

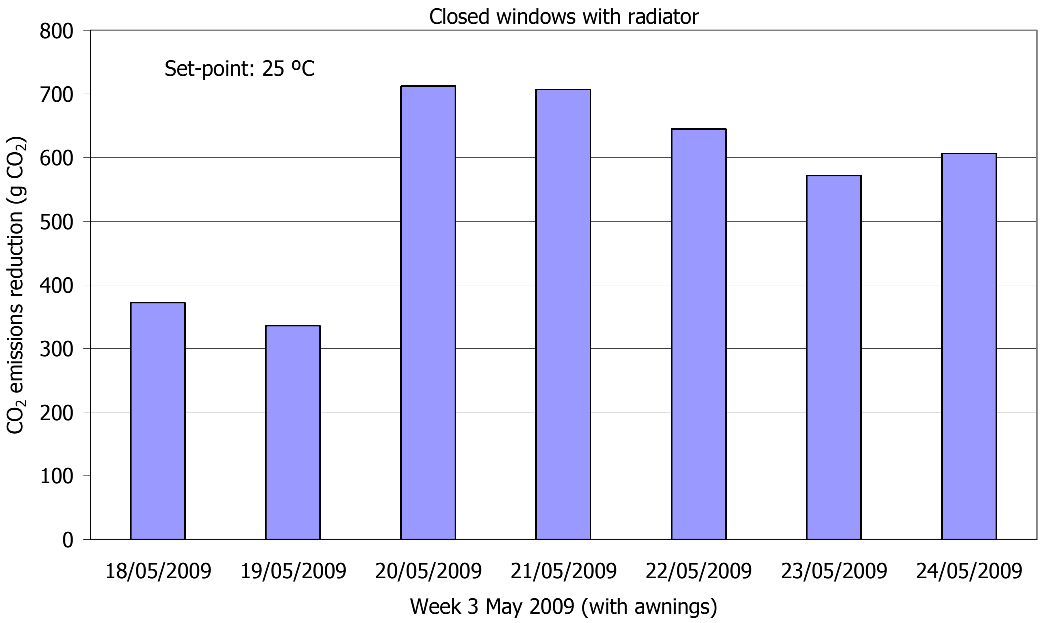


Figure 141. Daily CO_2 emissions reduction by usage of PCM in cubicles with awnings.

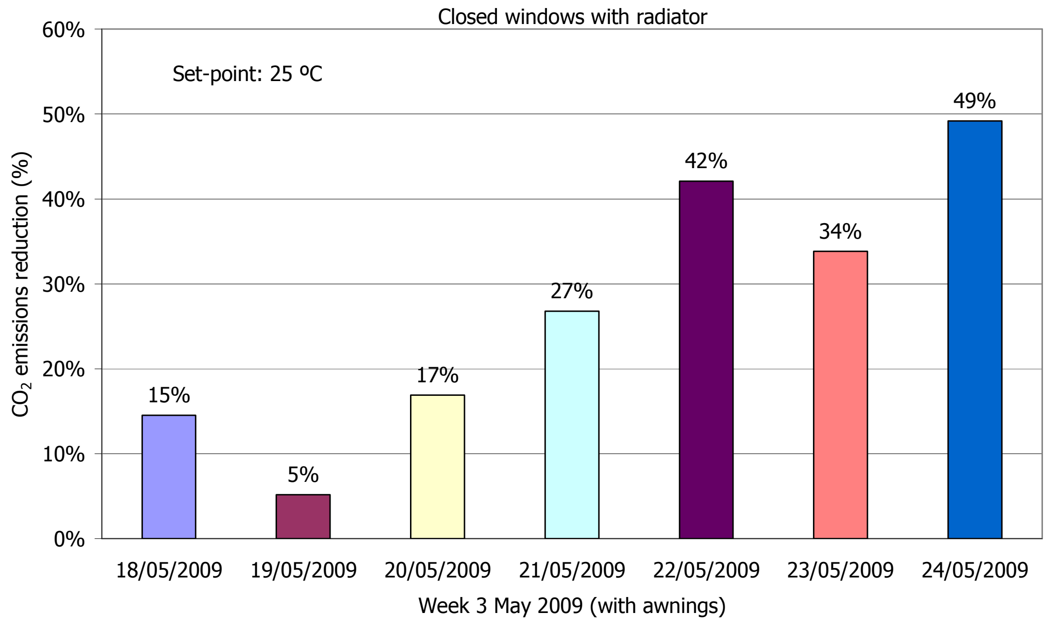


Figure 142. CO_2 emissions reduction percentage by usage of PCM in cubicles with awnings.

3.4.5.6 Conclusions to closed windows with radiator experiments

- The use of PCM and awnings lowered peaks of the wall temperature, cubicle inner temperature and operative comfort temperature (T_0) in 5 ºC (15%), 7 ºC (19-20%), and 7 ºC (21%) respectively.
- PCM did not absorb all the heat it was expected to, given that it could not complete full phase change cycles in cubicles with awnings, a phenomenon that did not take place in those without awnings.
- The time that the PCM remained active was increased in 2% in cubicles with awnings.
- The wall temperature, cubicle inner temperature (at 1.2 and 2.0 m) and operative comfort temperature in cubicles with PCM all exhibited a delay in reaching their peak values, however, in cubicles with awnings this delay was increased in 2 hours (100%), 1:20 hours (123%; at 1.2 m), 40 minutes (44%; at 2.0 m), and 1:10 hours (140%) respectively.
- The heat flux followed the same variation pattern as wall temperature; the flux peak values of cubicles with awnings were 4.5 W/m^2 (30%) lower than those of cubicles without awnings.
- The heat flux in cubicles with awnings exhibited a shorter time delay in reaching their peak values than the flux in cubicles without awnings; this delay was decreased in 2:47 hours (-27%) when comparing both cubicle types.
- Cubicles with awnings featured an inner cubicle temperature and operative comfort temperature with a more regular variation pattern along the week than those in cubicles without awnings.
- In cubicles with awnings, these ones reduced considerably the solar radiation reaching the cubicle, and therefore cubicles with PCM spent 13% more hours per week under comfort conditions; those without awnings and no PCM had 4% less hours in comfort instead.
- The PCM-awnings effect caused an electrical energy consumption and CO_2 emissions reduction of 19.4% respectively. No data for cubicles without awnings was available for further comparisons.

3.4.6 General conclusions to all performed experiments

- PCM functioned as an insulator in the cubicles and stored the heat coming from outside, the effect could be observed in a decrease of peak values of all considered temperatures.
- The use of awnings came to accentuate this effect, mostly favouring the heat storage process and preventing temperatures from reaching values too high to be overcome by the PCM, thus allowing it to remain active for more hours.
- In some cases, due to the climatic conditions and the shadows generated by the awnings, PCM was not able to complete full phase change cycles despite being active as wall temperatures were not high or low enough to exit the considered melting range limits.
- PCM also improved the cubicle thermal inertia, which was observed with a time delay for temperatures to reach their peak values, respect of the temperatures in cubicles without PCM.
- Awnings also favoured this aspect, as the mentioned time delay was increased in cubicles with awnings, however, when PCM did not complete full phase change cycles, it was not able to improve the thermal inertia as expected.
- Awnings allowed cubicles, both with and without PCM, to stay longer under comfort conditions along the week, as a result of favouring the peak temperatures reduction and the thermal inertia improvement, which led the considered temperatures to vary more uniformly along the week and within the comfort limits.
- Regarding the wall heat flux, it showed more uniformity, lower peak values, and a similar time delay increase to that experienced by temperatures; thanks to the effect of PCM-awnings over the thermal inertia.
- The use of PCM in cubicles with awnings reduced the energy consumption and CO_2 emissions respect of those of cubicles without PCM and with awnings.

4 Conclusions and outlook

4.1 Conclusions

Since the energy demand is constantly increasing and the effects of the climate change are beginning to be noticed on larger scales, the current energetic dependence on exhaustible fossil fuels must be changed, and TES has a role to play as energy efficiency will be a key factor in the near future.

This thesis has studied the potential of thermal energy storage (TES) both in Spain and Europe, presenting numerical data in order to back up all theoretical information found in literature. Only one similar study made for Germany had been previously done. Based on it, the model has been formalized with equations, definitions and required assumptions (as realistic as possible), also broadening the scope and considering a short scenario (10 years) when presenting results.

Of all the covered sectors in the performed TES potential study, one with a great influence is the building sector, which represents an important part of the total energy consumption of our society.

A specific application of TES in this sector is the PCM utilization in buildings, studied previously by other authors, and with a large field of application both in Spain and Europe, remarking that the introduction of this technology in the construction sector would multiply product sales and thus decrease significantly the price of the PCM.

In this work, the use of PCM in buildings which incorporate awnings has been studied under different usage configurations. The effect/influence of the combined presence of awnings and PCM over thermal and energetic parameters has been observed, though the effect of awnings alone could be observed as tests were also performed without including PCM. The experimental study has been performed at Puigverd de Lleida (with a Mediterranean climate) in concrete cubicles as concrete is part of the constructive solutions employed in Mediterranean countries. Results showed that the shadows generated by the awnings increased significantly the effects of PCM over thermal and energetic aspects. Also, awnings contributed by smoothing daily indoor measured temperature variations during hot seasons of the year.

Conclusions drawn by the present work are listed next:

1. Literature review

A brief overview of the energetic and environmental situation in Europe, based on available information, has been performed as a background to the TES potential study. Also, main theoretical aspects of thermal energy storage, the different existing technologies, their classification, characteristics, advantages and disadvantages, available substances for use as PCM and some examples of application have been compiled.

2. TES potential study

It has been determined that there are three main numerical variables that represent the potential of the application of thermal energy storage: the load reduction, energy savings, and CO_2 emissions reduction. All of them were evaluated within a 10-year scenario for Spain and Europe, and were quantified in percentages. It was determined that the potential load reduction at the EU may be of 1,160,695 MW_{th} during the next ten years.

Regarding the yearly potential energy savings, they are estimated to be of 7.5% and the yearly electrical energy savings of 0.1%, both at the EU. Finally, the estimated potential CO_2 emissions reduction is an average of 5.5% (based on 1990 and 2005 levels).

Although results are encouraging for TES technologies, final results are not very high at all cases, as TES implementation rates are still low and not expected to increase considerably during the considered period. However, R&D activities on TES are currently underway and a stronger technology penetration could be expected, thus increasing the calculated potential. It was also observed that there are two variables that greatly influence obtained results: the number of buildings and the industrial waste energy, as they are the ones with higher values among all variables, and as all of them are linearly related to each other.

3. Experimental results

Different experiments were performed in order to determine the thermal behaviour of the cubicles and the improvements achieved by the combined use of PCM and awnings. Experiments may be classified into those that featured a partially controlled environment inside the cubicles and those which did not. In the first case, the cubicle inner temperature was to be partially controlled by a heating device (a radiator) with a constant set-point so temperatures would not drop from that value, and the effects over the energy consumption of the device, the CO_2 emissions, and measured temperatures at different locations in the cubicle could be determined. In the second case, the inside temperature fluctuated with the weather conditions. This was accomplished by opening and/or closing the windows according to a predefined test schedule.

- Inner wall temperature and PCM activation:

PCM temperature could not be measured directly, but since PCM was integrated into the walls, the inner wall temperature was analyzed instead. The analysis helped to determine how PCM behaved under the experimental conditions and the effects it exerted over the parameters under observation. PCM effects over the building come from the heat stored in the material as the wall temperatures lie within the PCM melting range. In storing thermal energy the material melts and acts as an insulator, preventing part of the outside heat from entering the cubicle; on the other hand, this heat is released when the material solidifies. Therefore, an improvement of the building thermal inertia is accomplished by the use of PCM.

The mentioned aspects translate into two large effects inside the building: a reduction of the daily temperature and wall heat flux peaks and an increase of the time it takes those variables to reach their peaks (this increase was referred to as a "time delay"). Awnings came to favour these effects since the shadows projected over the walls lowered the solar radiation reaching the building, which helped the PCM stay active for longer and thus the described effects took place. Moreover, the variation of the mentioned variables was more stable while awnings were employed.

In general terms, the effects of PCM over the mentioned parameters during the summer (as first described by Castellón for concrete cubicles without awnings and a non-controlled inner environment), are improved by the presence of awnings.

It must be clarified that, depending on how severe the climatic conditions were and the building usage configuration (that is, if windows were closed, open, etc.), the use of awnings narrowed the wall temperatures variation range and temperatures remained whether below or above the PCM melting range limits, which led the PCM not to complete full phase change cycles (complete meltings and solidifications), and thus not being fully active.

The result of this was a lower amount of energy stored, that is, lower peak values reduction and a possible decrease of the associated time delay. Nevertheless, even when PCM did not complete full cycles, the resulting effect would still be benefitial as in this case PCM was often closer to phase change, and since the considered melting range (25 – 29 ºC) and the comfort zone for summer days (23 – 26 ºC) do not have very different values among them, PCM temperatures kept oscillating close to these ranges (with the correspondant derived benefits) and not above them as was the case of not employing awnings in the building.

Regarding experimental results, it was observed that temperature peaks were lowered an average of 6% and up to 15% in those cubicles featuring both PCM and awnings, and the time delay increased in up to 30% respect of that measured in cubicles with PCM and without awnings. The use of awnings increased the hours that PCM remained active in 2% to 10%. During winter seasons the PCM did not activate, however, the effect of awnings and the wall thermal mass increase by the presence of PCM over wall temperature could be then observed, translating into lowering wall temperature peaks in around 1.1 ºC (5.6%) and slight increases in the time delay (12%).

- Inner temperature

This variable has been measured at heights of 1.2 m and 2.0 m. As the relation between the inner temperature and the wall temperature is directly proportional, the PCM/awnings combination affected peak values and time delays for these temperatures in a similar way as with inner wall temperatures. In this case, peak values were lowered in up to 20%, and time delays were increased in an average of 50% and up to 131%.

- Operative comfort temperature and comfort time

The analysis of the operative comfort temperature is employed to provide an idea of how long the cubicle stayed under comfort conditions inside, whether with or without the use of any heating or cooling device. The operative comfort temperature also experienced the effects described for the other measured temperatures, as it is also directly proportional both to the wall and inner temperatures. The operative comfort temperature peak values were lowered in from 11% to 21%, and the time delays increased in up to 140%. Also, it has been observed that the comfort time was increased in 4% to 13% in cubicles with awnings.

- Wall heat flux

Awnings caused the wall heat flux to change with more uniformity along the considered time. Also, the flux peak values were mostly lower than in cubicles without awnings (from 10% to 30%), which received more solar radiation. The time delay for heat fluxes did not behave uniformly in terms of increasing or decreasing given the dependence of the heat flux on the climatic conditions and the building usage configuration, which makes hard to quantify the changes the time delay went through without detailing each experiment conditions.

- Energy consumption (partially controlled temperature experiments)

The partially controlled temperature experiments were performed with a set-point of 25 ºC, a value that lies close to the PCM theoretical melting point (26 ºC). It was specifically desired to evaluate the potential improvement in the energy consumption reduction, and subsequent CO_2 emissions reduction, that there would be as a result of attaching awnings to the building. Cubicles with awnings and PCM experienced a reduction in the energy consumption of 19%, respect of those without PCM and awnings.

As it happened with other parameters, the energy savings and CO_2 emissions reduction were improved by generating shadows on the building walls, thus confirming that in reducing the amount of solar radiation that reaches the building, the PCM effects may be more notorious. It is considered that, given the important temperature variations of the Mediterranean climate, if insulation had been present in the walls the achieved benefits would have been higher as it would have been easier to maintain the set-point inside the cubicle and get the PCM to be active.

4.2 Outlook

As the basis to estimate the TES numerical potential in Spain and Europe are already given, it is strongly advised to update results regularly as input data will change (particularly the number of buildings and the industrial waste energy). Besides, as new applications may appear in the future, they should be included in the study as well. It is also recommended to include the economical savings obtained as a result of energy savings by TES; a short analysis of the economical aspects may also be done. The scenario considered originally could also be changed according to data availability if necessary.

With regard to the experimental part of this work, since it was detected that the PCM could not complete full phase change cycles during some occasions due to high outside temperatures, it is recommended to install a ventilation system (natural or mechanical) inside the cubicles. As PCM did not activate during the cold seasons of the year, the inclusion of PCM with lower melting points in the cubicle (possibly at the coatings and/or the insulation) might also be taken into consideration for future experiments.

Regarding the different possibilities of PCM utilization in buildings, several experimental configurations are still to be tested so data as the ones obtained in this study may be generated. This is why in 2010 the experimental set-up (partially described in chapter 3) was improved by the construction of new cubicles with more flexibility, so the different constructive solutions may be tested efficiently, professionally, and in a less expensive way throughout time.

The current installation (Figure 143 and Figure 144) allows performing experiments under real conditions using all the materials employed for previous tests, but also the experimental measurement of the designed constructive systems parameters both for the use of PCM in buildings, and as for other industrial purposes. The use of sensors in the new cubicles allows performing a thermal analysis, as has been done with the cubicles studied so far; moreover, thermographic analysis and thermal transmittance studies may now be made thanks to equipment provided by the University of Lleida.

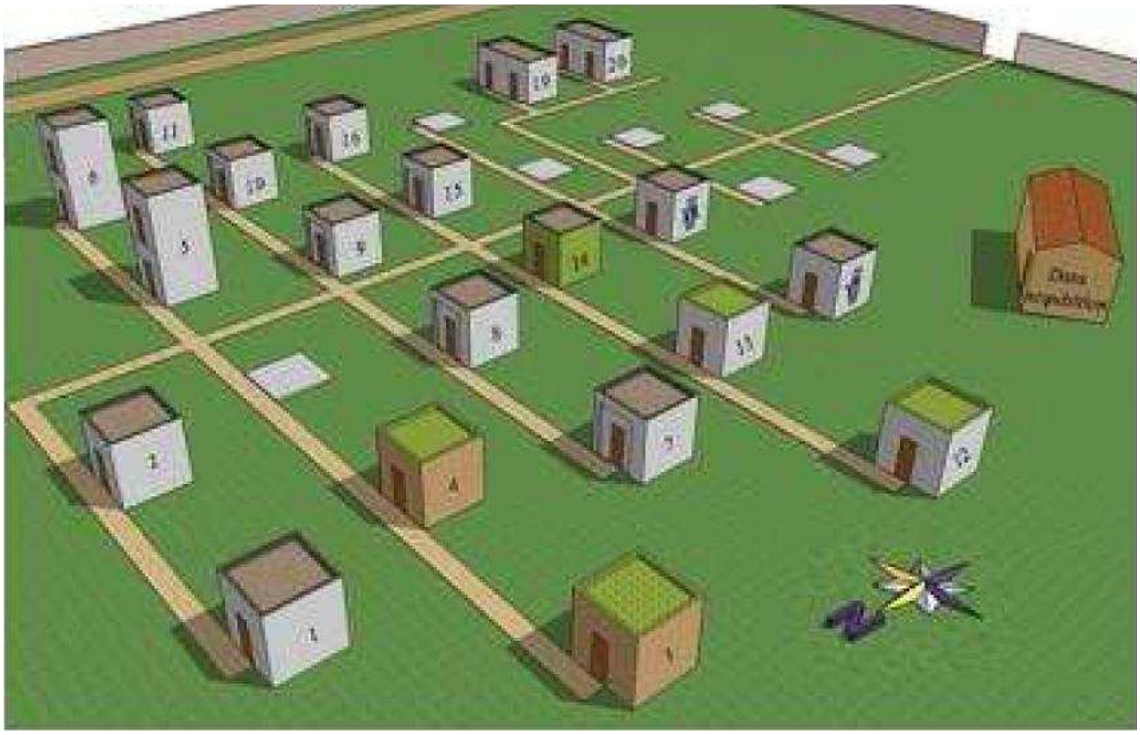


Figure 143. Design view of the experimental set-up in Puigverd de Lleida.

Figure 144. Panoramic view of the experimental set-up in Puigverd de Lleida (2010).

Out of the existing cubicles, only some ones are suitable for experimenting with PCM and the possibilities they offer within the construction field. Among these cubicles are those already employed, described, and mentioned in this work and the previous ones by Castell [18] and Castellón [17]: 5 cubicles made of brick, and 2 made of concrete. Currently, the concrete cubicles have been provided with an interchangeable inner insulation (cork) and plasterboard to help simulate more the environment inside a real building and allow for new experimentation possibilities (Figure 145). These cubicles do no longer have awnings attached.

Future scheduled experiments in concrete cubicles are meant for the study of the effect of the location of PCM on the outer or inner side of the insulation, so the optimal position of the material could be determined, and as no previous study of this nature has been performed. The interchangeability of the insulation and the plasterboard in these cubicles allows for this. Additionally, these cubicles may be employed to study the use of PCM in rehabilitation techniques, which may have a great impact on the energy consumption reduction without reducing the habitable space.

Figure 145. Current view of the concrete cubicles: outer view (left), and inner view with the interchangeable inner insulation and plasterboard (right).

Cubicles made of brick (Figure 146) will be employed to study the potential application of PCM in building inner linings, so they may absorb internal loads inside. The system could operate even during winter time in buildings with high internal loads such as computer rooms, meeting rooms, theatres, etc. The loads may be simulated by using simulation equipment inside the cubicles. It is also intended to study the behaviour of PCM under different operating modes of the heating, ventilating and air-conditioning systems (HVAC) in the building. PCM could be used to control and stabilize the inner temperature, and thus displace the time of utilization of the HVAC system towards the hours of lower energy consumption.

Other cubicles to be employed for experimentation with PCM and experiments to be performed are briefly described next.

First, there are 2 double height cubicles (2.4x2.4x5.1 m, inner dimensions), which feature a ventilated facade in the South wall and an interchangeable nogging between floors (Figure 147). The cubicles are made of the following layers: ventilated facade, cement mortar, alveolar brick (29 cm), and plastering.

It is intended to incorporate PCM into the ventilated facade, so the material will be able to store “cold” during the fresher hours of the day and/or at night, whether by natural or forced convection, and as this type of facade favours the circulation of air. The study might be useful since the ventilated facade system is starting to spread within modern construction systems.

Figure 146. Brick cubicles with macro-encapsulated PCM: outer view (left); detail of inner view (right).

Figure 147. Double height cubicles with an interchangeable nogging for experimentation with ventilated facades with PCM.

Second, there are 2 double width cubicles (5.25x2.7x2.7 m, inner dimensions), which consist of the following layers: cement mortar, alveolar brick (29 cm), and an interchangeable inner surface and inner wall that works as a separation between 2 environments (Figure 148).

Figure 148. Double width cubicles outer view.

The interchangeable items inside these cubicles provide the opportunity for testing the inclusion methods, behavior, and composition of different constructive solutions of using PCM in inner division systems (both pre-fabricated and manufactured in-situ), or even into building separation systems. The application of PCM in inner division systems may be useful to compensate for the heat losses and the energy consumption increase that take place when a controlled environment is next to a space with a different set-point or next to a space without temperature control, as PCM may stabilize the inner temperature without altering the energy consumption.

Last, there are 2 rammed earth cubicles, which consist of rammed earth and plastering; with one of them intended for featuring a macro-encapsulated PCM layer (0.7 cm) (Figure 149). In this case it is desired to study the incorporation of PCM into rammed earth, as it is a more sustainable and traditional construction material with a good thermal inertia. Previously, an analysis of the most suitable PCM, the constructive solution, and the encapsulation system in order to incorporate the PCM into the walls and the roof will be performed. Once this is done, the material will be added to the respective cubicle.

Figure 149. Outer view of the rammed earth cubicles.

Publications related to this work

Publications

Arce P., Medrano M., Gil A., Oró E. and Cabeza L.F. Overview of Thermal Energy Storage (TES) potential energy savings and climate change mitigation in Spain and Europe. Applied Energy. DOI: 10.1016/j.apenergy.2011.01.067

Arce P., Castellón C., Castell A. and Cabeza L.F. Use of microencapsulated PCM in buildings and the effect of adding awnings (in process).

Conferences

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2. Arce P., Medrano M. and Cabeza L.F. Spanish and European energy savings with increased use of thermal energy storage. Proceedings of EuroSun 2010, International Conference on Solar Heating, Cooling and Buildings. Graz (Austria). 2010.

This work has been a topic at the meetings of the Energy Conservation Through Energy Storage Implementing Agreement (ECES IA), from the International Energy Agency (IEA) in 2009.

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