Integration of thermal energy storage in buildings

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by

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The diurnal changes in temperature and solar radiation pose challenges for maintaining thermal comfort for people in buildings. Passive and energy-conserving buildings seek to manage the available thermal energy in order to maintain conditions for human comfort. This project investigates how heat storage strategies can be integrated in the building components as a strategy to reduce building energy consumption in hot climates. Specifically, it focuses on phase change materials that are integrated in the building structures and are used to substitute the thermal mass of a building in cases of lightweight construction.

A research protocol is performed on conventional structural materials that are used as integrated energy storage, their implementation and their effect on the nocturnal recharge of the envelope's thermal mass. Phase change materials that make use of the latent heat of a substance, storing and releasing the energy of the phase change of a substance are examined in detail. Several applications of phase change materials for temperature control of buildings are also investigated. During the second phase of this study, simulation research is performed to evaluate some of the investigated systems. Several solutions using new technologies and phase change materials are integrated on an experimental building and simulated using Energy Plus. Comparisons are made for the various simulated systems in terms of their performance and energy consumption. Last, but not least, an investigation of the economical feasibility of the examined systems is performed.

Phase change materials that have a melting point near room temperature can replace thermal mass without the bulk of large masonry structures. This can lead to a significant reduction of the building energy consumption, as well as reduction of conventional structure materials. These energy-storing building materials can reduce peaks in demand by creating a more even load-time characteristic. Furthermore, appropriate thermal storage can be used to achieve a significant reduction in equipment cycling frequency and thus achieve a noticeable increase in operating efficiency. The high initial cost of phase change materials can therefore be reclaimed by the savings in conventional materials, primary energy and peak load reduction, as well as increase in operation efficiency.

The building thermal mass, combined with smart materials and intelligent techniques of mass recharge can significantly affect the building energy consumption. These strategies can have a significant effect on hot-dry climates, as well as hot-humid climates when combined in the optimum way. This study aims at the development of a typology of integrated systems of thermal storage in the building envelope using smart materials in combination with mass recharge systems. An assessment of several phase change material applications is also achieved.

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1. Introduction

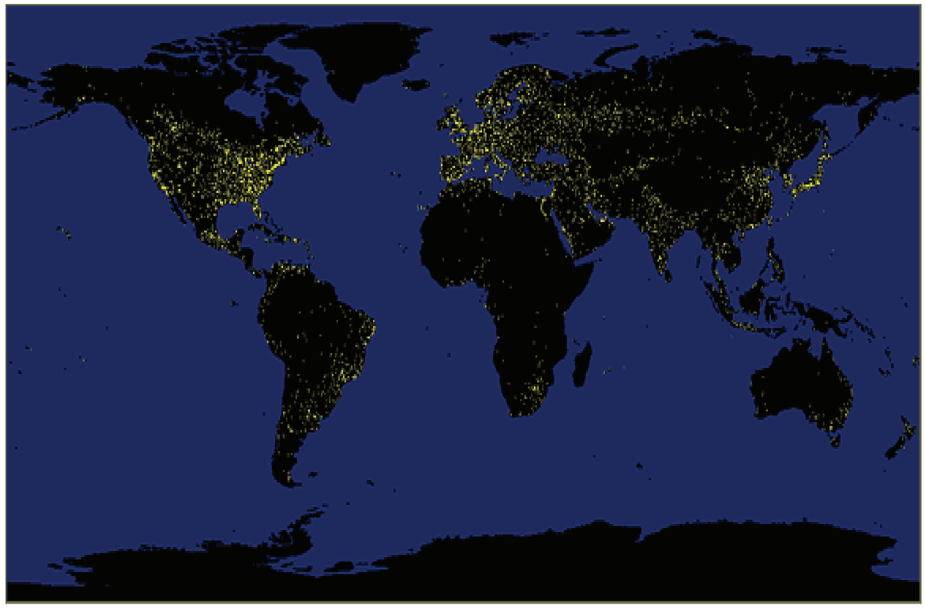


Fig. 01 World map at night

1.1. Motivation

An ever-increasing world population combined with a strong rise in energy demand has led to a significant environmental crisis that already shows its clear beginning. Fig. 02 shows a prognosis of global energy usage up to the year 2100 [1]. The question arises as to whether our planet possesses enough resources to satisfy such a demand for raw materials and primary energies. Fig. 03 shows the global primary energy consumption for the time span 1978-2005. This consumption, at present is fueled in essence by fossil energy sources and, to a very small degree, by hydro-electric power and nuclear energy. The terms energy change

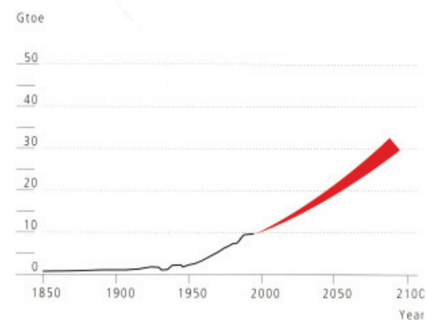


Fig. 02 Primary energy use

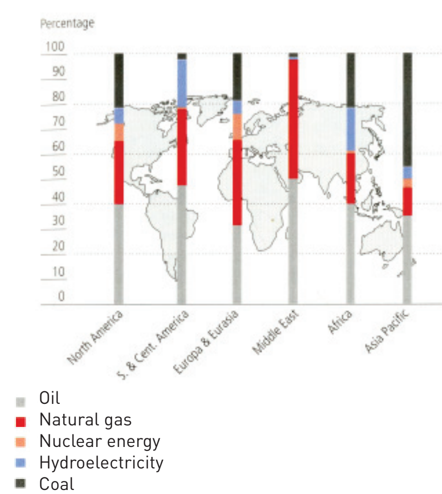


Fig. 03 Regional primary energy consumption

is being discussed controversially in public more and more often. The term is, however, somewhat ambiguous. Which elements of energy supply should be changed and to what direction? Is it a question of new sources of energy or only a question of sparing and efficient use of the sources of energy currently used? Usually the term energy change is associated with sustainability, but this explanation can sometimes be misleading. The use of nuclear power and fossil fuel is labeled as sustainable by the providers if they are a little safer or more efficient than before[2]. In real terms, energy change is an actual change from nuclear and fossil fuel sources to renewable ones.

The building sector, with its different trades, could have a significant role in the energy change if it took advantage of the opportunities offered by solar construction. Considering the building industry's claim on resources, the fact that it uses about 50% of all raw materials processed in the world makes the pressure for action more clear [2]. Almost 50% of the total invested capital in developed countries is tied up in the housing sector alone, approximately 70% in existing buildings [2]. Additionally, in 2006 the building sector in the USA was responsible for 38.9% of the total primary energy consumption; 20.9% for residential buildings and 18% for commercial buildings [3].

Architecture and building industry cannot remain aloof from a social development regarded as urgent. Building construction is an activity with long-lasting repercussions; with the current usual lifetime of buildings, a building that is designed and constructed today will probably be in use at the end of the oil and gas age[2]. In order to achieve sustainability in the building sector new objectives are necessary and they can be found in some diverse, but at the same time interrelated, fields of action; location and plot, energy, building materials and forms of construction, life cycle and adaptability .

The focus of this project is primarily the use of innovative materials that can improve the thermal comfort and the energy performance of a building. Energy and building materials and forms of construction are therefore the two fields mostly addressed in this study and thus explained in more detail.

Energy

Buildings fit for the future will exploit all the possibilities for energy efficiency, starting from choices of the site, shape and alignment of the building, choices of materials and insulation, technical equipment and many other parameters. There are significant opportunities in using site-specific, inexhaustible, renewable energy sources in buildings; geothermal power, solar energy, wind power, and much more besides. Drawing on these energy sources today generally requires higher investment, but the cost of running those offers an advantage that should not be underestimated. Based on this advantage, it is assumed that the future building market will be divided into two sectional markets; one that will still rely on fossil fuels and one of completely independent buildings [2].

Building materials and forms of construction

The use of materials for a building can be reduced considerably as a means of resource efficiency. Currently, the possibilities to use materials efficiently and to integrate building materials in closed cycles are only applied sporadically, yet legal rulings towards that direction are already in the planning stage[2]. This way it will be possible to develop lighter architecture and to be consistent in using reusable and renewable raw materials again and again. Additionally, using fewer materials leads to a decrease of the initial construction cost and thus increases the chance of being able to use high quality building materials. Furthermore, the use of high quality and innovative materials has a positive effect to the building performance and also reduces the danger of using substances that are damaging for homes or the environment [2].

1.2. Integration of thermal energy storage in buildings

The diurnal changes in temperature and solar radiation pose challenges for maintaining thermal comfort for people in buildings. Each day of the year offers the possibility of conditions that can be judged as too hot or too cold. Passive and energy-conserving buildings seek to manage the available thermal energy in order to maintain conditions for human comfort. Thermal mass is one of the powerful tools designers can use to achieve this goal and to control temperature and comfort. In buildings where solar gain is used as a heating strategy, diurnal effects can be managed by absorbing the heat of the winter sun during the day, while keeping the air temperature moderate, and releasing the heat at night to prevent the air temperature from plummeting[4]. On the other hand, in buildings where forced or natural ventilation is used as a cooling strategy, diurnal effects can be managed by mass which absorbs the heat of internal building loads during the summer's day and the day's accumulated heat is flushed by cool air each night[4]. Protection from the climate conditions in order to create a comfortable indoor environment is primarily a task of the building envelope.

The building skin is the dominant system in all subsystems of a building through which prevailing external conditions can be influenced and regulated to meet the comfort requirements of the user inside the building. It must fulfill a multitude of vital functions and is a principal factor in the energy consumption of a building[5]. The building skin has become increasingly important in recent years in the areas of research and development as a result of a growing awareness of environmentally sustainable forms of living. Research on new materials, manufacturing methods and facade components, as well as new forms of generating energy is vitally important[5]. Continued demand for high-performance and flexible facade systems will drive the development of the external skin from a static system to a dynamic multi-leaf and multi-layered building skin. The future façade will therefore take more functionality by integrating new technologies in more than one single layer of materials. A variety of control functions will join and complement the traditional function of shelter; the building skin will fulfill load bearing, insulating, sealing, ventilating and daylighting functions, as well as contributing to the energy generation. A vital function that the building envelope should fulfill is regulating thermal comfort, as well as energy gain and consumption of buildings.

This study focuses on the energy storage strategies integrated within the building envelope and the internal building components, by using its thermal mass, in order to regulate indoor temperature swings and enhance thermal comfort. Specifically, phase change materials that make use of the latent heat of a substance, storing and releasing the energy of the phase change of a substance are investigated. Phase change materials are used in building construction in order to substitute the thermal mass of a building in cases of lightweight construction. The aim of this study is therefore, in both the field of energy, and the field of building materials and forms of construction, since it focuses on the integration of smart materials that adapt to prevailing external conditions or even make use of them, in the building structures. More specifically, the objective of this study is to investigate the performance of phase change materials, and the energy balance equations that best describe their performance. Subsequently, this study focuses on the development of a model that will be inegrated into Energy Plus simulation software and evaluated with some experimental data. Finally, the evaluated model is used to identify the effect of different phase change materials, with different properties, in the building performance.

2. Thermal energy storage

The outer shell of a building defines the boundary between outside and inside. The history of the building envelope is dominated by features and attributes that govern appearance, proportion, choice of materials and cultural aspects. Its primary function, though, is to protect the building against wind precipitation and solar radiation. As comfort demands have grown, however, the building envelope has taken on a more complex, climate regulating function. Numerous demands are placed on the building envelope as the energy interface between the ambient conditions and the internal climate[2]. The heat capacity of the enclosing components is an important parameter for controlling the indoor temperature and reducing the temperature swings during the day.

The use of thermal energy storage for thermal applications has received much attention during the past decades; a variety of thermal energy storage techniques have been developed as industrial countries have become highly electrified. Such thermal energy storage systems have an enormous potential to make the use of thermal energy equipment more effective and for facilitating large scale energy substitutions from an economic perspective[6]. Many types of energy storage play an important role in energy conservation. Thermal storage in a building may be decisive for the reduction of cooling loads and the reduction of temperature increases. External surfaces of building envelopes show higher or lower temperatures not only as a function of ambient air temperature, intensity of solar radiation and the radiation physics of the envelope itself, but also dependent on their own thermal properties. Additionally, the transmission of external temperature fluctuations through a building envelope is a function of the capacity of the envelope and the building structures to store heat[1].

In this section, the basic methods of thermal energy storage systems and their basic principles are explained in detail. The differences and the use of each type are also analyzed.

Thermal energy storage (TES) systems, are commonly called heat and cold storage systems, allow the storage of energy to be used later. To be able to retrieve the energy later, the method of storage needs to be reversible. Thermal energy quantities differ in temperature. As the temperature of a substance increases, the energy content also increases[6]. The basic methods of thermal energy storage can be divided into physical and chemical processes. The physical methods of energy storage, which will be examined for the purposes of this study, are sensible and latent heat storage [7]. The selection of a thermal energy storage system mainly depends on the storage period required; diurnal or seasonal, economic viability, operating conditions and many more [6].

The basic principle is the same on all thermal energy storage applications. Energy is supplied to a storage system for removal and use at a later time. What mainly varies is the scale of the storage and the storage method used. A complete storage process involves at least three steps: charging, storing and discharging. In practical systems, some of the steps may occur simultaneously and each step may occur more than one in each storage cycle [6]. There are numerous criteria to evaluate thermal energy storage systems and applications, such as technical, environmental, economic, energetic, sizing, feasibility, integration and storage duration. Each of these should be considered carefully for a successful thermal energy storage application [6].

2.1. Sensible heat storage

Sensible heat storage is by far the most common thermal energy storage; heat that is transferred to the storage medium leads to a temperature increase. Sensible heat storage systems utilize the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of stored heat depends on the specific heat of the medium, the temperature change, and the amount of storage material [6]. Specifically, the ratio of stored heat ΔQ to the temperature ΔT is the heat capacity of the storage medium and it is expressed:

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_p(T_f - T_i)$$

Fig. 04 graphically shows the function between temperature and sensible heat stored by the material. Often the heat capacity is given with respect to the amount of material, the volume, or the mass and is called molar, volumetric or mass specific heat capacity, respectively. In order to be effective as a thermal mass, a material must have a high heat capacity, a moderate conductance, a moderate density, and a high emissivity[7]. Sensible heat storage is often used with solid materials, like stone, brick or concrete, or with liquids like water, as storage materials. Among common building materials, wood does not make a good thermal mass because it not only has a low heat storage potential, but is also not very conductive. Therefore, heat is not conducted readily to the material's interior to be stored for later use, but is rejected prematurely, as surface temperature rises, by radiation to cooler objects [4]. Steel, while having a seemingly high potential for heat storage, has two drawbacks—its low emissivity indicates that a large majority of the incident radiation is reflected, rather than absorbed and stored, and its high conductivity signals an ability to quickly transfer heat stored in the material's core to the surface for release to the environment, thus shortening the storage cycle to minutes rather than the hours needed

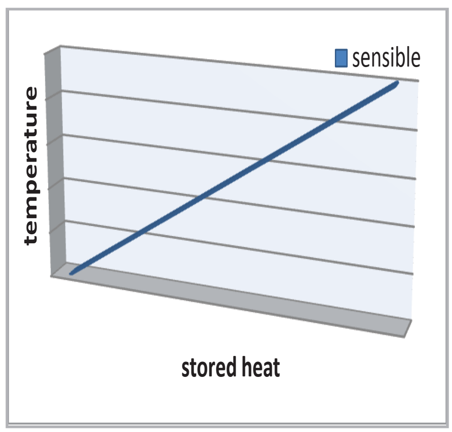


Fig. 04 Heat stored as sensible heat leads to a temperature increase when heat is stored

for diurnal thermal tempering[4]. Glass also seems to have a high potential for heat storage, but it is relatively transparent to near infrared radiation and reflective of far infrared radiation. Adding pigments to glass, especially blue and green, increases its ability to absorb radiation, which can become a thermal problem during the cooling season[4]. In the case of both steel and glass, the thickness required in order to act effectively as diurnal thermal mass is so large, heavy, and costly that it is not practical. Concrete and other masonry products are ideal, having a high capacity for heat storage, moderate conductance that allows heat to be transferred deep into the material for storage, high emissivity to allow absorption of more radiation than that which is reflected. When sized properly, concrete is effective in managing diurnal energy flow[4]. Conveniently, structural concrete and thermal mass share common dimensions, so there is no wasted mass when building a structure. Water is also effective as a thermal mass in that it has high potential for heat storage and it can be effective in a diurnal thermal management scheme. Water use is more problematical in that, unlike concrete, it serves no structural purpose in construction, but when stored in clear or translucent containers can provide light and/or views through the normally opaque thermal mass[4]. Gases have very low volumetric heat capacity and are therefore not used for sensible heat or cold storage[7]. Sometimes in order to effectively use the material thermal mass, a significant material thickness is required. Some common thermal energy storage materials and their properties are presented in figure 05.

Material	Density (kg/m³)	Specific heat (J/kgK)	Volumetric thermal capacity (10^6 J/m³K)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wod	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

Fig. 05 Thermal energy storage materials and their physical properties

2.2. Latent heat storage

Latent Heat Storage (LHS) is based on the heat absorption or release when a storage material

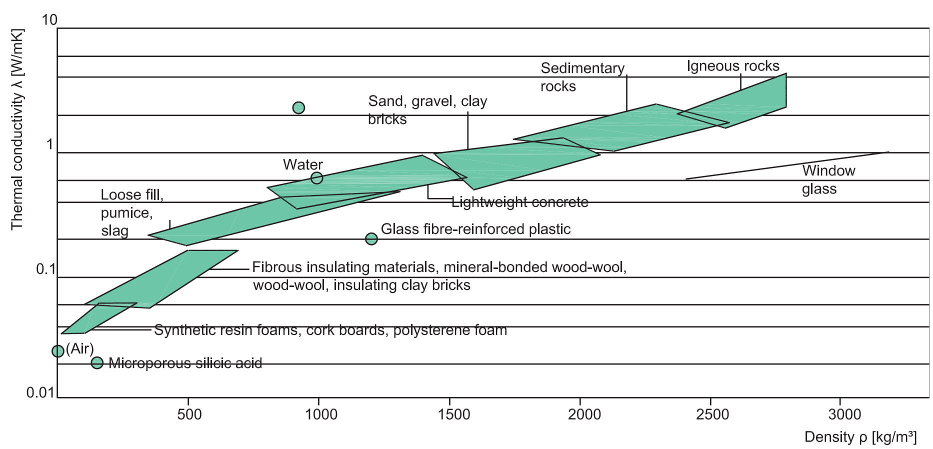


Fig. 06 Thermal conductivity of various materials in relation to their density

undergoes a phase change from solid to liquid or liquid to gas or vice–versa. The storage capacity of the LHS system with a PCM medium is given by

$$Q = m a_m \Delta h_m + \int_i^m mC_p dT + \int_m^f mC_p dT$$
$$= m\left[a_m \Delta h_m + C_{sp}(T_m - T_i) + C_{lp}(T_f - T_m)\right]$$

If heat is stored in latent form, the energy stored is largely associated with phase change in the storage medium. Latent heat storage provides a high energy storage density and has the capacity to store heat as latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the phase change materials [8]. Latent heat storage can be accomplished through solid-liquid, liquid-gas, solid-gas and solid-solid phase transformations, but the only two of practical interest are the solid-liquid and solid-solid. Solid-gas and liquid-gas transition have a higher latent heat of fusion but their large volume changes on phase transition are associated with containment problems and rule out their potential utility in thermal storage systems[9]. The phase change solid-liquid by melting and solidification can store large amounts of energy, if suitable material is selected. Materials with a solid-liquid phase change, which are suitable for heat or cold storage, are commonly referred to as latent heat storage materials or simply phase change materials.

Melting is characterized by a small volume change, usually less than 10%. If a container can fit the phase with the larger volume, usually the liquid, the pressure is not changed significantly and consequently melting and solidification of the storage material proceed at a constant temperature. During this process the material absorbs a certain amount of heat, known as melting enthalpy. Despite the heat input, the temperature of the material stays at a relatively constant temperature, even though phase change is taking place. We thus speak of latent heat having been taken up by the material. Equally, when the phase change process is reversed, that is from liquid to solid, the stored latent heat is released, again at a nearly constant temperature[9]. If the melting is completed, further transfer of heat results again in sensible heat storage [7]. Figure 07 graphically shows the function between temperature and latent heat stored by the materials. Because of the small volume change, the stored heat is equal to the enthalpy difference. The latent heat, that is the stored heat during the phase change process, is then calculated from the enthalpy difference between the solid and the liquid phase.

Some solid-solid phase changes have the same characteristics as solid-liquid phase changes, but usually do not pose a large phase change enthalpy. However, there are some exceptions that are used in a few applications [7]. In solid-solid transitions, heat is stored when the material is transformed from one crystalline to another. This transition usually has smaller volume changes than solid-liquid transition. Solid-solid phase change materials offer therefore the advantages of less rigorous container requirements and better design flexibility[9]. Most promising materials are organic solid solutions of pentae-

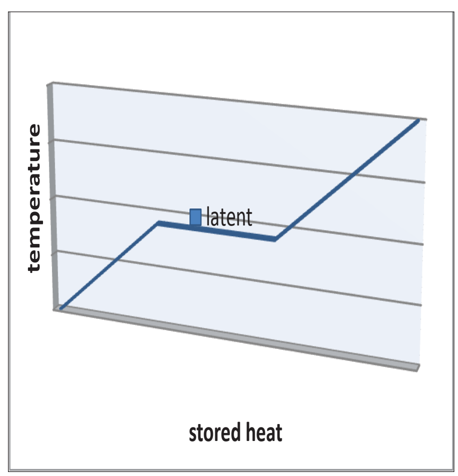


Fig. 07 Heat storage as latent heat for the case of solid-liquid phase change

rythritol, pentaglycerine, Li_2SO_4 and KHF_2[9].

The liquid-vapor phase change by evaporation and condensation usually has a large phase change enthalpy; however the process of evaporation strongly depends on some boundary conditions. In closed systems with constant volume, evaporation leads to a large increase of the vapor pressure. The temperature necessary for a further phase change also rises, as a consequence. Liquid-vapor phase change in a constant volume is therefore usually not effectively used for heat storage. In closed systems at constant pressure, evaporation leads to a large volume change. This is difficult to measure and thus also not applied for heat storage. Finally, open systems have the disadvantage of storage material being lost to the environment. In this case, to retrieve the stored heat from the storage, the storage material has to be retrieved from the environment. The only technically used material today is water[7].

Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing. However, many practical problems are encountered with latent heat storage due to its low conductivity, variation in thermo-physical properties under extended cycles, phase separation, sub-cooling, incongruent melting, volume change and high cost[9]. Phase separation occurs in a substance that consists of two or more components and instead of keeping the same homogeneous composition while melting, it separates into different phases one for each component. Sub-cooling or super-cooling occurs when a material does not solidify immediately upon cooling below the melting point, but starts crystalization after a temperature well below the melting point is reached. These problems should be investigated and technically resolved before latent heat storage can be widely used and they are further analyzed in section 3.3. The different types of phase change materials and their properties are investigated in more detail in section 3. Considering the solid-solid and the liquid-vapor phase change disadvantages, latent heat storage and phase change materials will refer to solid-liquid phase changes for the purposes of this study.

2.3. Potential applications of latent heat storage with solid-liquid phase change in buildings

Thermal energy storage for space heating and cooling is becoming increasingly important. Particularly, in extremely cold/hot areas, electrical energy consumption varies greatly during the day and the night partly due to domestic space heating and cooling. Such variation leads to a peak load period and an off-peak period, usually between midnight and early morning. In order to level the electrical load, different pricing policies have been implemented in several countries, including the USA. If the thermal energy of heat or coolness is provided and stored during the night and then released to the indoor ambient during the day, part or all peak loads can be shifted to the off-peak period. Thus, effective energy management and economic benefit is achieved[15].

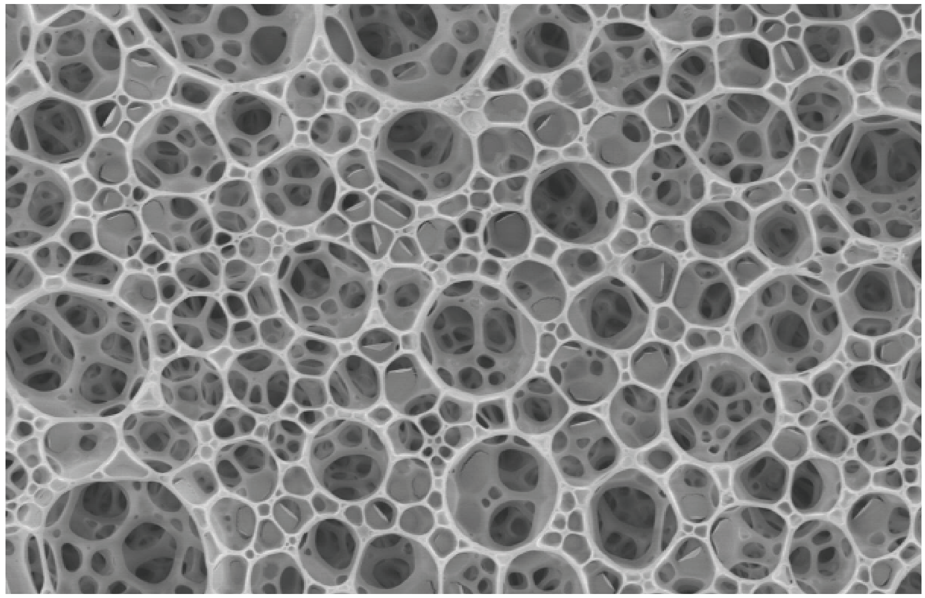
On the other hand, solar energy has potential for space heating for a building in winter in warm regions. However, solar radiation is a time-dependent energy source with an intermittent and variable character with the peak solar radiation occuring near noon[9]. These problems can be addressed by storing thermal energy during the day and releasing it to the indoor air when the room temperature falls at night. Also, cold can be collected and stored from ambient air by natural convection during the night in summer, and then released to the indoor ambient air during the hottest hours of the day. Thermal energy storage can provide a reservoir of storage to adapt the fluctuation of solar energy and, therefore, decrease the indoor temperature swings and improve the indoor comfort levels.

Based on these principles, the applications of latent heat thermal energy storage in buildings have the following advantages:

- the ability to narrow the gap between the peak and off-peak loads of electricity demand,
- the ability to save operative fees by shifting the electrical consumption from peak periods to off-peak periods since the cost of electricity at night is lower of that during the day,
- the ability to utilize solar energy continuously, storing it during the day and releasing it at night, particularly for space heating in winter thus improving the degree of thermal comfort and finally,
- the ability to use natural ventilation at night in summer, store the cold, and release it to decrease the room temperature at night, thus reducing the cooling load of air conditioning[15].

Potential fields of application for phase change materials can be found directly from the basic difference between sensible and latent heat storage. For simplification, latent heat storage systems can be divided into applications for temperature control and applications for storage and supply of heat or cold with small temperature change[7]. In applications for temperature control, the focus is on temperature regulation and not on the amount of heat supplied. In applications of heat or cold storage with high density the situation is the opposite. Applications for thermal inertia and thermal protection are the ones where phase change materials have achieved a higher penetration in the market[9].

3. Phase change materials



3.1. Requirements

The investigation of PCM for applications for heating and cooling in building mass has a long history. Already in the 1930s, M. Telkes investigated the use of PCM to store solar heat and use it for space heating. After the oil crisis in 1973 other researchers continued these investigations. However, applications were not yet economical. In the past decade, the situation has started to change because of rising energy prices. The energy demand to ensure indoor thermal comfort has increased worldwide, especially the demand for cooling and air-conditioning. People like to have room temperatures in a very narrow temperature range. In this case phase change materials can be used to control the temperature swings or for energy storage with high storage density. Especially in buildings with low thermal mass, the temperature can change significantly very quickly and therefore create an uncomfortable environment. Therefore, applications for heating and cooling in buildings are expected to have large market potential for phase change materials.

Phase Change Materials (PCM) are latent heat storage materials. The phase change is a heat-seeking (endothermic) process and therefore, the material absorbs heat. Phase change materials are organic compounds or inorganic salts with variable environmenportant criteria in selecting them, and they both depend on molecular effects. Therefore it is not surprising that materials within one material class behave similar [7]. Figure 08 shows the typical range of melting enthalpy and melting temperature of common material classes used as PCM. Probably thousands of materials and mixtures of two or more materials have been investigated for their use as phase change materials in the past decade. In 1983 Abhat gave a useful classification of the substances used for thermal energy storage shown in figure 09. As mentioned above, a majority of PCMs do not have all the required properties for an ideal thermal storage media. Therefore, one has to use the available materials and try to make up for the poor physical properties by an adequate system design. For example, metallic fins can be used to increase the thermal conductivity of PCMs, super-cooling may be suppressed by introducing a nucleating agent in the storage material, and incongruent melting can be inhibited by the use of a PCM of suitable thickness [9]. Phase change materials can be either inorganic or organic materials [13]. For their very different thermal and chemical behavior, the properties of each sub-group, which affect the design of latent heat storage systems using PCMs of that sub-group, are discussed in detail below [9].

3.2.1. Organic materials

Organic phase change materials, such as paraffins, fatty acids and sugar alcohols, have a number of characteristics which render them useful for latent heat storage in certain building elements. These materials cover the temperature range between 0°C-200°C. Due to the covalent bonds in organic materials, most of them are not stable in higher temperatures[7]. Their density is usually less than 103 kg/m^3, and thus smaller than the density of most inorganic materials like water and salt hydrates. The result is that organic materials, with the exception of sugar alcohols, have smaller melting enthalpies per volume than inorganic materials[7].

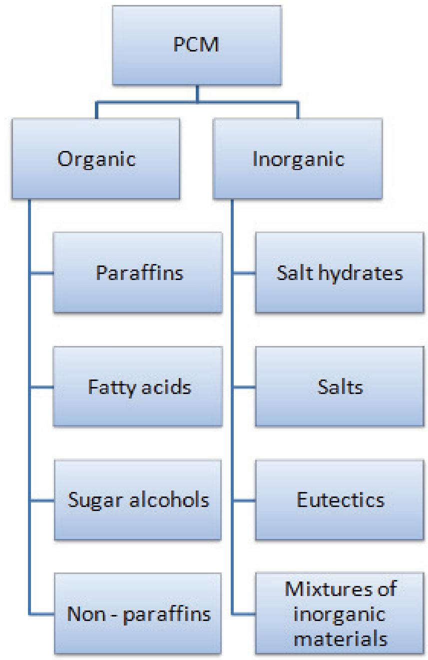


Fig. 08 Classification of phase change materials

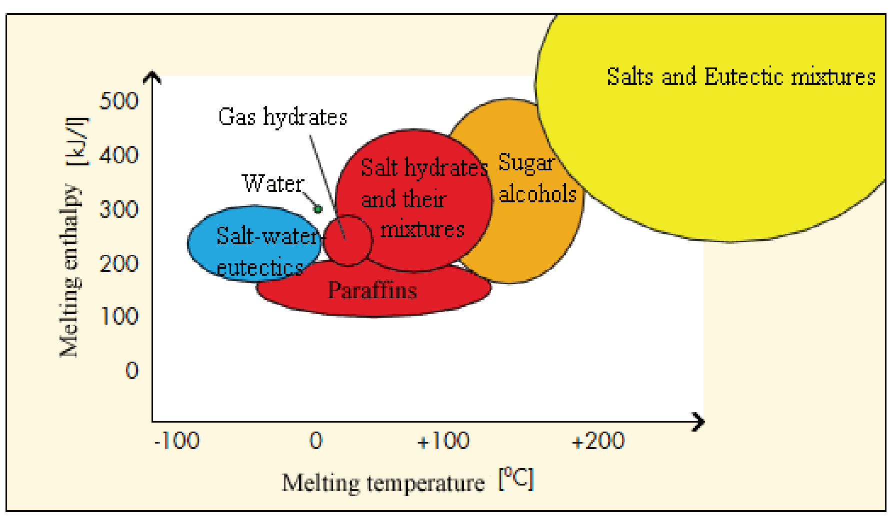


Fig. 09 Melting enthalpy of various phase change material groups in relation to their melting temperature

tal credentials, which store and release latent heat by changing chemical bonds through a phase transformation, unlike sensible heat storage materials which change structure mechanically[9]. Latent heat storage can be used in a wide temperature range. Energy balance simulations of a PCM wall suggest that the phase change material melting temperature should be related to the climate-specific optimal temperature to achieve maximum performance of the storage[6]. A non-optimal melting temperature significantly reduces the latent heat of the storage capacity; a 3°C difference from the optimal temperature causes a 50% loss of latent heat storage capacity[6]. A large number of PCMs are known to melt with a heat of fusion in any required range. There are a large number of phase change materials, which can be identified as PCMs from the point of view melting temperature and latent heat of fusion. However, except for the melting point in the operating range, a majority of PCMs do not satisfy the criteria required for an adequate storage media[9]. The PCM to be used in the design of thermal storage systems should accomplish desirable thermophysical, kinetics and chemical requirements.

Thermo-physical Requirements[9, 7]

- Phase change temperature in the desired operating temperature range.
- High latent heat of fusion per unit volume so that the required volume of the container to store a given amount of energy is less.
- High specific heat to provide for additional significant sensible heat storage.
- High thermal conductivity of both solid and liquid phases to assist the charging and discharging of energy of the storage systems.
- Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problem.
- Congruent melting of the PCM for a constant storage capacity of the material with each freezing/melting cycle.
- Reproducible phase change, also called cycling stability, in order to use the storage material as many times for storage and release of heat as required by the application.
- Little or no sub-cooling during freezing to assure that melting and solidification can proceed in a narrow temperature range.

Kinetic Requirements [9]

- High nucleation rate to avoid super-cooling of the liquid phase.
- High rate of crystal growth, so that the system can meet demands of heat recovery from the storage system.

Chemical Requirements[9]

- Chemical stability of the PCM to assure long lifetime of material if it is exposed to higher temperature, radiation, gases, etc.
- Complete reversible freeze / melt cycle.
- No degradation after a large number of freeze / melt cycles.
- Compatibility of the PCM with the construction materials to assure long lifetime of the vessel that contains the PCM, and of the surrounding materials in the case of leakage of the PCM
- Non-toxic, non-flammable, and non-explosive materials for safety.

Economic requirements

- Low price
- Large scale availability
- Good recyclability for environmental and economic reason

3.2. Classification of materials

The melting temperature and the melting enthalpy of phase change materials are the two most im-

They are more chemically stable than inorganic substances, they melt congruently and super-cooling does not pose as a significant problem[13]. Moreover, they have been found to be compatible with and suitable for absorption into various building materials[13]. Although the initial cost of organic PCMs is higher than that of the inorganic type, the installed cost is competitive[13].

• Paraffins
Paraffin is the technical name for an alcane, but it is especially used for linear alcanes with the general formula C_nH_{2n+2}. Little information is given for their crystal structure[7]. The normal paraffins of type C_nH_{2n+2} are a family of saturated hydrocarbons with very similar properties. Paraffins between C_5 and C_{15} are liquids, and the rest are waxy solids[9]. Pure alcanes are rather expensive. Commercial paraffin is obtained from petroleum distillation and it is a combination of different hydrocarbons[7]. These mixtures show a lower melting range and a lower heat of fusion than the pure alcanes. In general, the longer the average length of the hydrocarbon chain, the higher the melting temperature and heat of fusion[7]. Paraffin wax is the most-used commercial organic heat storage phase change material. It consists of mainly straight chain hydrocarbons that have melting temperatures ranging from 23 to 67 °C[14]. Paraffins are easily available from many manufacturers and are usually more expensive than salt hydrates[9]. Paraffins show good storage density with respect to mass and melt and solidify congruently with little or no super-cooling[7]. They are chemically stable, although they present slow oxidation when exposed to oxygen; therefore, they require closed containers[9]. Their volume increase upon melting is in the order of 10% of their volume; this is similar to that of many inorganic materials, but less critical as paraffins are softer and therefore build up smaller forces upon expansion[7]. Paraffins are insoluble in water as they are water repellent. Paraffin waxes are safe and non-reactive; they do not react with most common chemical reagents[15]. The compatibility of paraffins with metal is very good and they can easily be incorporated into heat storage systems[7]. Care should be taken however when using plastic containers, as paraffins have a tendency to infiltrate and soften some plastics[9].

Paraffins, on the other hand, have comparatively low thermal conductivity in their solid state. This presents a problem when high heat transfer rates are required during the freezing cycle[9]. This problem can be decreased using finned containers and metallic fillers, or through a combination of latent/ sensible storage systems[9]. Also, aluminum honeycombs have been found to improve system performance[9]. Paraffins, unlike salt hydrates, do not have sharp, well-defined melting points and therefore sometimes decrease heat storage capacity[16]. Paraffins are flammable, but this can be easily changed by a proper container[16]. At elevated temperatures, paraffin bonds can crack and the resulting short chain molecules evaporate. Paraffins are combustible and people often conclude that paraffins burn easily. The fact that candles do not burn as a whole, shows that this conclusion is not correct[7].

• Fatty acids
Fatty acids are characterized by the chemical formula $CH_3(CH_2)_{2n}COOH$. Their melting enthalpy is similar to that of paraffins and their melting temperature increases with the length of the molecule[7]. Their characteristics are generally similar to paraffins. A difference to paraffins can be expected in the compatibility of fatty acids to metals, due to their acid character[7]. Fatty acids are stable upon cycling; because they consist of only one component there cannot be phase separation. Like paraffins, fatty

acids also show little or no supercooling and have a low thermal conductivity[7]. Their advantage of sharper phase transformations is offset by the disadvantage of being about two or three times the cost of paraffins[15]. They are also mildly corrosive. Different fatty acids can be mixed to design phase change materials with different melting temperature than pure fatty acids; the combination of fatty acids to obtain melting temperatures ranging from 20–30 °C with an accuracy of ± 0.5 °C can be promising[9]. This would allow a designer to select the optimum operating temperature to obtain the maximum performance of a heat storage system.

• Sugar alcohols
Sugar alcohols are a hydrogenated form of a carbohydrate. The general chemical structure is $HOCH_2[CH(OH)]_nCH_2OH$. Different forms are obtained depending on the orientation of the OH groups. Sugar alcohols are a rather new material; therefore little general information is available. They have melting temperatures in the 90°C to 200°C range and their specific melting enthalpies are comparatively high in most cases[7]. Additionally, sugar alcohols have high density which results to very high volume specific melting enthalpies. In contrast to many other organic materials, sugar alcohols show some supercooling[7].

• Non-paraffins
This is the largest category of candidate materials for latent heat storage. There is a number of esters, fatty acids, alcohols, and glycols suitable for energy storage that are further subgroups of fatty acids and other non-paraffin organics. The non-paraffin organics are the most numerous of the phase change materials, with highly varied properties. Each of these materials will have its own properties, unlike the paraffins, which have very similar properties. These materials are flammable and should not be exposed to excessively high temperature, flames or oxidizing agents[9].

3.2.2. Inorganic materials
Early efforts in the development of latent heat storage materials used inorganic phase change materials. These materials are salt hydrates, salts or mixtures and they cover a wide temperature range. These materials have some attractive properties including high latent heat values, they are not flammable and their high water content means that they are inexpensive and readily available. Compared to organic materials, inorganic materials usually have similar enthalpies per mass, but higher ones per volume due to their high density [7]. Their main disadvantage is material compatibility with metals, since corrosion can be developed in some combinations of phase change materials with metals [7]. Some other unsuitable characteristics include instability, improper re-solidification, and a tendency to super-cool[13]. Finally, they have been deemed unsuitable for impregnation into porous building materials, because they require containment[13].

• Salt hydrates
Salt hydrates are the oldest and most studied heat storage phase change materials[9]. They consist of a salt and water, which combine in a crystalline matrix when the material solidifies. They can be used alone or in eutectic mixtures [14]. Salt hydrates often have comparatively high storage density with respect to mass, but even more with respect to volume due to their high density[7]. There are many different materials that have melting ranges of 5 to 130 °C [7]. Salt hydrates are the most important group of phase change materials, and have been extensively studied for their use in latent heat thermal energy storage systems. Three types of behavior of the melted salts can be identified: congruent, incongruent and semi-congruent melting. Congru-

ent melting occurs when the anhydrous salt is completely soluble in its water of hydration at the melting temperature. Incongruent melting occurs when the salt is not entirely soluble in its water of hydration at the melting point. Semi-congruent melting occurs when the liquid and solid phases are in equilibrium during a phase transition[9].

Some of their advantages include low cost and easy availability, which makes them attractive for heat storage applications[9]. Salt hydrates have a sharp melting point and high thermal conductivity when compared with other heat storage phase change materials. This can increase heat transfer in and out of the storage unit. They have a high heat of fusion, which decreases the needed size of the storage system. Salt hydrates also show a lower volume change than other phase change materials. This makes it easy to design a container to accommodate volume change.

Among the disadvantages of salt hydrates is segregation, which is a formation of other hydrates or dehydrated salts that tend to settle out and reduce the active volume available for heat storage. This problem can be eliminated to a certain extent by using gelled or thickened mixtures, though this process negatively influences the heat storage characteristics of the mixture and the mixture still degrades with time[14]. Because salt hydrates consist of several components, at least one salt and water, they can potentially separate into different phases and thus show problems with cycling stability[7]. Salt hydrates show super-cooling because they do not start to crystallize at the freezing point of other phase change materials. This can be avoided using suitable nucleating materials to start crystal growth in the storage media. Therefore, it is necessary to design containers to contain the material without letting water out. Another problem of salt hydrates is their tendency to cause corrosion in metal containers, which are commonly used in thermal storage systems[14]. Compatibility of a phase change material and its container should always be checked before use.

• Salts

Different salts can be used as phase change materials for temperatures above 150°C. Because the melting enthalpy rises proportional to the melting temperature given in K, salts with high melting temperatures show high melting enthalpy[7]. The thermal conductivity of salts can be quite good. Super-cooling is not more than a few K and their vapor pressure is very low. The volume change from solid to liquid can be up to 10% volume. Many of the salts are chemically stable; however carbonates and nitrates can decompose under unsuitable conditions. A salt always consists of two components, so theoretically phase separation is a potential problem. However, unless the rare case of two different salt compositions exist, phase separation is not possible. Regarding the compatibility to other materials, salts can be corrosive to metals.

• Eutectics

A eutectic is a minimum melting composition of two or more components, each of which melts and freezes congruently, forming a mixture of the component crystals during crystallization[9]. Therefore none of the phases can sink down due to a different density. Eutectics nearly always melt and freeze without segregation because they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting, both components liquefy simultaneously, again with separation unlikely. Eutectic compositions show a melting temperature and good storage density[7]. Eutectic water-salt solutions have melting temperatures below 0°C, because the addition of salt reduces the melting temperature and usually good storage density[7]. The thermal conductivity of eutectic water-salt solutions is similar to that of water and they can super-cool like water, by several K or more. Water-salt solutions can be very stable, but can cause corrosion to other materials like metals. Compared to water, the addition of salts usually makes the problem worse. Most of the salt solutions are rather safe, but should no leak in large amounts. They are usually cheap, less than 1€/kg, and therefore the basis for many commercial PCM used in large scale applications[7].

• Mixtures of inorganic materials
In order to get materials with different melting temperature or improved properties, mixtures of inorganic materials have been tested. For example, small amounts of NaCl and KCl are added to $CaCl_2{\cdot}6H_2O$ to achieve a better melting behavior without significant change of the melting temperature[7]. In another example, the combination of $Mg(NO_3)_2{\cdot}6H_2O$ and $MgCl_2{\cdot}6H_2O$ results in a much lower melting temperature of the mixture compared to the base materials of the mixtures[7]. The search of mixtures of different materials is usually done experimentally; mixtures with different compositions are initially prepared and their melting temperature and enthalpy are determined, subsequently the composition is optimized in a second set of experiments. This procedure involves a lot of work and it is very time consuming. Another way to determine the mixture properties is to calculate the liquidus curves of salt-hydrates and multi component systems. In this case, only a few experiments should be performed[7].

3.2.3. Clathrates
A class of materials that is not generally organic or inorganic is the clathrates. Clathrates are crystalline structures where molecules of one type are enclosed in the crystal lattice of another[7]. Clathrates do not have a stochiometric composition; instead, there is an ideal composition when all free lattice positions are occupied. When the crystal lattice is formed by water, the clathrate is called a clathrate hydrate and the crystal structure of the solid clathrate hydrate is a modification of the crystal structure of ice[7]. The molecules of the added substance are enclosed within free spaces in the crystal lattice of the ice and thereby stabilize it and raise the melting temperature. When the enclosed molecules are from a gas and the surrounding crystal lattice is water, the clathrate is called a gas hydrate[7]. Gas hydrates have melting temperatures in the range from 0 °C to 30 °C, with the enclosed molecules being noble gases, chlorofluorocarbons, or straight chain hydrocarbons[7]. The best-

	Advantages	Disadvantages
Organic materials	Simple to use Non-corrosive No supercooling No nucleating agent Recyclable	More expensive Lower latent heat density Often quite broad melting range Can be combustible Some react to concrete
Inorganic materials	Generally cheap Good latent heat density Higher thermal conductivity Well defined phase change temperature Non-flammable Biodegradable & recyclable	Need careful preparation Need additive to stabilize Prone to supercooling Can be corrosive to metals

Fig. 10 Presentation of advantages and disadvantages of organic and inorganic materials

known gas hydrate is methane hydrate. The gas molecules in a gas hydrate usually dissolve only at higher pressures in water and thus gas hydrates are often not stable at ambient pressure[7]. This makes them difficult to use as phase change materials. Several exceptions however exist where the solubility in water is good and stability at ambient pressure is given[7]. Other examples use special unpolar liquids or organic salts instead of gases.

3.3. Typical phase change material problems and possible solutions

3.3.1. Phase separation

When a pure substance with only one component, like water, is heated above its melting temperature and thereby melted, it will have the same homogeneous composition in the liquid as before in the solid. When the material is solidified again by cooling it below the melting temperature, the solid will again be of the same homogeneous composition throughout and the same phase change enthalpy and melting temperature is observed at any place. Such a material is said to melt congruently. When a substance consists of two or more components, the system now behaves very different. A salt-water solution with a composition of 10 wt.% salt and 90 wt.% of water is a homogeneous liquid above -4 °C. When cooled below -4 °C, water freezes out of the solution and consequently the remaining solution has higher salt concentration. This means the substance separates into two different phases, one with only water, and a second one with a higher salt concentration than initially. Due to gravitation, the phase with higher density will sink to the bottom and the one with lower density to the top. This phenomenon is called phase separation or decomposition, because the original composition is changed. When the temperature is reduced further, more water freezes out, and the salt concentration in the remaining liquid increases. For different initial compositions, the temperature where water starts to freeze out is also different: the higher the salt concentration, the lower the temperature where water starts to freeze out of the solution[7].

If phase separation has occurred, artificial mixing can be used to solve the problem. The PCM is allowed to separate on macroscopic distances, but instead of waiting for diffusion to homogenize the PCM, the faster process of mixing is used[7]. This approach has been used successfully with many salt hydrates. Its main disadvantage is the necessary equipment. An easy approach on the level of the material is to add additional water to the salt hydrate[7]. The drawbacks of this method are that due to the addition of water, the overall storage density is reduced, and that the melting range becomes broader. A second way to reduce the problem of phase separation on the material level is by using diffusion processes for homogenization. Diffusion is however only efficient on small scales, because the speed of diffusion processes goes with the square of the distance. Therefore, this approach can work only if the PCM separates only on small distances. One way to limit the distance that the phases can separate to the scale of several mm is to use shallow containers for the PCM. But often this is not sufficient. To reduce the distance that the phases can separate down to a microscopic scale, gelling can be used. In gelling, a three dimensional network is formed within the bulk of the PCM. This network holds the different phases of the PCM together on a microscopic scale. The gel can be formed by a polymer, for example. The same effect as with gelling can be achieved if the PCM is infiltrated into a micro porous material[7]. Another way to reduce the distance that the phases can separate is by thickening the PCM. Thickening means the addition of a material to the PCM to increases its viscosity. Due to the high viscosity, different phases cannot separate far until finally the whole PCM is solid[7]. There is a third way to reduce phase separation on the material level; it is probably the best but also most complicated one. This way is changing the phase diagram of the PCM itself by the addition of other materials until congruent melting results[7].

3.3.2. Supercooling

Many PCM do not solidify immediately upon cooling below the melting temperature, but start crystallization only after a temperature well below the melting temperature is reached. This effect is called subcooling or supercooling. During the supply of heat, there is no difference whether a PCM shows subcooling or not. During extraction of heat however, the latent heat is not released when the melting temperature is reached due to subcooling. The effect of subcooling makes it necessary to reduce the temperature well below the phase change temperature to start crystallization and to release the latent heat stored in the material. If nucleation does not happen at all, the latent heat is not released at all and the material only stores sensible heat. In technical applications of PCM, subcooling can therefore be a serious problem[7].

The most common approach to get rid of subcooling on the level of the PCM is to add special additives, also called nucleator, to the PCM to cause heterogeneous nucleation. Nucleators have been developed for most well investigated PCM, and reduce subcooling typically to a few K. Most nucleators are materials with a similar crystal structure as the solid PCM to allow the solid phase of the PCM to grow on their surface, but a higher melting temperature to avoid deactivation when the PCM is melted. The problem with this method is that usually a similar crystal structure also means a similar melting temperature. Therefore, many nucleators are only stable up to a temperature 10 K to 20 K above the melting temperature of the PCM. There are also other nucleators where the mechanism is completely unknown. The fact that there is still no reliable theoretical approach makes the search for a new nucleator time consuming[7].

3.3.3. Material leakage

In most cases, except for some applications of water-ice, the PCM needs to be encapsulated in order to hold the liquid phase of the PCM, and to avoid contact of the PCM with the environment, which change the composition of the PCM. Additionallly, the surface of the encapsulation acts as heat transfer surface. In some cases, the encapsulation also serves as a construction element, which means it adds mechanical

Problems	Solutions
Phase separation	Artificial mixing Addition of water to the salt hydrate Diffusion processes for homogenization Gelling or thickening of material
Supercooling	Add special additives, nucleators, to cause heterogeneous nucleation
Material leakage & low heat transfer	Encapsulation • macro-encapsulation (ml-l of material in container) • micro-encapsulation (1µm – 1000µm of material in container)
Low mechanical stability & low thermal conductivity	Create composite materials • embedding another material into PCM • embedding PCM into matrix of another material

Fig. 11 Presentation of possible problems and solutions of PCMs

stability. Encapsulations are usually classified by their size into macro- and microencapsulation[7]. Macroencapsulation means filling the PCM in a macroscopic containment that fit amounts from several ml up to several liters. These are often containers and bags made of metal or plastic. Macroencapsulation is very common because such containers or bags are available in a large variety already from other applications. In that case, macroencapsulation is mainly done to hold the liquid PCM and to prevent changes in its composition due to contact with the environment. If the container is rigid enough, the encapsulation can also add mechanical stability to a system. Microencapsulation is the encapsulation of solid or liquid particles of 1 μm to 1000 μm diameter with a solid shell. Physical processes used in microencapsulation are spray drying, centrifugal and fluidized bed processes, or coating processes[7]. Besides the containment of the liquid phase, other advantage of microencapsulation regarding PCM are the improvement of heat transfer to the surrounding because of the large surface to volume ratio of the capsules, and the improvement in cycling stability since phase separation is restricted to microscopic distances[7]. A potential drawback of microencapsulation is that the chance of supercooling increases.

3.4. Commercial phase change materials

Many substances have been studied as potential phase change materials, but only a few of them have been commercialised as so. Often a potential phase change material cannot be sold as pure phase change material, because handling of the pure material is critical, for example with respect with its water content. In this case, materials are sold in an encampsulated form[7]. Pure commercial phase change materials and composites materials have to fulfill harder requirements in their development than encapsulated materials[7]. It is usually necessary that the main properties of the phase change materials products are well documented. For this reason, a standard to control product quality has been developed by the ZAE Bayern and the FhG-ISE recently. The objective is to guarantee the quality of the storage materials themselves and objects which contain the storage materials. After completion of the work, the RAL quality mark was introduced in April 2007. The main quality criteria to be monitored are the stored amount of heat as a function of temperature, the cyclic reproducibility of the storage process and the thermal conductivity of the storage materials, which is important in determining the charging and discharging time for the storage unit[17].

The different types of commercial phase change materials are analysed in this section, follwed with some specific examples of materials. The number of commercial PCM, PCM composite materials and encapsulated PCM is growing from year to year, it is therefore impossible to give a complete description of all the available commercial products.

3.4.1. Pure PCM

Currently, more than 50 PCMs are commercially available with a wide range of phase change temperature and enthalpy per volume and mass. Most commercial phase change materials are based on materials from the material classes of the salt hydrates, paraffins and eutectic water-salt solutions. They are however not identical to these materials. The composition of salt hydrates is often changed; a nucleator is added, the material is gelled or thickened or the PCM is a mixture of different base materials. Commercial grade paraffins usually contain a mixture of different alcanes because pure alcanes are

expensive.
Many companies are engaged in the development of raw PCMs for several applications, among which Climator, Cristopia, EPS Ltd., Mitsubishi Chemical Corporation and Rubitherm GmbH.

The price of commercial PCMs is typically in the range from 0,5€/kgto 10€/kg, which has a large influence on the economics of phase change material applications. For a rough estimate, an energy price of 0.05€/kWh for heat can be assumed[7]. Additional investment cost for the storage container and heat exchanger should also be taken under account. Seasonal storage using pure PCM is therefore far from being economic at current prices for fosil fuels. To be competitve in energy systems, one should charge and discharge a storage daily, or in even short periods[7]. Latent heat paraffins and salt hydrates are shown in Fig. 12 and Fig. 13, respectively.

3.4.2. PCM composite materials
A composite material is a material that is composed of several different materials, usually to improve a property of a material or to combine properties of different materials. In case of phase change materials, a PCM composite material is produced to improve at least one of the PCM properties or to improve the heat storage capacity of another material. In order to form a PCM composite material, PCM is embedded in a matrix of another material or another material is embedded into the PCM.

One example of PCM composite materials is the use of composite materials with paraffin as PCM, mainly to improve handling and integration of the material into a product. A set of different materials have been developed and commercialised by Rubitherm Technologies GmbH in the form of latent heat powder, latent heat granulate and latent heat compound, shown in Fig. 14, Fig. 15 and Fig. 16, respectively. Latent heat powder is a fine, dry powder that is based on a composition of latent heat storage material and an ecologically friendly silica (Fig. 14).[18] With its high PCM content of approximately 60 %, the RUBITHERM® latent heat powder offers a high heat storage capacity at a relatively constant temperature level during the phase change process. The powder form of this bound PCM allows for filling of containers of any conceivable geometry.The RUBITHERM® latent heat powder is non-toxic.[18] The latent heat granulate is a new generation of ecological heat storage granulate in which approx. 35% weight of a phase change material is bound (Fig. 15).[18] Various melting temperatures, as defined by the operating temperature of the application, as well as different granulate particle sizes are available. Presently, the major applications for RUBITHERM® latent heat granulate are electric and water based underfloor heating systems and latent heat storage

Fig. 12 Latent heat paraffins

Fig. 13 Salt hydrates

elements for food transport.[18] One of the many potential applications is the use as a passive heat storage material, effectively adding thermal mass to buildings constructed of lightweight materials. RUBITHERM®latent heat compound is a latent heat compound with a very high content of PCM and therefore high storge capacity (Fig. 16).[17] Depending on the melting temperature of the PCM bound in the compound, the product is more or less flexible and white in colour when the PCM is in its solid state. When the product is heated up causing the PCM to melt, the material becomes transparent and very flexible. All the RUBITHERM® bound phase change materials offer the advantage of maintaining their macroscopic solid form during phase change. The PCM is bound within a secondary supporting structure which ensures that the PCM, when in the liquid form, does not leak out of the granulate. The result is that the bound PCM is always a "dry" solid product and liquid handling is eliminated.
For many applications therefore, large quantities of thermal energy can be stored and released at a relatively constant temperature without any volume changes, even when limited volumes and low operating temperature differences are applicable.[18]

Materials that come as boards or plates constitute another example of PCM composites that are used to improve handling and applicability of phase change materials. DuPont™ Energain® comes in aluminiumlaminated panels, bordered at the edge with aluminium tape, which contain a copolymer and paraffi n wax compound, with about 60% weight of paraffin (Fig. 17).[19] The panels are installed on the interior walls and ceilings of a building, behind the plasterboard lining, together with a mechanical ventilation system. The wax in DuPont™ Energain® thermal mass panels melts and solidifies at around 22°C and 18°C respectively.[19]

If the thermal conductivity of a material is not large enough, it is a common strategy to form a composite with a highly conductive material. In many applications, metal or graphite is used as additive in the form of fibers or powders. Besides the high thermal conductivity of graphite, its stability to high temperatures and corrosive environments is a big advantage compared to metals. PCM-graphite composites are therefore used to increase the thermal conductivity of phase change materials, especially when applied in combination with salts, salt hydrates, water or water-salt solutions. PCM-

Fig. 14   Rubitherm GmbH powder

Fig. 15   Rubitherm GmbH granulate

Fig. 16   Rubitherm GmbH compound

graphite compositions in different forms, granules and powder made of pure graphite, graphite foils and sheets of widely varying densities, PCM-graphite compound materials and lightweight panels, are available under the brand name ECOPHIT from SGL TECHNOLOGIES GmbH. The base material for ECOPHIT is expanded graphite. This is manufactured from natural graphite flakes with well-orderd crystalline structures. During the production the granite flakes increase in volume by a factor of 200 to 400; the natural graphite expands to firm a loose-textured vermicular structure of pure graphite, which can be further processed as required. ECOPHIT is a material with excellent thermal conductivity.[20] By using PCM with graphite contents, typically 10% volume of graphite, the conductivity can be enhanced by a factor of up to 100. ECOPHIT lightweight construction paneling is a homogeneous, binder-free material made from expanded natural graphite (Fig. 18).[20]It is thermally and electrically conductive, light, compressible and non-flammable. Because of the graphite's high thermal conductivity, cooling ceilings typically fitted with such systems provide excellent heat distribution acros the surface[20].

3.4.3. Encapsulated PCM

As already mentioned, in most cases phase change materials need to be encapsulated to prevent leakage and to improve heat transfer. Encapsulations are classified according to their size as macroencapsulation and microencapsulation. Macroencapsulation is by far the most widely used type of encapsulation, however microencapsulated PCMs are also produced on the industrial scale. When encapsulating phase change materials, several aspects should be taken into account. Initially, the material of the container wall must be compatible with the PCM. Subsequently, taking into account the selected wall material, the container wall has to be sufficiently thick to assure the necessary diffusion tightness. Finally, the encapsulation must be designed in a way that it is able to cope with the mechanical stress on the container walls caused by the volume change of the PCM.[7]

- Macroencapsulation

To encapsulate salt hydrates, usually plastic containers are selected because of material compatibility. Plastics are not corroded by salt hydrates, however attention has to be paid to the water tightnes of the material of the capsule wall. Plastic encapsulations can also be used for organic PCM, but the combination

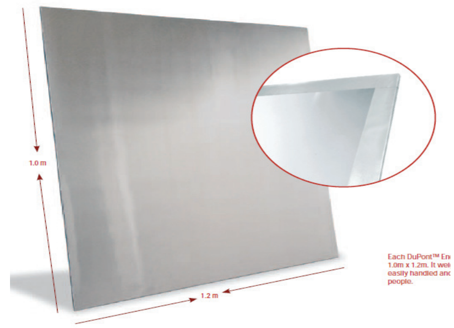


Fig. 17 Dupond Energygain panel

Fig. 18 ECOPHIT lightweight panels

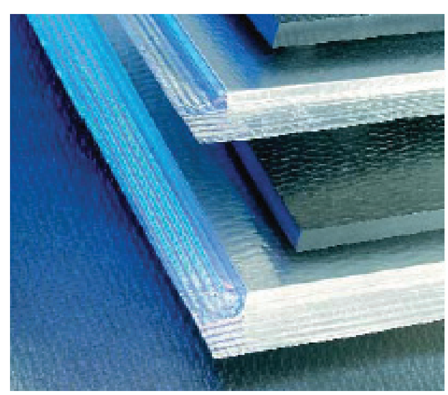


Fig. 19 PCM graphite compound from BASF

of PCM and encapsulation material has to be chosen very carefully because organic materials may soften plastics. Many companies produce a selection of different encapsulations. Because plastic containers can nowadays be produced easily in a high variety of shapes, there are few restrictions on the geometry of the encapsulation. The PCMs are integrated into open-pored, porous granulates with millimetric grain size and subsequently encapsulated to prevent the PCM from leaking when in liquid state. The granulate encapsulated in this manner can be integrated into construction boards. Such macroencapsulation is relatively cost-efficient; paraffin as well as salt hydrates can be used. Typical examples are panels from Dorken and PCP, as well as flat containers from Kissmann. Another example of macroencapsulation are the spherical nodules from Cristopia[4]. They are blow moulded from a proprietary blend of polyolefins and filled with PCM (Fig. 20). A range of PCMs allow thermal energy to be stored at temperatures between -33°C and +27°C.[21] Another form of macroencapsulation constitutes of plastic sheets that form small containments for the PCM and are sealed with a plastic foil. Such encapsulations called capsule stripes or dimple sheets are useful to cover large surfaces and can be manufactured on a fully automated production line.
It is of course also possible to use only foils as a wall material, the resulting product is PCM encapsulated in bags.
If good heat transfer is important, the low thermal conductivity of container walls made of plastic can be a problem. An option is to chose containers with metal walls. Metal walls also have the advantage of higher mechanical stability if a sufficient wall thickness is chosen. It is however necessary to select a suitable metal which is not corroded by the PCM. This selection should also take into account that depending on the metal different options and restrictions for shaping or welding. A coated aluminum plate filled with from Rubitherm Technologies GmbH is shown in Fig. 21.

- Microencapsulation

Microencapsulation of PCM is technically feasible today only for organic materials and it is currently applied on commercial scale only to materials that are not soluble in water.[7] Commercial products seem to use exclusively paraffins. Fig. 22 shows commercial microencapsulated paraffin, with a typical capsule diameter in the 2-20 μm range, produced by the company BASF. The microencapsulated PCM is available as fluid dispersion or as dried powder.[22] For integration into the boards, the micro-encapsulated latent heat storage material can be stabilised in large packages and sealed (Fig. 22).[22] In the form of the gypsum wallboard, Knauf PCM Smart- Board®, Micronal® PCM can be quickly and simply integrated into innovative building concepts in dry construction (Fig. 23).[22] Every square meter of

Fig. 20 Cristopia modules

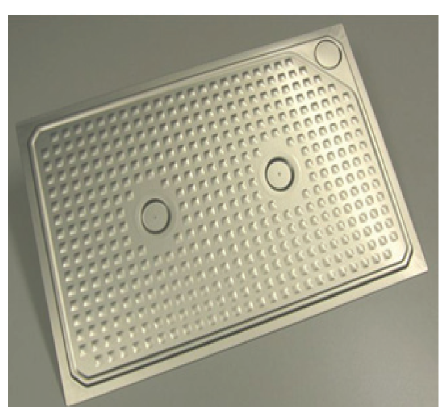


Fig. 21 Rubitherm GmbH coated aluminum plate filled with PCM

this building material contains three kilograms of the Micronal® PCM latent heat storer. The heat capacity of a wall construction, twice equiped with 15mm PCM SmartBoard®, is thus comparable to a 14 cm thick concrete wall or a 36,5 cm thick brick wall.[22]
Brand name: Micronal PCM SmartBoard
Technical details:
Length=2.00m
Width=1.25m
Thickness=15mm
Weight=11.5kg/m2
PCM content=3kg dry/m2
Melting temperature=23°C or 26°C depending on the local climate
Heat capacity (latent) =330kJ/m2 minimum

Another example of use of microencapsulated PCM is Maxit clima® machine-applied plaster from maxit Deutschland GmbH. Maxit clima is a PCM machine-applied plaster for making single-layer interior plaster with a temperature regulating effect . Through varying the thickness of the layer, the quantity of Micronal® PCM latent heat storer can be controlled according to requirements. Finally, H+H Deutschland GmbH produced concrete block with encapsulated phase change materials, under the commercial name CelBloc Plus® (Fig. 24). The green aerated concrete CelBloc Plus offers the capability for latent heat storage in addition to good heat, fire and sound insulation characteristics and positive environmentally compatible characteristics for adjusting air humidity . The migration of the heat front through the outer wall is slowed down by the active PCM component. The result is a highly insulating stone that shows smaller temperature fluctuations on the inner wall surface for the same U-value and therefore leads to more constant indoor temperatures.[23]

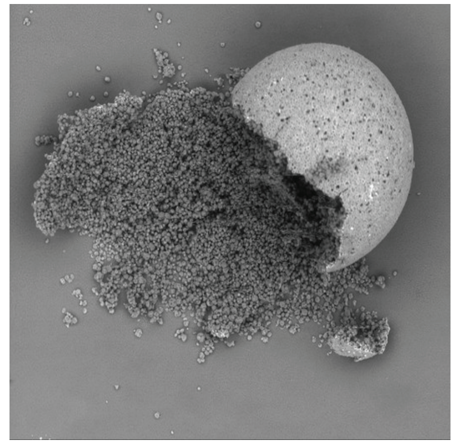


Fig. 22 Packages of PCM

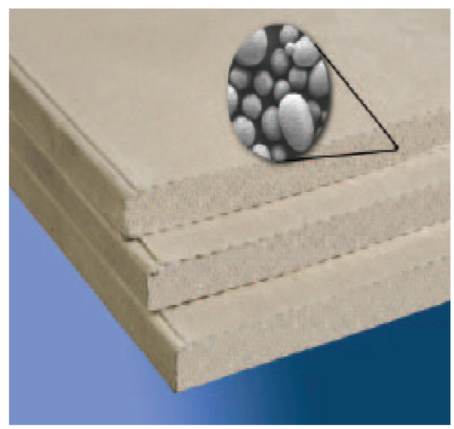


Fig. 23 PCM smartboard

Fig. 24 CelBlock from H+H Deutschland GmbH

4. PCM applications in buildings

4.1. Introduction

People like to have room temperatures in very narrow temperature range. The reason is explained by the metabolism of the human body. A range of temperatures, air movement, and relative humidity defines the optimum boundary conditions for heat exchange between the human body and the environment by thermal conduction, convection, radiation and evaporation. This set of boundary conditions is called human comfort requirements. The primary function of most buildings is to be a shelter to prevent freezing and overheating of the human body.

It is important to keep in mind that for the human comfort with respect to heat transfer it is the combination of the temperature of the air and room surfaces, the air motion and humidity that is important. For PCM technology, the key parameters of human comfort requirements are the temperatures of the air and the surrounding surfaces, because PCM can influence only these parameters. The relative humidity can be influenced indirectly, since it is a function of the air temperature [7].

The indoor air temperature of a building is influenced by many factors including climate conditions, building structure and the building material's thermophysical properties, indoor heat source, air change rate per hour (ACH) and auxiliary heating/cooling installations etc. The difference between the indoor temperature and the comfort range determines the heating and cooling load when there is no space heating and cooling. Therefore, the heating and cooling load will decrease with decreasing this temperature difference.[11] Zhang et al. defined two parameters that describe the indoor discomfort level of the building in winter and in summer and are called integrated discomfort level for indoor temperature in summer (I_{sum}) and integrated discomfort level for indoor temperature in winter (I_{win}), respectively. If there are certain building materials whose thermo-physical properties (i.e., the thermal conductivity, k, and the product of specific heat and density, p_{cp}) can make the given room meet the condition $I_{win}=I_{sum}=0$, we call these materials ideal building materials. This means that the indoor temperature will be in the comfort range all year round without auxiliary heating or cooling.[11] In reality, it is very difficult to find any material with such a high p_{cp} value. PCMs can provide high latent heat thermal energy storage density over the narrow

range of temperatures typically encountered in buildings.
As mentioned in previous chapters, potential fields of application of PCM can be divided into temperature control of buildings and in storage and supply of heat or cold with small temperature change. In this section of this study a typology of PCM applications for temperature control in buildings is provided. In applications for temperature control, the focus is on the temperature regulation of the space and not on the amount of heat supplied.

4.2. Potential of PCM for temperature control

In order to understand the potential of PCM for temperature control, it is necessary to look at the case without PCM as a reference. Regarding the influence of the building structure on the control of indoor temperatures, there are two extreme cases: tents and caves. Tents have extremely low heat storage capacity; caves are the opposite. In a tent, the temperature can be unbearably high on a summer afternoon and freezing cold during the night of the same day. In caves, the large heat capacity of the cave walls regulates the temperature and fluctuations are often less than 1K between day and night; in deep caves even between summer and winter. Buildings fill the wide gap between tent and cave. Big churches with massive walls are more like caves and modern lightweight buildings with a wooden frame are more like tents. Many modern buildings have a low thermal mass, because massive walls are missing completely, or because massive walls are only a small fraction of the building structure. Often the interior walls, for example in office buildings, are constructed as lightweight walls because of architectural and cost reasons.

To understand the potential of PCM for temperature control is somewhat more difficult due to the additional latent heat. Therefore, two different cases of temperature control are used as example:
1. The temperature fluctuates around the phase change temperature more or less evenly. In this case, the PCM with a melting temperature at the average temperature generally buffers temperature fluctuations. This however cannot be the general case, because the phase change temperature is fixed, while the room temperatures usually shift somewhat with the seasons (Fig. 25a).
2. The temperature does not fluctuate evenly around the phase change temperature; it is somewhat higher or lower. Consequently, the PCM slows down the rise or fall of the temperature beyond the phase change temperature, which means it cuts the temperature peaks (Fig. 25b).
For a quantitative analysis of the buffering of temperature fluctuations, it is necessary to compare the heat capacity of a phase change material with the values of ordinary materials.Fig. 26 lists the heat capacities of different building materials and the heat stored in a temperature interval of 4K. Assuming a volumetric density of 800kg/m^3, the volumet-

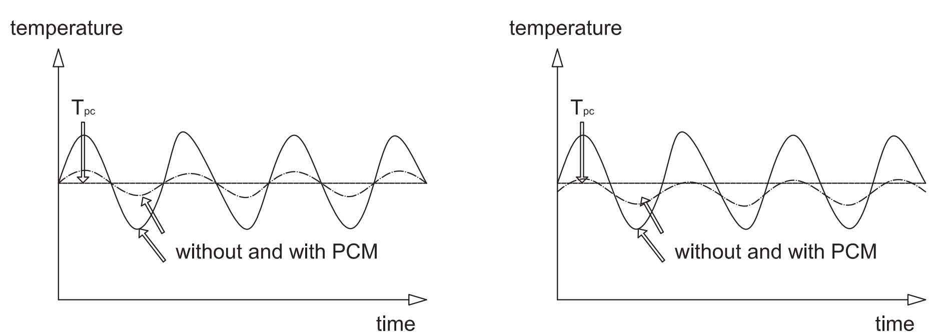


Fig. 25 a. PCMs with melting temperature at the average buffer temperature fluctuations. b. PCMs with higher melting temperature peaks ric heat capacity of PCM outruns even the materials for massive walls like concrete, sandstone or brick, by more than a factor of 30.7, as shown inFig. 26. For a quantitative analysis of the second case, where PCM is used to cut temperature peaks, the situation is different. In this case, the PCM is used to avoid that the temperature rises or falls below a certain level. This means it is necessary to know how much heat the PCM can store or release in the temperature interval between the regular or starting temperature and the critical temperature.[7] Fig. 27 compares the different materials in another way: it shows the necessary layer thickness of the different building materials to store as much heat as 1cm thick layer of PCM. The values are again based on the temperature interval of 4K. For a massive wall made of brick, a thickness of about 18 cm is necessary, for concrete the thickness is 24 cm. For wood and gypsum boards, as used for lightweight buildings, a wall thickness in the range of 30 to 50 cm would be necessary. Therefore, adding

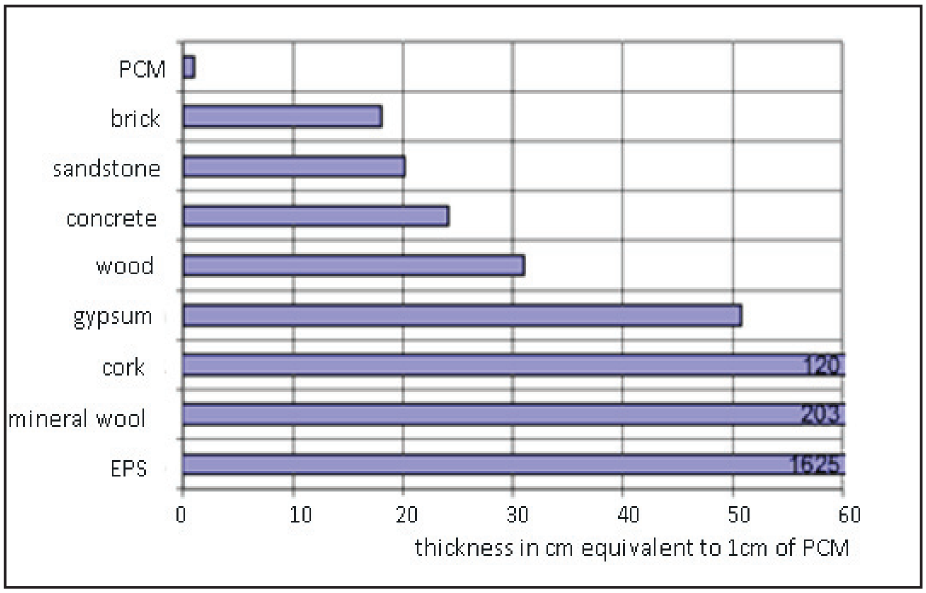


Fig. 26 Heat capacities and heat stored in a 4K interval for different building materials compared to PCM

material	c_p per mass [kJ/kgK]	ρ [kg/m]	cp per volume [MJ/m³K]	Q/V for ΔT=4K [MJ/m³]
EPS	1.2	16	0.02	0.08
mineral wood	0.8	200	0.16	0.64
cork	1.8	150	0.27	1.08
gypsum	0.8	800	0.64	2.56
wood	1.5	700	1.05	4.20
concrete	0.84	1600	1.34	5.38
sandstone	0.7	2300	1.61	6.44
brick	1	1800	1.80	7.20
PCM: peak values	>=75	800	>=60	
PCM: 22°C to 26°C				130

Fig. 27 Necesary layer thickness of different building materials to store as much heat as 1cm layer of PCM . The PCM has130 MJ/m³ and the temperature is 4K

even small amounts of PCM to the building structure can significantly enhance the thermal mass of the building and maybe make a lightweight building perform like a massive building with respect to thermal comfort. The integration of PCM can be as part of separate building components, or as additive to ordinary building materials, which makes them PCM-composite materials.

Applications of PCM in buildings include space heating and space cooling. In space heating the goal is to keep a space warm, more specifically to avoid the temperature going below a certain level. This can be achieved in three ways: the reduction of heat loss, the supply of heat, and the reduction of temperature fluctuations in low temperatures. In the last way, a PCM with a phase change temperature (or range) within the comfort range is used to store excess heat from the day from internal sources or solar radiation to prevent temperatures going down at night. To supply heat, an additional heat source at a higher temperature is necessary .[7] PCMs incorporated in building envelopes used for passive solar heating in winter can increase the thermal capacity of light building envelopes, thus reducing and delaying the peak heat load and reducing room temperature fluctuation. Together with a solar collector system, a PCM building component can store more solar thermal energy during the day and discharge the heat during the night, thus maintaining good thermal comfort of the room. With a heat pump or under-floor electric heating system etc., PCM building envelopes can store heat with cheap electricity at night and then discharge heat during the day, thus decreasing the space-heating load.[11] The shift of electrical consumption from peak periods to off-peak periods will provide a significant economic benefit. In space cooling the goal to keep a space cold, more specifically to avoid the temperature rising above a certain level, can be achieved in three ways: the reduction of heat input, the reduction of temperature fluctuations to elevated temperatures, and the improvement of heat rejection.[7]
A space cooling application is a nighttime ventilation system with PCM building components for cooling storage. When the outdoor temperature is lower than the indoor air temperature, the ventilation system starts and the outdoor cooling can be stored in the PCM envelope such as a PCM ceiling or PCM walls, and then released during the day, which could decrease the cooling load of air-conditioning systems.[11] The nighttime cooling storage can be achieved by natural ventilation or by fan.[11]
One advantage of integrating PCM in building components is that the walls, the floor and the ceiling of a building offers large areas for passive heat transfer within every zone of the building, which would add thermal storage for passive solar heating as well as create an opportunity for ventilation cooling and time-shifting of mechanical cooling loads. Further, except for the expense of the PCM, little or no additional cost would be incurred compared with ordinary envelope components. Several types of PCM applications in buildings are shown in Fig. 28.

Applications of phase change materials are divided in passive and active systems; with passive systems the regenerations of the thermal storage medium after melting occurs solely by means of free ventilation and natural cooling, while -there is no actively moved heat transfer fluid[24]. Heat is stored in the building material in daytime; at night the stored heat is retrieved from the PCM and discarded by ventilation to the outside. The discharge of the stored heat at night with cold night air is a key issue. The reason is that the difference between the temperature of the air at night and the PCM is usually only a few K. Further on, to cool down the PCM the cold night air has to reach the PCM in the building [7]. To improve the heat rejection an active ventilation system can be applied. This assures that the air temperature inside the building is closer to the night air temperature outside. The frequent exchange of air increases the temperature gradient for heat transfer inside the building. However, this does not mean that the heat transfer at the surface of the PCM changes from free to forced convection, because the velocity of the air can still be small [7].

During long hot periods, when temperatures remain high at night or where unwanted direct insolation of the PCM occurs, it is not possible to activate the latent heat storage medium for some time. After the discussion of building materials and components with ventilation of the building to discharge the stored heat at night, a logic continuation is to discuss systems where the PCM is integrated in a way that the active ventilation leads to a better heat transfer coefficient at the surface of the PCM. For that, the airflow must be directed along the surface of the PCM in a way that heat transfer is by forced convection instead of free convection. The active solidification of the melted PCM can be achieved with a minimum of energy: by running water-bearing pipes through the substance, for example, or by blowing cool air over the surface of the elements with the aid of small fans.[24]

A typology diagram of the phase change material applications for temperature control of buildings is presented in Fig. 29. It is observed in this diagram that PCM applications are initially divided in space cooling and space heating applications, respectively.

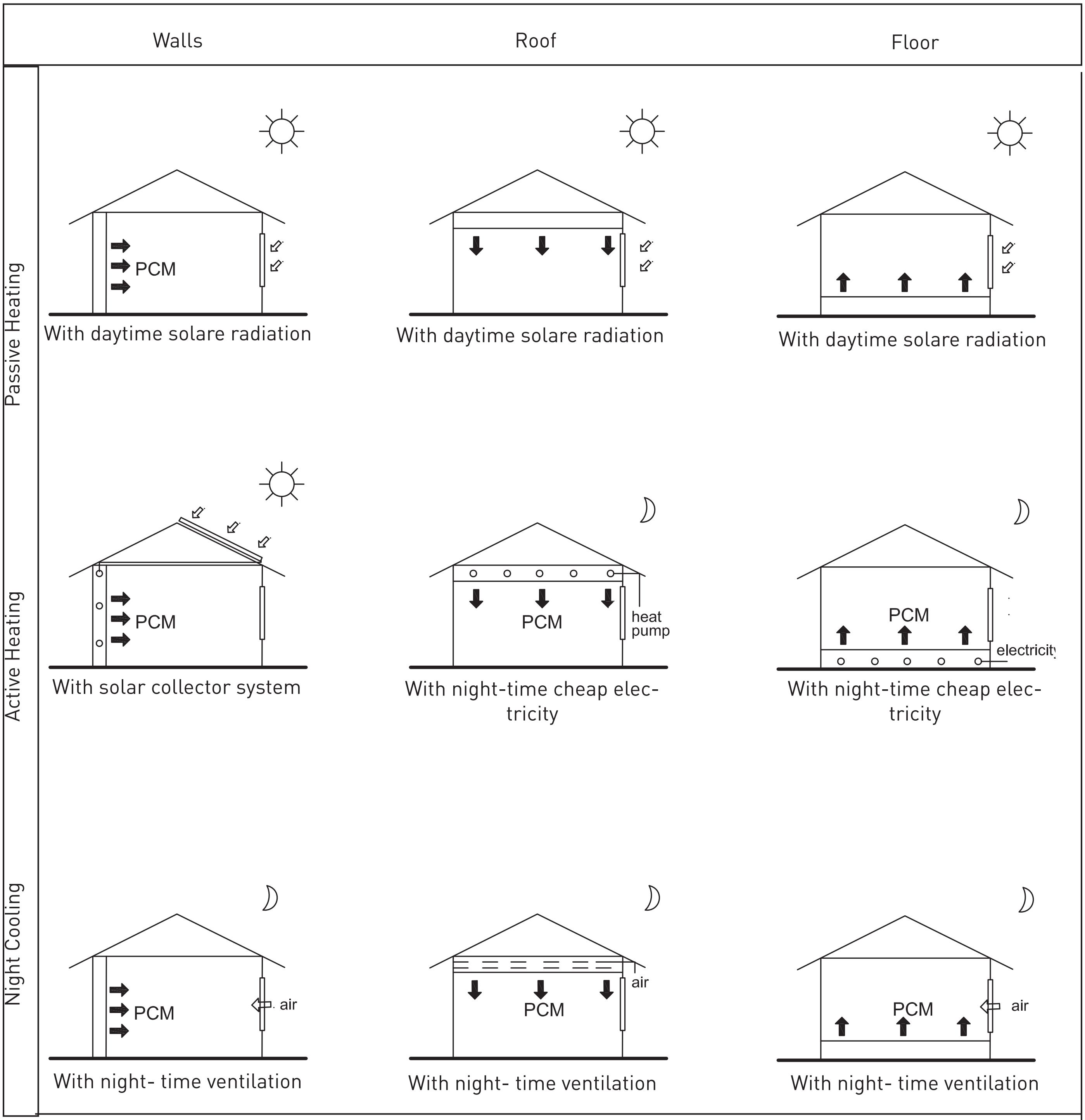


Fig. 28 Types of PCM applications in buildings

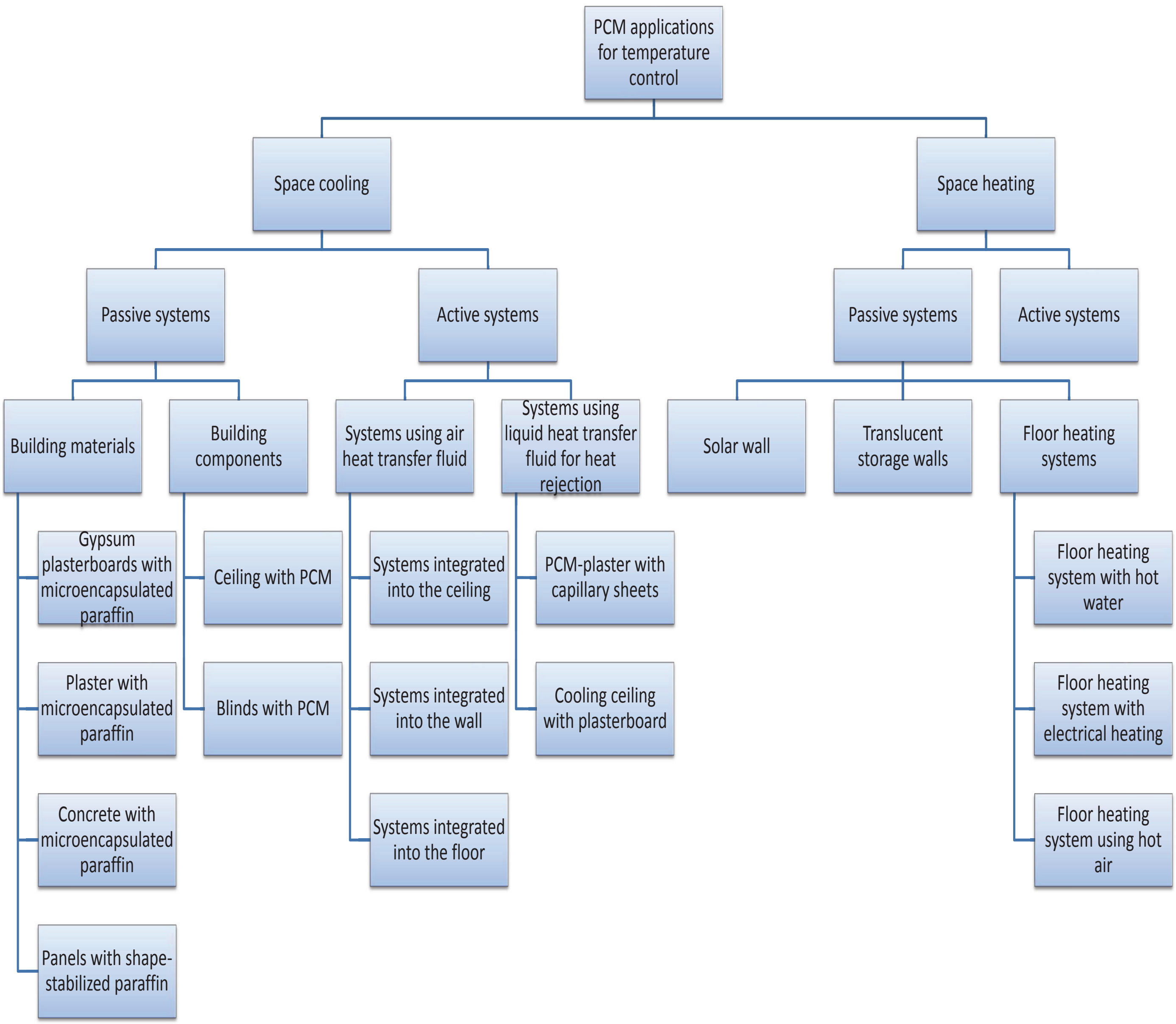


Fig. 29 A typology diagram of phase change material applications for temperature control of buildings

4.3. PCM applications for space cooling

4.3.1. Passive systems

4.3.1.1. Building materials

The potential of PCM to reduce temperature fluctuations, and specifically to cut peak temperature, is quite large, as already explained. Since the 1980s, many attempts have been made to incorporate PCM into building materials like plaster, wood, or fiberboards. The general concept for cooling with PCM integrated into building materials is shown in Fig. 30. Usually, in the early attempts the PCM used was a paraffin or a fatty acid and it was integrated by impregnation. However, the PCM was only absorbed in pores and channels and therefore leakage and evaporation of the PCM components was a common problem. A usual approach to these problems is encapsulation, but the handling of building materials includes cutting them or putting nails or screws in them. Therefore, microencapsulation is a possible solution, since in this case there is no loss of PCM under regular use and the amount of PCM released when a capsule is damaged is very small. This is a big advantage, since no especially trained craftsmen are necessary for installation. Besides microencapsulation, it is also possible to form a composite between paraffin and a polymer [7]. Microencapsulated paraffin was used for the first time as a PCM in conventional plasterboard fixed to the ceilings and walls. Where PCM plasters are used, care must be taken when applying a further plaster skim coat or wallpaper, since this is likely to impair the thermal transmission. In spite of high paraffin content, PCM plaster finished with an insulating coat of emulsion paint can be classified as a fire-resistant material.[24]

Building materials with incorporated PCM include:

- Gypsum plasterboards with microencapsulated paraffin
- Plaster with microencapsulated paraffin
- Concrete with microencapsulated paraffin
- Panels with shape-stabilized paraffin

Technical details, as well as more information on these materials are given in section 3.4.3.

4.3.1.2. Building components

Besides building materials, building components can also be equipped with PCM. The basic difference is that a component can have a special design and can be fabricated before the building is constructed. The use of PCM in building components gives more possibilities, such as the use of macro encapsulation and salt hydrates.

Building components equipped with PCM are:

- Suspended ceilings with PCM

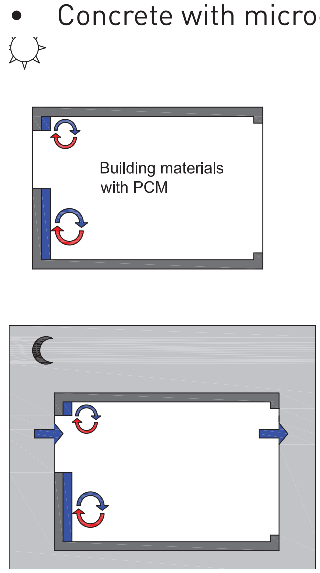


Fig. 30 The general concept for cooling with PCM integrated in building materials

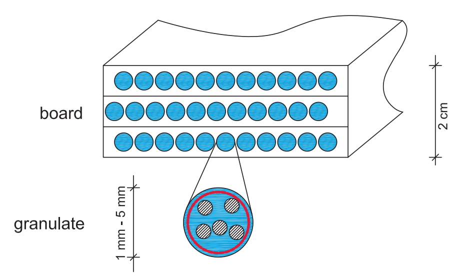


Fig. 31 Microencapsulation of PCM

In this case, the PCMs are salt hydrates and come in various encapsulations, such as encapsulation in plastic containers, in capsule stripes, in bags or in metal containers. For coffered ceilings it is possible to use PCM -in capillary form of storage- in foam or hollow-fiber slabs or filled in aluminum pouches. These containers can be designed to the usual grid dimensions of a building. The subsequent insertion of additional pouches or their removal in the event of a relocation of the office presents no problem. The coffered ceiling s should be in sheet metal to ensure good thermal conductivity.

The company Dörken sells a whole range of PCMs under the brand name DELTA®-COOL system, shown in Fig. 32, respectively.

Brand name: DELTA-COOL 24
Technical details:
Length=610mm
Width=610mm
Thickness=17mm
Melting temperature range 22-28°C
Crystalization temperature=22°C
Heat capacity=2.7 kJ/kgK

To improve the effectiveness of DELTA®-COOL, materials surrounding the system should provide good heat conductivity and should allow air movement to accelerate the heat exchange.

- Blinds

Blinds can be equipped with PCM to keep a space cold. One of the mayor sources of heat input into a building are solar gains through windows. Especially in modern office buildings, often whole façades are made of glass. To avoid direct solar radiation entering into the rooms behind, blinds can be installed inside the building, or outside in front of the window. Internal blinds are usually installed although they cause a thermal problem. Solar radiation transmitted through the window is absorbed at the surface of internal blinds, they heat up, and release the heat into the room. To avoid the problem of heat release from an internal blind into the building it is necessary to reduce the temperature rise of the blinds. This can be done by integrating PCM into the blinds. Then, the blinds still absorb the same amount of solar radiation; however, the PCM integrated into the blinds delays the temperature rise and consequently delays the heat release into the room.

Within the project “Innovative

Fig. 32 Delta Cool 24, upper face

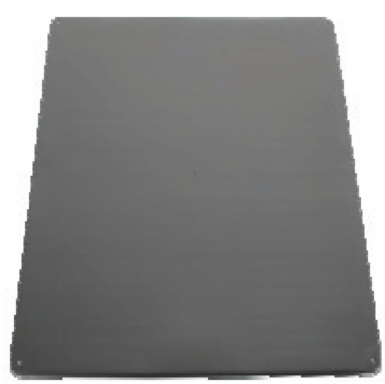


Fig. 33 Delta Cool 24, rear face

Fig. 34 Internal blinds with integrated PCM

PCM-technology", funded by the German Ministry of Economics (BMWi), the company Warema and the ZAE Bayern have investigated the idea of reducing and delaying the temperature rise of the blinds by integrating PCM. Measurements in a test room under realistic conditions have shown very promising results: the temperature rise of the blinds decreased by about 10 K and was delayed by approximately 3 hours. The air temperature in the room was about 2 K lower. Further investigations by numerical simulation showed a decrease of the operative temperature of the room by about 3 K and a time shift of the heat release from noon to evening. The thermal comfort during working hours is therefore significantly improved. At night, the heat has to be released to the outside by ventilation.

Looking at the heat transfer in this approach to use PCM is quite interesting. Ordinary building materials and components use only free convection for heat transfer to store and to reject heat. In the case of the blinds, comparatively little space and material is necessary because the problem of heat storage is addressed directly at the source. The heat transfer to the PCM is by absorption of solar radiation and therefore not restricted by the heat transfer coefficient for free convection in air. However, in the case of the blinds no internal heat sources are buffered, only the solar heat input. The concept of internal blinds with integrated PCM is shown in Fig. 35

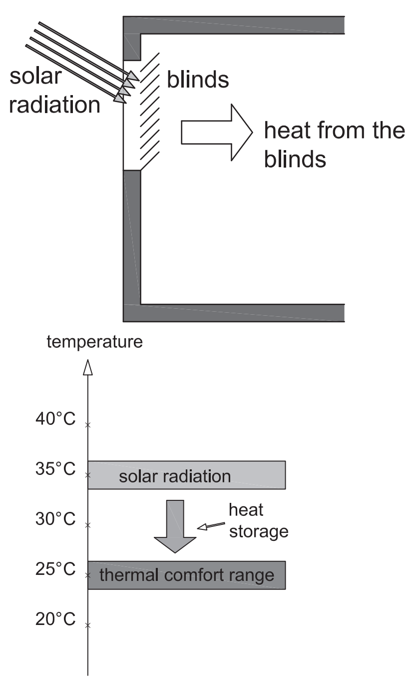


Fig. 35 Internal blinds absorb solar radiation and release the heat into the room, in order to cool the space by reducing the solar heat input of PCM

4.3.2. Active systems

4.3.2.1. Active systems using air as heat transfer fluid

- Systems integrated into the ceiling

The concept of using forced convection is based on the integration of PCM into a ceiling construction.[7] The principle of suspended ceilings can be developed into an active system by providing a small fan to blow air over the PCM pouches to effectively discharge the absorbed heat [24]. In this case, the ceiling is constructed in a way that it builds a two-dimensional channel that directs the air flow, as shown in figure Fig. 36. The PCM is located in this channel and, in combination with the channel, can be regarded as heat storage. At night, cold night air is first directed across the PCM surface to discharge the stored heat and cool down the PCM. The air is then discharged

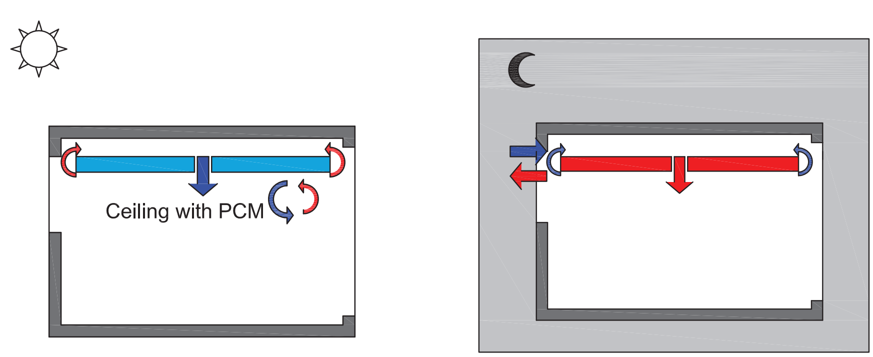


Fig. 36 The general concept for cooling with PCM integrated into the building. Excess heat from the room is stored in the PCM during and discarded and discarder at night to the cold night air

to the outside of the building. For cooling in daytime, warm air from the room is forced to move across the PCM and heat it up. The air is thereby cooled and then supplied back to the room.[7]
Several modifications of this concept exist. To increase the surface are of the PCM elements and thus speed up the heat transfer process, aluminum panels with cooling ribs have been developed. These also offer greater resistance to mechanical damage.[24]
The Swedish company Climator uses one modification in a system called "CoolDeck". This system has been installed as part of a demonstration project in the town hall of Stevenage in England and it is presented in section 4.5.1. Fig. 37 shows the ceiling construction. The Cool Deck consists of the PCM C24, a salt hydrate with a melting temperature of about 24°C encapsulated in bags, the fan and a metallic channel to direct the air.

Fig. 37 Cool Desck 24

The CoolDeck cassette is a holder of the PCM. The ClimSel CoolDeck Pouch in an aluminium laminate pouch filled with phase change material. The main ingredients are sodiumsulphate and additives. Installed in a room or cabinet, this is a unique component for stabilizing the temperature at 24°C.

Brand name: CoolDeck C24
Technical details for the Cooldeck cassette:
Length 24cm
Width 5.6cm

Two ClimSel modules can fit in one cassette.

Technical details for one module of ClimSel CoolDeck C24:
Phase change temperature: 24°C
Maximum temperature: 50°C
Storage capacity at 19-29C: 173Wh
Latent heat of fusion: 163Wh
Specific heat appr in PCM: 1Wh/°C
Specific gravity: 1.45kg/l
Thermal conductivity: 0.5-0.7W/m/°C
Weight: 5.8kg
Thickness: 15mm
Length: 11cm
Width: 4.9cm

- Systems integrated into the wall

It is possible to implement the same approach as for the ceiling in a wall construction Wall systems have been in use for longer period than other applications. The cooling system is installed in the space between the covering plates. Bags filled with PCM are placed on a shelf-like structure and a fan placed at the bottom is used to move the air. Intake and exit of air from the room is via openings at the bottom and the top. At the exit, it is necessary to assure that the volume flow of air, which is necessary to achieve a significant cooling power, does not lead to uncomfortable air velocities. For direct intake of cold night air, optionally an extra intake at the outside of the wall can be used.[7]

- Systems integrated into the floor

After discussing the integration of PCM into the ceiling and the wall it is not surprising that it is also possible to integrate a similar system into the floor. The general concept of such a system is shown in Fig. 38. The PCM is located directly under the floorboards. During daytime, cooling can be achieved by extracting the warm air from the room, cooling it while melting the PCM, and then bringing the cooled air back to the room. Permeable floorboards can be used for this reason. At night, cold night air can be circulated under the floor space to cool down the PCM and reject the stored heat. A possible modification of this concept is that during cooling, warm air from the room is discarded to the outside, and replaced by fresh air from the outside that is cooled down by the PCM before it enters the room; this system is for cooling and additionally for supplying fresh air by ventilation.

4.3.2.2. Active systems using a liquid heat transfer fluid for heat rejection

All examples discussed so far have used air heat transfer fluid to discard the stored heat. Starting from free ventilation, to forced ventilation, and finally to storage integrated into the ventilation channel, the heat transfer is improved and the rejection of heat is more reliable. Using air as heat transfer medium to discard the stored heat means that the cold night is used as cold source. This is very efficient in terms of energy consumption, but it is not absolutely reliable that the temperature of the night air drops to a temperature low enough to discard all the heat stored in daytime.[7] In order to solve this problem, it is possible to integrate a liquid-air heat exchanger and to attach it to a cold source with a liquid heat transfer fluid. This way, the cooling with cold nights can be supported, but there is a backup for the warm night. Additionally, since the demand side for cold and the source side have separate heat transfer fluids, it is possible to charge and discharge the PCM at the same time. For the heat transfer in the demand side, there are two basic options. The first is that the heat transfer is at a surface within the storage, usually with a ventilator causing forced convection. The second option, which is the one mostly investigated experimentally, the heat transfer is at the surface of the storage, which is identical with any of the room surfaces, by free convection and radiation.[7] Two very common approaches are further analyzed.

- PCM-plaster with capillary sheets

A very common approach for the thermal activation of concrete walls is to integrate capillary sheets as heat exchanger into the wall. The capillary sheets can be fixed at the surface of the concrete wall and then covered by a layer of plaster. A straightforward modification is simply to use plaster with PCM.[7]

- Cooling ceiling with PCM-plasterboard

This is an example of panels that are suspended from the ceiling. The company ILKATHEMR has developed a plate for dry construction, which consists of a PUR-foam as an insulating layer sandwiched between two coatings made of metal, plastics, plaster-

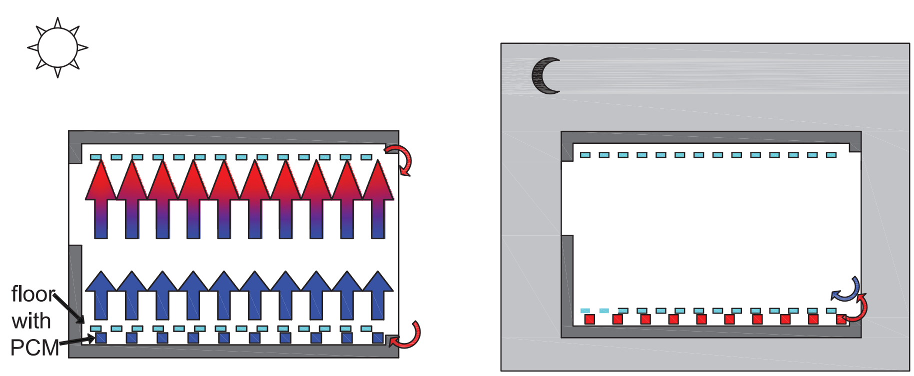
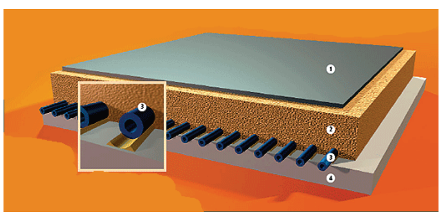


Fig. 38 General concept for cooling with PCM integrated into the floor

board, wood or others.[7] This plate can be used as a wall or ceiling element. In this case, the coating can be PCM plasterboard. The discharge of heat, in this case, is achieved by means of a cooling liquid that that flows through an inlaid mat with capillary tubes.[7] Fig. 39 and Fig. 40 show the construction and the installation of the PCM plasterboard.



1. sheet metal coating
2. PU rigid foam
3.capillary tube mats
4. Micronal PCM smartboard gypsum construction panel

Fig. 39 Construction of ILKATHERM PCM board

Fig. 40 Installation of ILKATHERM PCM board

4.4. PCM applications for space heating

4.4.1. Passive systems

4.4.1.1. PCM solar wall
Wall elements for exterior walls to heat a building have been investigated for decades. On an ordinary wall, the temperature gradient within the wall results to heat loss from the heated interior to the cold exterior, as shown in Fig. 41.a. The loss of heat can be reduced using a transparent insulation. Additionally, the transparent insulation transmits solar radiation, which is then absorbed at the surface of the wall. The use of this transparent insulation reduces the loss of heat to the outside and can even lead to a net heat gain to the building interior, as shown in figure Fig. 41.b.

A solar 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 four inches in front of the wall's surface. Solar heat is collected in the space between the wall and the glazing. The outside surface of the wall is of black color that absorbs heat, which is then stored in the wall's mass. Heat is distributed from the solar wall to the house over a period of several hours. When the indoor temperature falls below that of the wall's surface, heat begins to radiate into the room. Heat loss from the

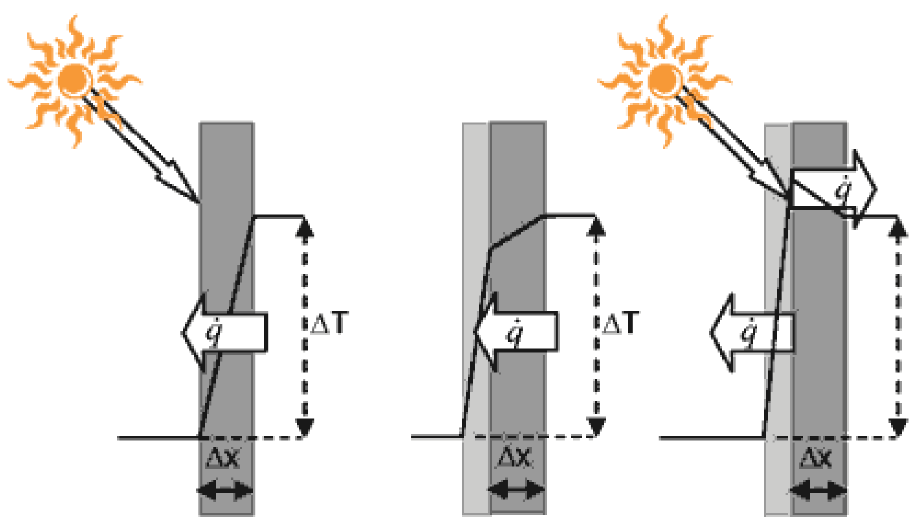


Fig. 41 Ordinary wall and wall constructionwith transparent insulation to use solar gains a. Ordinary wall with heat loss, b. Ordinary wall with transparent insulation. The transparent insulation helps reduce the heat loss when there is no sun, while it provides some net gains when there is sun-shine

solar wall can be controlled by an insulating curtain that is closed at night in the space between the glazing and the wall. Traditionally, solar walls relay on sensible heat storage, but because of the potential for greater heat storage per unit mass, the PCM solar wall is an attractive concept still awaiting successful implementation.[25] Additionally, traditional solar walls have one disadvantage: to ensure enough storage capacity, the wall needs to have a sufficient thermal mass resulting in a wall of significant thickness. This is where PCM offer a unique solution: a thin layer of PCM can replace a thick massive wall [7]. A wall filled with PCM is constructed on the south-side window of a house. The wall is heated during the day by incoming solar radiation, melting the PCM. At night the heat is withdrawn to warm the house. A construction detail of a solar wall is shown in Fig. 42. For a given amount of heat storage, the phase change units require less space than water walls or mass solar walls and are much lighter in weight. These are, therefore, much convenient to make use of in retrofit applications of buildings. Salt hydrates and hydrocarbons are commonly used as PCMs in the solar wall [25].

4.4.1.2. Translucent storage walls

If the PCM is partly transparent, the whole element can be constructed in a way that it transmits light and illuminates the building interior. This idea has been investigated by the company Glaswerke Arnold and ZAE Bayern. The compound material from Rubitherm, as well as the double skin sheet from Dorken, shows a transparency which changes to some degree between the solid and liquid state of the PCM, and therefore they can be used for a diffuse illumination of the space behind the wall element. A complete system is constituted by a transparent insulation of two glass sheets on the outside and a macro-encapsulated PCM on the inside layer of construction.[7]

The company INGLASS has investigated a system called the INGLAS PCM element, which developed a heat reservoir for facades with transparent thermal insulation. These "thermal batteries" efficiently absorb solar light, and the heat developed in

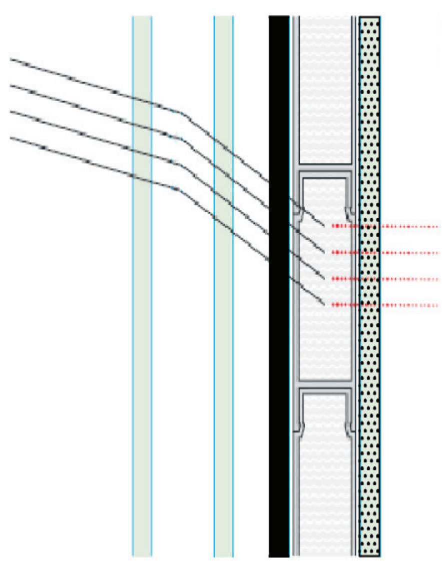


Fig. 42 Construction detail of solar wall. The wall is heated during the day by incoming solar radiation, melting the PCM.

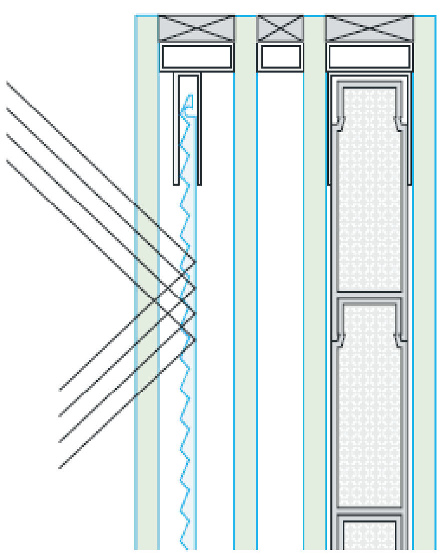


Fig. 43 Construction detail of a translucent storage wall. During the summer, the outer prismatic glass reflects the high-angle rays of the sun.

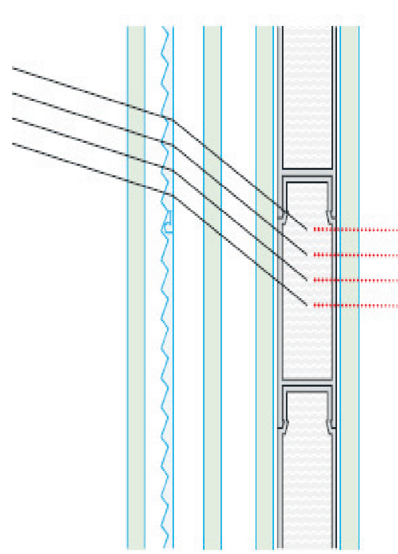


Fig. 44 Construction detail of a translucent storage wall. During the winter, the flat rays of the sun enter the space, melting the wax in process.

the process goes into melting the wax-like filling of the elements. In this way large amounts of solar energy can be stored during daytime and released into the building at night, when the material cools down and hardens. INGLAS PCM thus replaces many centimeters of concrete and brick, which would be needed to store energy in the walls of conventional buildings. Even more new design possibilities emerge from the variable translucency of the material. It provides a dynamic wall, whose "energy state" is visualized as transparent when molten and milky when hardened.[7]

A prototype translucent PCM façade, consisting of plastic elements filled with paraffin was developed by the Swiss architect Dietrich Schwarz[25]. He commercialized a system with his own company, GLASSX AG, using PCM from Dorken. The wall element, called GLASSX crystal, consists of four functional units: a transparent insulation, a protection from overheating, an absorber, and the heat storage. The transparent insulation consists of three glass sheets with a total U-value of $0.5W/m^2K$. To protect the element from overheating, a prismatic glass reflects light from the sun in summer incident at high angles, and transmits sunlight in winter when it comes at low angles. A construction detail of this translucent storage wall is shown in Fig. 43 and Fig. 44, for summer and for winter, respectively. The PCM used is salt hydrate DELTA COOL 28 from Dorken with a melting range 26°C to 28°C, macro-encapsulated in plastic containers. The newly developed GLASSX crystal combines the characteristics of PCM with self-regulating solar control in highly insulating, energy saving double-glazing. PCM produces clean solar energy to heat the room to a comfortable level exactly between 26°C and 28°C. GLASSX crystal uniformly radiates the stored energy in a controlled way into the room. At the same time it lightens the room with a good dose of diffuse daylight.[27]

The Fraunhofer Institute for Solar Energy Systems ISE in Freiburg has proven that a reduction of heating costs by over 50 % can be achieved in winter months in comparison to opaque walls (U-Value 0,3 $W/m^2.K$). In summer months GLASSX crystal protects from summer overheating, since it does not release any energy over 27°C into the room. Significant amounts of energy are absorbed from overheated rooms by reducing spikes in energy load. GLASSX crystal is therefore suitable not only for light and

Fig. 45 Glass X in its clear state

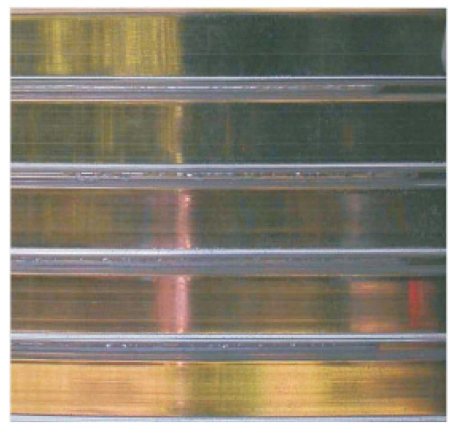


Fig. 46 Glass X in its liquid state

Fig. 47 GlassX crystal component

medium-sized buildings but also serves to significantly reduce load spikes for climate control and air-conditioning[27].

Brand name: GLASSX crystal
Technical details:
Element thickness 79 mm
Thickness tolerance -1/+4 mm
Min. fold width ~ 84 mm
Weight max. 95 kg/m²
Max. Surface area 4.2 m²
Max. Height 280 cm
Max. Width 150 cm
Heat transmission coefficient (U-value) up to 0.48 W/m²K
Light transmission for crystalline PCM 0 - 28 %
Light transmission for liquid PCM 4 - 45 %
Vertical direct irradiation 48 %
Diffuse irradiation 29 %
Seasonal (winter months) 34 - 40 %
Seasonal (summer months) 17-22%
Storage capacity 1185 Wh/m²
Storage temperature 26 - 30°C

4.4.2. Active systems

4.4.2.1. Floor heating systems

Floor heating systems have the advantage of a large heat transfer area. Additionally, the heat convection coefficient for heating from the floor is even higher. This allows a high energetic efficiency, since the necessary heating power is achieved at a lower surface temperature. The combination of the heating by warm air with thermal radiation also improves the comfort feeling. Floor heating with thermal storage can be achieved with hot water, and electricity.[7]

- systems with hot water

A floor heating system using hot water as heat transfer fluid and PCM as heat storage has been investigated by the company Rubitherm Technologies GmbH. In this case, the storage material is a granulate filled with a paraffin, as described in section 3.4.2. The heating pipes are embedded in the storage material. The floor thickness is reduced in this case, but 0.5kWh/m^2 of heat can be stored in the floor.[7]

- systems with electrical heating

A floor heating system with electrical heating has been developed by Sumika Plastech Company in Japan. SUMITHERMAL floor-heating system stores heat at night, when electricity rates are low, and discharges it during the day. This system can reduce energy costs by about 30% compared with systems that use electricity at regular rates. Electricity costs can be reduced a further 15% through use of a system equipped with microcomputer control.[28] The working principle is similar to the case of floor heating system with hot water. Instead of water pipes embedded in PCM-granulate, their design consists of electrical heating wires in contact with especially designed PCM modules. These modules are flat plastic containers filled with a salt hydrate.[7]

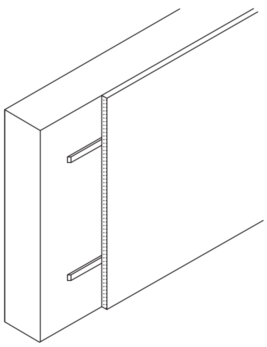
Passive systems

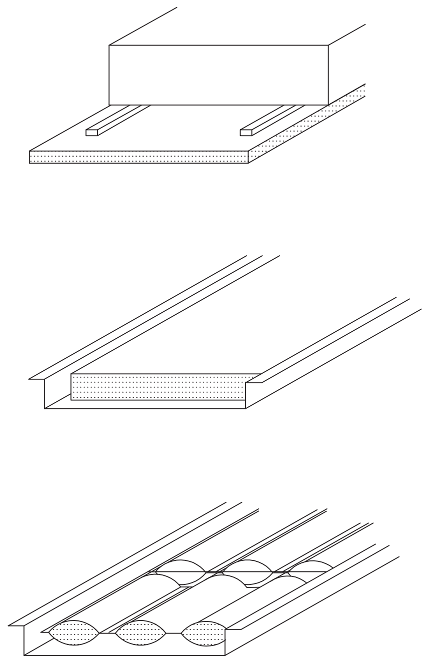
Wall applications

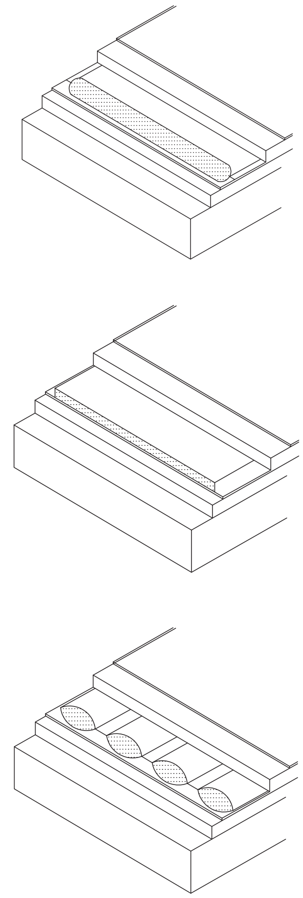
Ceiling applications

Floor applications

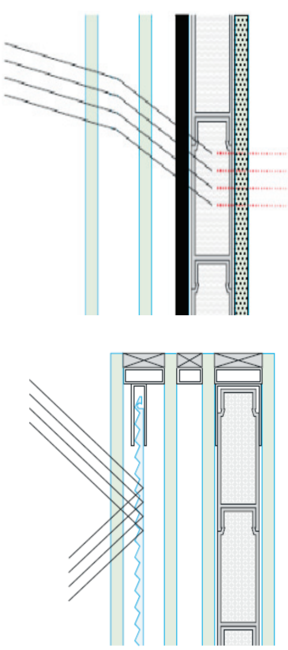
Space cooling

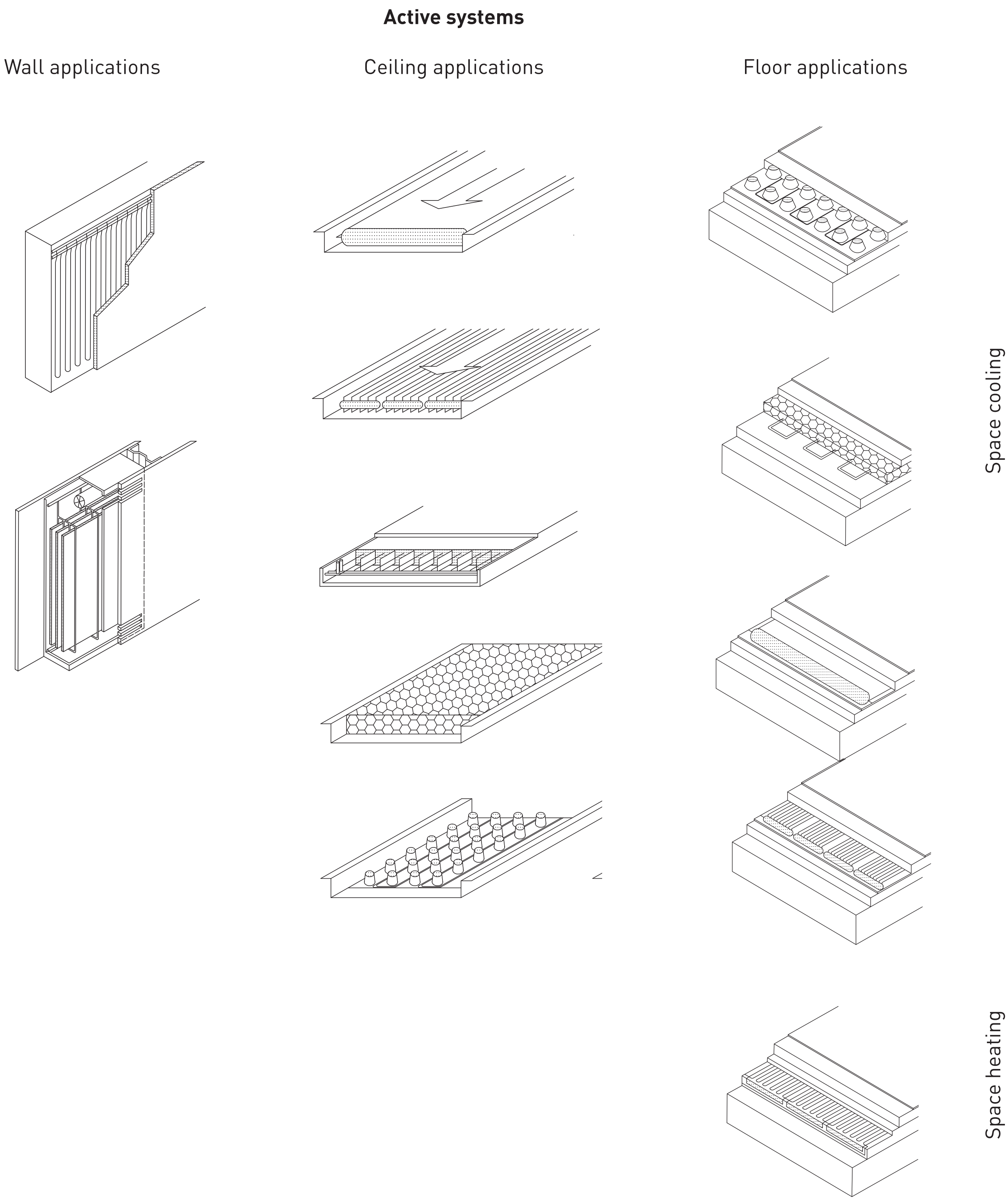






Space heating




Active systems
Wall applications
Ceiling applications
Floor applications
Space cooling
Space heating

4.5. Case studies

4.5.1. Stevenage Borough Council's offices

CoolDeck has been installed in Stevenage Borough Council's offices as part of the Council's Best Value approach to dealing with office comfort conditions.
A ceiling void CoolDeck system was used in combination with solar blinds to provide a passive solution to reduce summertime overheating rather than resort to full air conditioning.

CoolDeck elements are attached to the slab surface in the void and air is circulated by a fan through the narrow air paths formed. Turbulent flow enhances heat exchange between the air and the slab surface. Storage takes place at night with cool ambient air being circulated through the air paths to cool the slab. This stored cooling is then released the next day when air is again circulated through the air paths with the slab cooling the air. The CoolDeck elements have been designed to optimise heat exchange without incurring unnecessary pressure drop penalties.
The elements are sized to integrate into ceiling and floor voids and for ease of handling. The elements are constructed from sheet steel with returned edges along the length for rigidity. A spigot connection is located centrally for connection to the fan system. Spacers/seals are fixed along the underside edges to form and seal the air path from the spigot to the ends of the element.

The floor void arrangement has a central air supply via distribution ducts feeding headers connected to the CoolDeck elements. The ceiling void system above has a modular arrangement with local


Fig. 48 Stevenage Borough Council's building

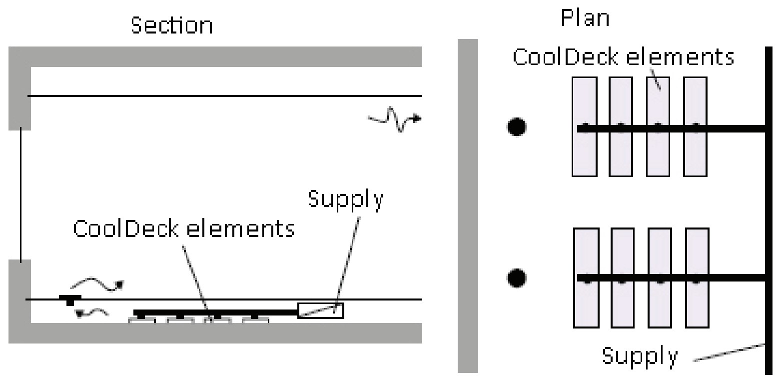


Fig. 49 Floor void option, central supply

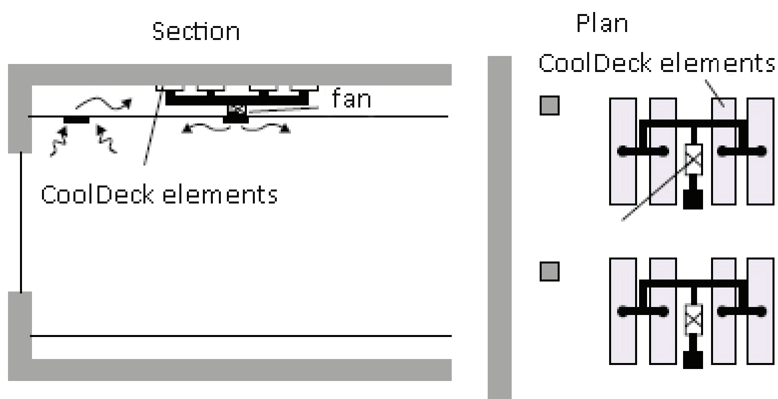
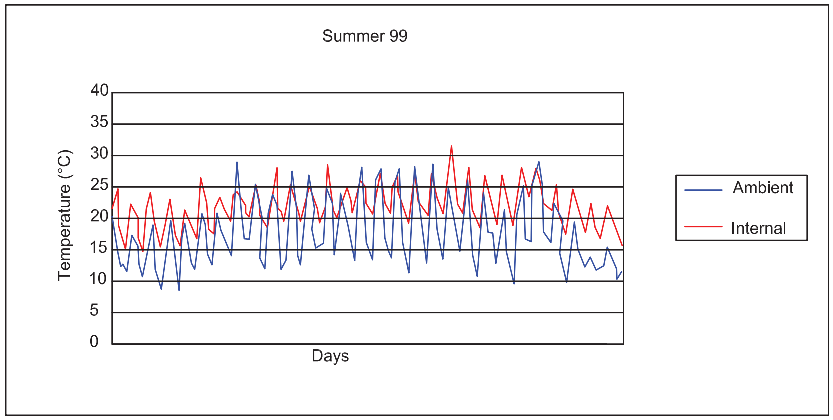


Fig. 50 Ceiling void option, central supply

fans circulating air between the space and CoolDeck elements in the ceiling void. Outside air for night cooling can be introduced into the space locally by window / wall fans or by a central air supply system. A local CoolDeck system may be more appropriate for isolated areas. A section and plan for both installations, floor and ceiling are shown in Fig. 49 and Fig. 50, respectively.

The following key points can be drawn from the installation:

• The CoolDeck system can be installed in restricted floor and ceiling voids – the ceiling void at Stevenage is approximately 220 mm deep.
• Monitoring before and after the refurbishment works indicates a reduction of 3-4ºC in internal temperatures due to the CoolDeck system, demonstrating its effectiveness.
• The CoolDeck system has been installed at a fraction of the cost of the proposed air conditioned alternative.
• Energy consumption is low - the design Coefficient of Performance (cooling / fan energy) is COP=20.
• There has been a noted improvement in the "freshness" of the offices in the morning following night cooling
• Phase Change Materials have been integrated into a subsequent installation to provide additional thermal storage.



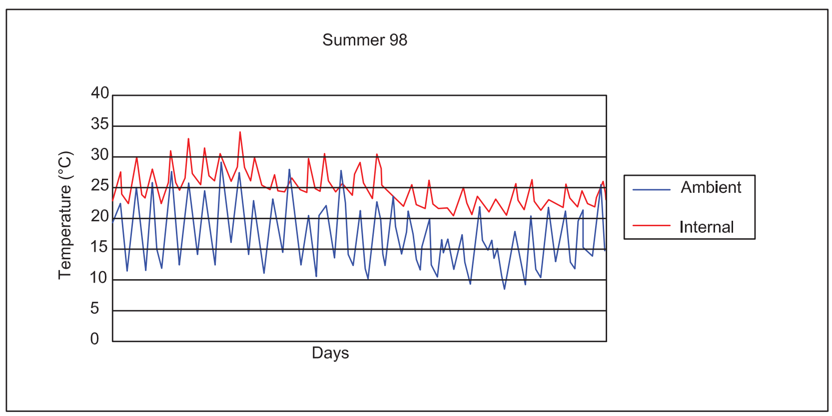


Fig. 51 Comparative graphs of the ambient and internal temperature without the CoolDeck elements (top) and after the addition of the CoolDeck elements (bottom). The reduction of internal temperature after the addition of CoolDeck elements is obvious.

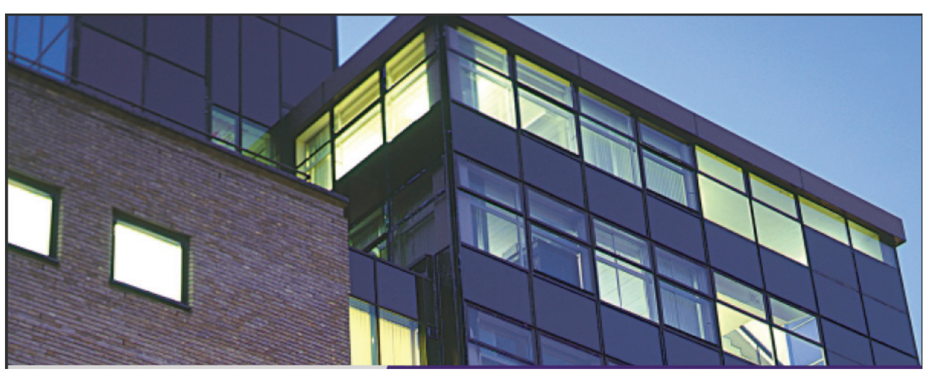


Fig. 52 Stevenage Borough Council's building

4.5.2. Senior citizens' apartments with a latent heat-storing glass façade

Swiss architect Dietrich Schwarz has shown in several of his buildings how, in addition to their latent heat-storing properties, the ability of PCMs to change their optical appearance can also be used in a facade. The initial solution involved pure paraffin in transparent hollow plastic blocks, used as latent heat storage facade elements in the south facade of a zero energy house in Ebnat-Kappel, Switzerland. In contrast, for this project a salt hydrate was used as the PCM, due to fire safety reasons. On the south side of this complex the architect installed GLASSXcrystal over an area of 148 m^2. The 78 mm wide system is constructed like an ordinary triple insulation glazing unit, but with a light-directing prism panel outside and a PCM panel inside, consisting of polycarbonate containers filled with a salt hydrate mixture, which stores heat at +26°C to +28°C, as described in section 4.4.1.2.
In summer the solar radiation is reflected back outside by the prismatic panels. During the winter the lower sun angle allows the solar radiation to pass almost unimpeded into the facade construction, where it hits the PCM

Fig. 53 Close biew of the south facade of the senior citizens' apartments with latent heat storing glass facade

Fig. 54 South facade of the senior citizens' apartments with a latent heat storing glass facade

panel, is converted into thermal radiation and stored by the melting of the salt hydrate. If the room temperature falls below +26°C, perhaps at night or on cloudy days, the salt hydrate crystallizes and releases its stored heat energy into the room. The charge state of this latent heat-storing glass facade can be observed directly from its optical appearance, which is determined by the different phases of the salt hydrate: if the facade looks opaque (seen from outside through the prismatic panels or from the inside), then the salt hydrate is uncharged. If it appears translucent (seen from outside through the prismatic panels) or transparent (from the inside, with no printed pattern), the salt hydrate is being charged or is fully charged.

A comparison of the required heat output for several systems was performed in oerder to test the performance of GlassX. The examined systems are glassX, system with thermal conductivity 0.3W/m²K, system with thermal conductivity 0.2W/m²K and system with thermal conductivity 0.1W/m²K. After this comparison, it is revealed that the system with a GlassX facade needs about half of the heat output required in the other systems, as shown in Fig. 57.

Fig. 55 Detail of the facade system from the outside

Fig. 56 Detail of the facade system from the inside

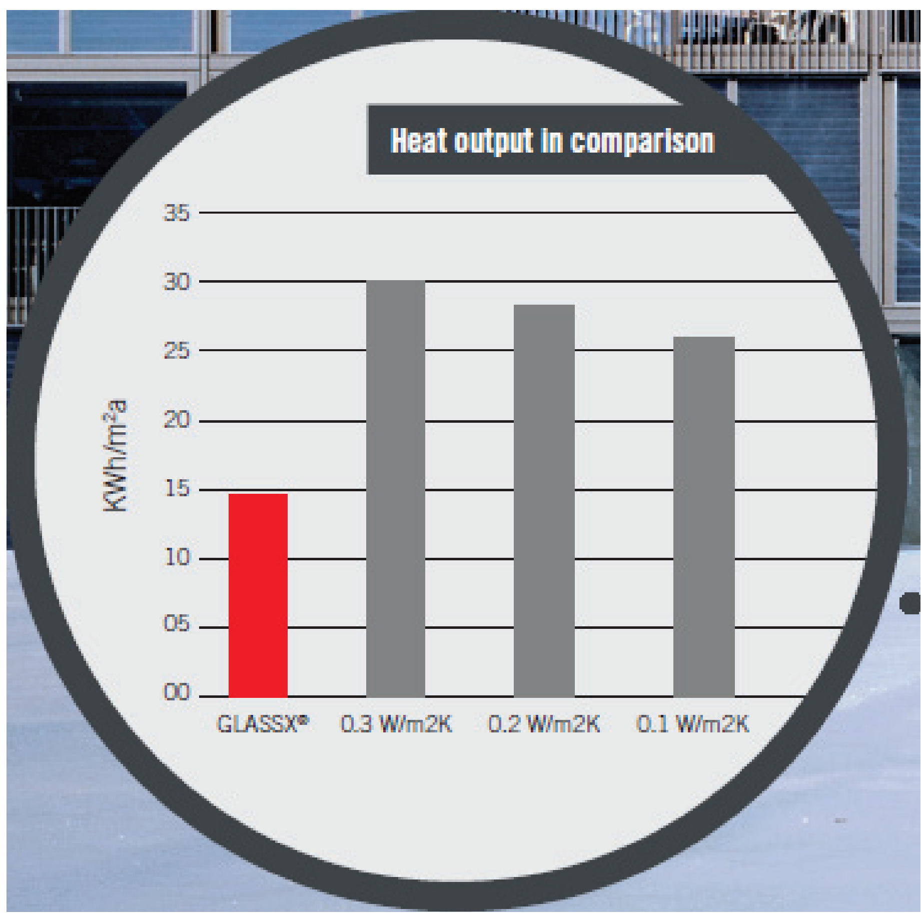


Fig. 57 Comparative graph of the heat output required in various cases

5. Simulation of PCM

5. Simulation of PCM

5.1. Motivation

Quantitative and qualitative performance based sumulation is used nowadays to accurately perform structural, energy and fluid dynamics analysis for buildings of any formal complexity. The challenges of the developing such software, however, are far from trivial. Most of the commercially available building performance simulation software, whether for structural, lighting, acoustical, thermal or air-flow analysis, requires high resolution and detailed modelling.

Simulation tools can be used to analyze the performance of building thermal mass, it is accepted that different tools deliver different results given the assumptions that are built into them. All the existing software has their advantages and drawbacks, some are more accurate that others in specific type of modeling. Most of the available software, if not all, base their calculations on the assumption of one dimensional energy transfer. Since the potential for PCM is great, the development of an accurate calculation model for such materials will have as much potential.

5.2. Simulation software

5.2.1. Overview

As with every design decision, before the construction phase, the choise of the most adequate melting temperature of the PCM, the percentage of PCM to mix in the mortar with conventional materials, or the position of panels with PCM in the building is depending on the use and architectural characteristics of the building. The optimization of these parameters is fundamental to demonstrate the possibilities of success of the phase change materials in building structures. The thermal improvement of a building with phase change materials depend on numerous parameters, such as the climate, the orientation and the design of a building, the construction and the operation of a building, and finally the amount, the type and the application of phase change materials. Therefore, in order to evaluate the thermal performance of a project, a complete simulation of thermal performance of the designed space in the conditions of use is required. Nowadays, there are several commercial programs for the thermal simulation of buildings, including Energy Plus, TRNSYS, ESP-r, RADCOOL, BLAST, BSim, DOE-2, IDA-ICE 3, Ecotect, eQUEST, HVACSim, CLIM2000.

Although all the possibilities of these programs, most of them do not have modules that allow direct simulation of the effect of adding PCM in a wall or window. However, they include algorithms to simulate active walls with tubes including a circulating fluid. A comparative study of several simulation programswas performed by Nature Resources Canada (NRC)[28]. Additionally, International Energy Agency (IEA) performed the BESTEST validation methodology in order to evaluate the performance of simulation software.[29] Some studies performed outline the first three software for their versatility and reliability[32, 28].

• Energy Plus[30]

EnergyPlus has its roots in both the BLAST and DOE–2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. Their intended audience is design engineers or architects that wish to size appropriate HVAC equipment, develop retrofit studies for life cycling cost analyses, optimize energy performance, etc. Born out of concerns driven by the energy crisis of the early 1970s and recognition that building energy consumption is a major component of the American energy usage statistics, the two programs attempted to solve the same problem from two slightly different perspectives. Both programs had their merits and shortcomings, their supporters and detractors, and solid user bases both nationally and internationally. Like its parent programs, EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would. Many of the simulation characteristics have been inherited from the legacy programs of BLAST and DOE–2. Below is list of some of the features of the first release of EnergyPlus. While this list is not exhaustive, it is intended to give the reader and idea of the rigor and applicability of EnergyPlus to various simulation situations. Links to other popular simulation environments/components, such as WINDOW5, WINDOW6 and DElight are possible, to allow more detailed analysis of building components.

No program is able to handle every simulation situation. However, it is the intent of EnergyPlus to handle as many building and HVAC design options either directly or indirectly through links to other programs in order to calculate thermal loads and/or energy consumption on for a design day or an extended period of time. While the first version of the program contains mainly features that are directly linked to the thermal aspects of buildings, future versions of the program will attempt to address other issues that are important to the built environment: water, electrical systems, etc. One of the features of the newest versions of Energy Plus (Version 3.0 and Version 4.0) is the incorporation and simulation of phase change materials into the building structures.

• TRNSYS[32]

TRNSYS, which stands for TRaNsient System Simulation program is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems, such as wind, solar, photovoltaic, hydrogen systems. One of the key factors in TRNSYS' success over the last 25 years is its open, modular structure. The DLL-based architecture allows users and third-party developers to easily add custom component models, using all common programming languages, such as C, C++, PASCAL and FORTRAN. This simplifies extending existing models to make them fit the user's specific needs. The modular structure of TRNSYS is also appropriate to achieve such simulation with phase change materials.

• ESP-r[33]

ESP-r allows an in-depth appraisal of the factors which influence the energy and environmental performance of buildings. The ESP-r system has been the subject of sustained developments since 1974 with the objective of simulating building performance in a manner that is realistic and adheres closely to actual physical systems, supports early-through-detailed design stage appraisals, and enables integrated performance assessments in which no single issue is unduly prominent. ESP-r attempts to simulate the real world as rigorously as possible and to a level which is consistent with current best practice. By addressing all aspects simultaneously, ESP-r allows the designer to explore the complex relationships between a building's form, fabric, air flow, plant and control. ESP-r is based on a finite volume, conservation approach in which a problem, specified in terms of geometry, construction, operation, leakage distribution, is transformed into a set of conservation equations which are then integrated at successive time-steps in response to climate, occupant and control system influences. ESP-r comprises a central Project Manager around which are arranged support databases, a simulator, various performance assessment tools and a variety of third party applications for CAD, visualisation and report generation.

In addition to state of the art standard simulation features, ESP-r has powerful capability to simulate many innovative or leading edge technologies including daylight utilisation, natural ventilation, contaminant distribution, combined heat and electrical power generation and photovoltaic facades, adaptive 3D transient CFD, multi-gridding (2D and 3D conduction), and control systems. On the other hand, specialist features require knowledge of the particular subject. Although robust and increasingly used for consulting, ESP-r retains much of the look and feel of a research tool and lacks the extensive databases associated with commercial tools. The current Windows implementation does not conform to the standard look and feel of most Windows applications and lacks a few features available on other platforms. ESP-r does yet provide a built-in undo function. ESP-r dialogs and contextual help messages are a bit heavy on jargon. ESP-r is much better learned via interactions with a mentor than by self-instruction.

5.2.2. Energy Plus

As already mentioned, the simulation of phase change materials is incorporated in the newest versions of Energy Plus. This is the primary reason that Energy Plus is used for the purpose of this study.

EnergyPlus models follow fundamental heat balance principles very closely in almost all aspects of the program. However, the simulation of building surface constructions has relied on a transfer function transformation carried over from BLAST. This has all the usual restrictions of a transformation-based solution: constant properties, and fixed values of some parameters. Four values are allowed to select which algorith will be used. The "ConductionTransfer Function" selection is a sensible heat only solution and does not take into account moisture storage or diffusion in the construction elements. The "Moisture Penetration Depth Conduction Transfer Function" selection is a sensible heat diffusion and an inside surface moisture storage algorithm that also needs additional moisture material property information. The "Conduction Finite Difference" selection is a sensible heat only solution and does not take into account moisture storage or diffusion in the construction elements. This solution technique uses a 1-D finite difference solution in the construction elements. The "Combined Heat And Moisture Finite Element" is a coupled heat and moisture transfer and storage solution. The solution technique uses a one dimensional finite difference solution in the construction elements and requires further material properties described in the "Heat and Moisture Transfer" material properties objects.

As the energy analysis field moves toward simulating more advanced constructions, such as phase change materials (PCM), it becomes necessary to step back from transformations to more fundamental forms. Accordingly, a conduction finite difference solution algorithm has been incorporated into EnergyPlus. This does not replace the "Conduction Transfer Function" (CTF) solution algorithm, but complements it for cases where the user needs to simulate phase change materials or variable thermal conductivity. It is also possible to use the finite difference algorithm for zone time steps as short as one minute, corresponding to the system time step. The algorithm uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase change energy accurately.[31]

Therefore, this conduction model is achieved when the appropriate materials are specified and the "Solution Algorithm" parameter is set to "Conduction Finite Difference". This permits simulating temperature dependent thermal conductivity and phase change materials (PCM). The temperature – enthalpy set of inputs specify a two column tabular temperature-enthalpy function for the basic material. Sixteen pairs can be specified. Specify only the number of pairs necessary. The tabular function must cover the entire temperature range that will be seen by the material in the simulation. It is suggested that the function start at a low temperature, and extend to 100°C. Note that the function has no negative slopes and the lowest slope that will occur is the base material specific heat. Enthalpy contributions of the phase change are always added to the enthalpy that would result from a constant specific heat base material.[31]

6. Methodology

6.1. Model description

An experimental chamber, 5.48m long, 4.5m wide and 2.38m high, located in Pickle Research Campus of The University of Texas at Austin is used for the purposes of this study. It is an indoor chamber with heat sourcesces located on the south side, in order to immitate an external façade oriented towards the south. The radiation provided by these applied sources is analogous to the real life solar radiation. It is therefore safe to assume that the chamber has an external facade oriented towards the south. A window 1.4m high and 4.5m wide is located on the south façade of the chamber allowing the heat to enter the space. This chamber is used in order to simulate the thermal performance of a typical office space when phase change materials are used to regulate the indoor temperature. A set of experiments is performed on this chamber in order to understand the different performance if different situations are applied. In order to investigate the performance of phase change materials, these experiments are performed assuming that the chamber is rotated and the external facade has south, north, east and west orientation, respectively.

Phase change materials are used in building construction in order to substitute the thermal mass of a building in cases of lightweight construction. A lightweight wall construction is therefore used for the performed experiments. The construction of the external lightweight envelope, starting from the outside layer, is metal surface, 50mm insulation board, wall air space, 19mm gypsum board, based on the ASHRAE 2005 construction dataset provided with Energy Plus. The construction of the indoor walls is 19mm gypsum board, wall air space and 19mm gypsum board. Finally, the construction of the floor and ceiling, from the inside layer to the outside, is acoustic tiles, air space and 100mm lightweight concrete, based on the ASHRAE 2005 construction dataset provided with Energy Plus. The details of the wall sections are presented in Fig. 59, Fig. 60 and Fig. 61.

6.2. Model development and assessment

A set of experiments is performed on this chamber using Energy Plus, in order to develop and evaluate the model. In order to evaluate the simulation model and test its performance two extreme and ideal cases are investigated; one assuming that the chamber is constructed of 75mm insulation and one assuming that the chamber is constructed of 20mm heavyweight concrete. These two cases are selected in order to see the effect of phase change materials in a space with different amounts of thermal inertia; the first case representing a lightweight construction, while the second case representing a heavyweight construction. As already mentioned, these are two extreme test cases that can not be found in reality and they are only used to tune-up the simulation model used for the purposes of this study. The material selected for this calculation as octadecane, an organic material with melting temperature 25.3°C, solidification temperature 26.3°C and melting enthalpy 245kJ/kg.

This initial model of the chamber, which is used to tune-up the model and evaluate its performance is assumed to have adiabatic surfaces, in order to isolate the phase change phenomenon and make it easier to understand the performance of the materials. It is also assumed that it is a completely enclosed space, without openings or ventilation. The only loads of the space are internal loads, Q=2000W, that exist only from 8am to 6pm. All the other time there are no loads, Q=0. All surfaces are assumed to have a convection coefficient

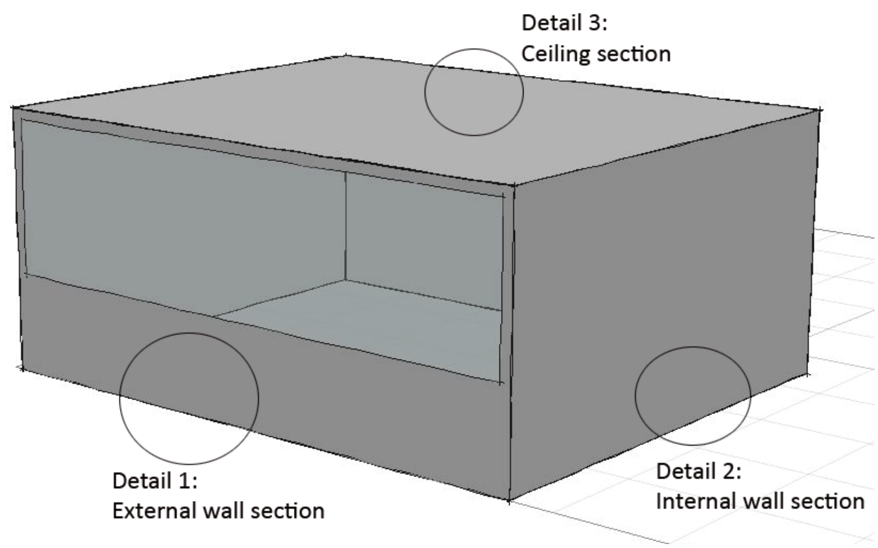


Fig. 58 The experimental chamber with the details of wall sections marked

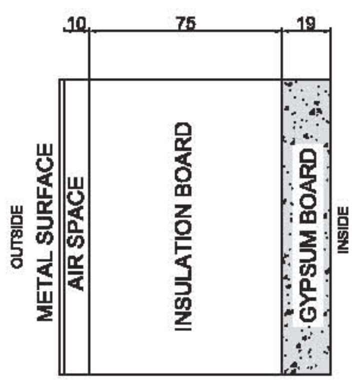


Fig. 59 Detail 1 - external wall section

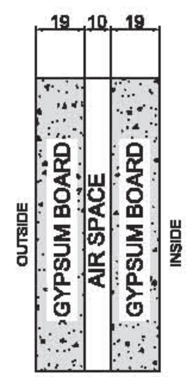


Fig. 60 Detail 2 - internal wall section

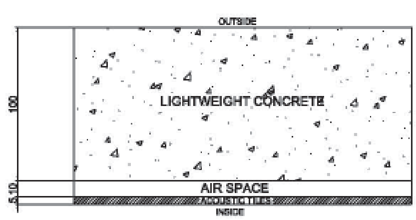


Fig. 61 Detail 3 - ceiling section

h=3W/m²K inside.

Initially, the temperature of the space is assumed to have a schedule based on the hours of operation of an office building. It is assumed that from 8am to 6pm the temperature is 27°C, so that the PCM will absorb the excess heat and from 6pm to 8am the temperature is set to 19°C, so that the PCM discharges and releases the heat to the air. A layer of 3mm plaster board with the properties of octadecane, as phase change material, is located inside all the surfaces of the chamber in the initial model. Specifically, the construction cases that are compared in this model are:

- 75mm insulation versus 75mm insulation with 3mm PCM inside
- 20mm heavyweight concrete versus 20mm heavyweight concrete with 3mm PCM inside

As already mentioned, phase change materials are used to substitute thermal mass in lightweight buildings. It is expected that the addition of phase change materials on a lightweight construction will control the temperature swings of the surface temperatures. Additionally, it is expected that the required space cooling loads will be decreased and also shifted in terms of time. The temperature of the interior surface of the floor and ceiling in the case of insulation construction is presented in Fig. 62. The temperature differences throughout the day are significantly reduced when a 3mm layer of phase change material is applied. Specifically, the inside surface temperature swing is only 3°C when phase change material is

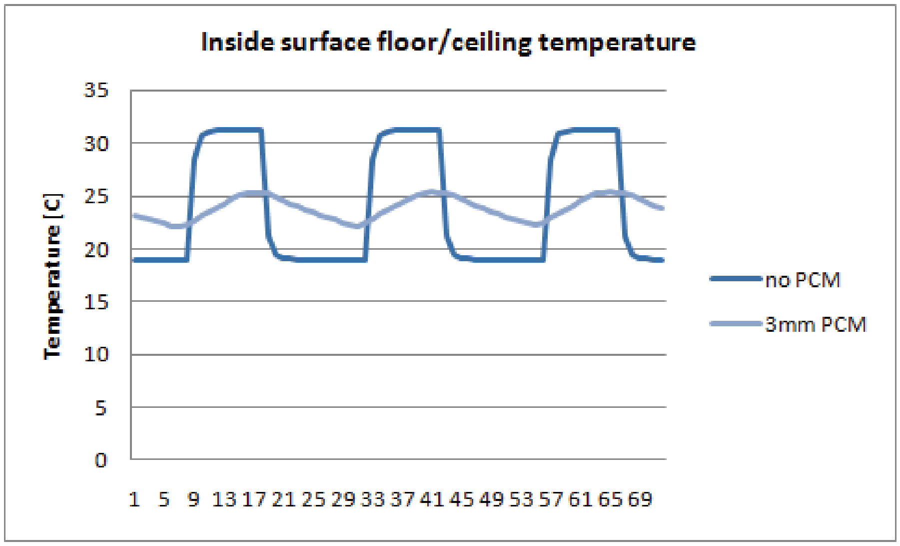


Fig. 62 Case 1 - insulation construction. Inside surface temprature of the floor and the ceiling of the initial chamber model, tested with and without PCM

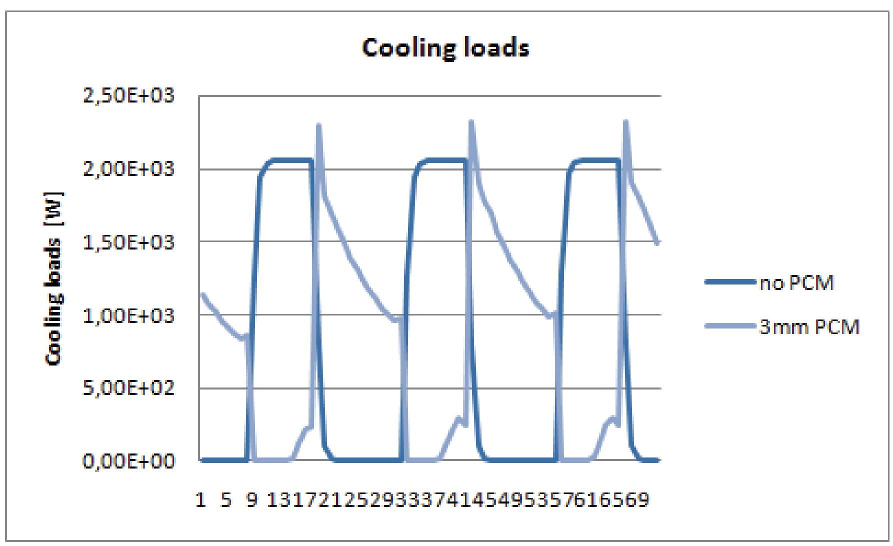


Fig. 63 Case 1 - insulation construction. Required cooling loads of the initial chamber model, tested with and without PCM

used, compared to 12°C when there is no phase change material. The required cooling loads are presented in Fig. 63. The cooling loads that are required during the operation hours are reduced significantly when phase change materials are used. Specifically, in this case, there are no cooling loads during the operation hours and the cooling loads occur later in the day compared to the case without phase change materials. The phase change materials absorb all the internal loads of the space, shifting the peak cooling load later in the day, when cheaper electricity rates occur. This effect is very important for a commercial building with high internal loads.

Heavyweight concrete is a material with high thermal mass, it is therefore expected that the effect of phase change materials will not be so significant in this case, compared to the case of insulation construction. It is expected that the temperature swing of the the interior floor and ceiling surface is controlled a little. Additionally, the required cooling loads are expected to be affected, but without shifting the cooling load peak. The temperature of the interior surface of the floor and ceiling of the concrete construction case is presented in Fig. 64. The temperature differences throughout the day are slightly reduced when a 3mm layer of phase change material is applied. Specifically, the inside surface temperature swing is 5°C when phase change material is used, compared to 8°C when there is no phase change material. The reduction in temperature swing is a lot smaller in this case, compared to the insulation construction. The required cooling loads are presented in Fig. 65. The cooling loads that are required dur-

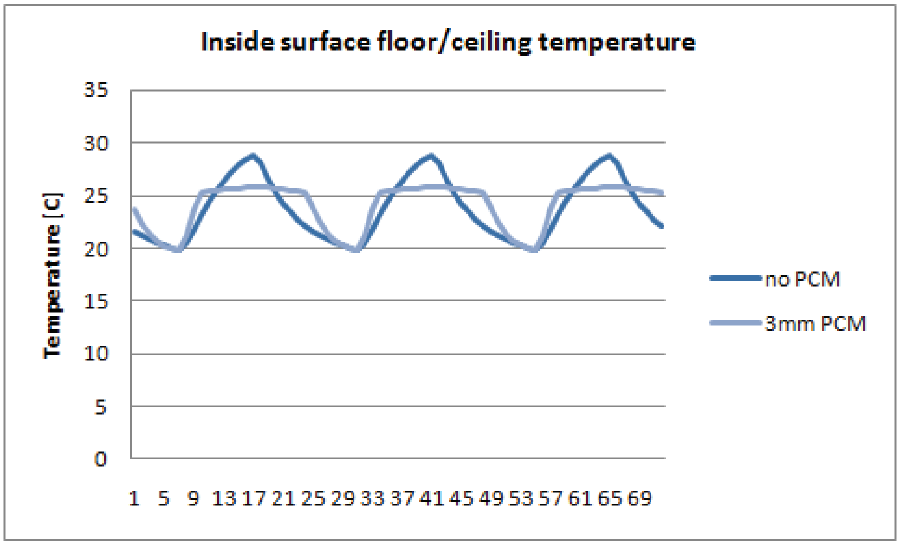


Fig. 64 Case 2 - heavyweight concrete construction. Inside surface temperature of the floor and the ceiling of the initial chamber model, tested with and without PCM

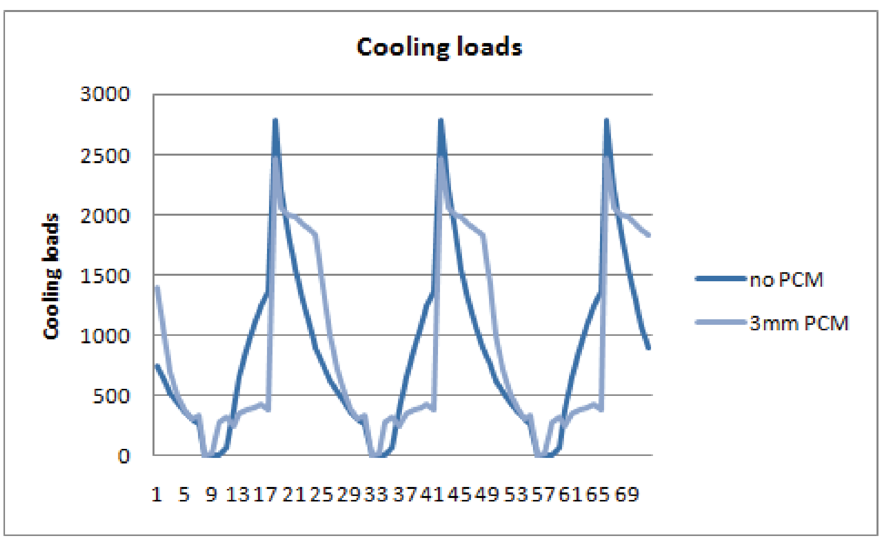


Fig. 65 Case 2 - heavyweight concrete construction. Required cooling loads of the initial chamber model, tested with and without PCM

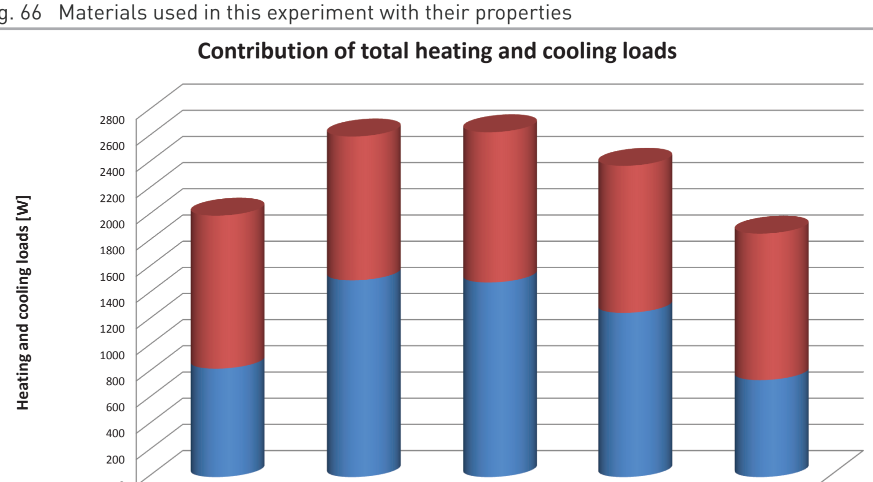
ing the operation hours are not significantly reduced when phase change materials are used. Specifically, in this case, only a small portion of the cooling loads is shifted later during the day. The phase change materials absorb all the internal loads of the space and releases it a little later in the day. The cooling load peak occurs exactly at the same time and its value is only 10% lower when phase change materials are used.

6.3. Material selection

Energy balance simulations of a PCM wall suggest that the phase change material melting temperature should be adjusted from the climate-specific optimal temperature to achieve maximum performance of the storage.[Fig. 63] A non-optimal melting temperature significantly reduces the latent heat of the storage capacity; a 3°C difference from the optimal temperature causes a 50% loss of latent heat storage capacity.[Fig. 63] In order to find the optimal melting temperature for the climate of Austin, the use of several different materials is tested. Specifically, a PCM/graphite composite material with melting temperature 21°C, solidification temperature 19°C and latent heat storage capacity 140kJ/kg[20], a compound material containing a PCM of paraffin wax with melting temperature 21.7°C, solidification temperature 18.7°C and latent heat storage capacity 170kJ/kg[22], an encapsulated organic material with melting temperature 23°C, solidification temperature 22°C and latent heat storage capacity 330kJ/kg[19] and, finally, encapsulated octadecane with melting temperature 26.3°C, solidification temperature 25.3°C and latent heat storage capacity 245kJ/kg are examined. A layer of 3mm plasterboard with the properties of the above materials is located

Material	Melting temperature [C]	Solidification temperature [C]	Latent heat capacity [kJ/kg]
PCM/graphite composite material	21	19	140
compound material containing a PCM of paraffin wax	21.7	18.7	170
encapsulated organic material	23	22	330
encapsulated octadecane	26.3	25.3	245

Fig. 66 Materials used in this experiment with their properties



	NO PCM	PCM/GRAPHITE COMPOSITE Tmelt=21C	PARAFFIN WAX Tmelt=21.7C	ORGANIC MATERIAL Tmelt=23C	OCTADECANE Tmelt=26.3C
Heating loads	1169,04296	1098,894551	1147,911225	1123,671646	1119,405217
Cooling loads	828,6179972	1503,475544	1486,956395	1254,852153	741,0531303

Fig. 67 Comparison of annual heating and cooling loads for various phase change materials

inside the chamber surfaces and the thermal performance of all cases is measured. The temperature of the space is set in a way that achieves the phase change of the materials, during the cooling period, and therefore achieves the optimal annual thermal performance. Specifically, the set-point temperature is assumed to be 1°C above the material's melting temperature during the office operation hours, from 8am to 6pm, so that the PCM absorbs the excess heat, and the temperature is set 1°C below the solidification temperature of the material from 6pm to 8am, so that the PCM discharges and releases the heat to the air. After performing this test, encapsulated octadecane with melting temperature 26.3°C, solidification temperature 25.3C and latent heat storage capacity 245kJ/kg appeared to have the lowest required cooling loads and thus it was used for the needs of this research. In[Fig. 66], there is a detailed overview of the various material properties. A comparison of the total heating and cooling loads for the examined cases is presented in Fig. 67.

6.4. Simulation description

The goal of this research is to examine the performance of phase change materials when the charging cycle of the materials is controlled. This way, the cooling energy demand is shifting towards the off-peak period. In order to perform this experiment several cases with various set-point temperature schedules were examined. For the purposes of this study the temperature of the space is assumed to have a schedule based on the hours of operation of an office building.

In order to investigate the optimum charging and discharging conditions of PCM, a layer of 2mm plasterboard with encapsulated octadecane is located on the chamber surfaces. This layer is located on the internal surface of the walls and below or above the acoustic tiles on the floor or ceiling, respectively. In order to effectively charge and discharge the phase change material during the cooling period, a set-point temperature schedule is created. It is assumed that in the morning, during the operation hours, the temperature is above the material's melting temperature, so that the PCM absorbs the excess heat, and the temperature is set below the solidification temperature of the material during the night time, so that the PCM discharges and releases the heat to the air. The set-point temperature is kept constant at 21°C during the winter, when the use of phase change materials is not desired. The energy performance of phase change materials after a ten hour, a twelve hour and a fourteen hour charging cycle is examined.

It is known that to keep the indoor air temperature in the comfort range for long time without heating and cooling load, the heat of fusion of a PCM should be high enough so as to keep the wall's inner surface at the melting temperature for a whole day or even a whole year. Another very important criterion for selecting the PCM is the melting temperature, which should be in the comfort temperature range. For a given climate condition and given buildings, if the melting temperature is too high, the quantity of solar radiation heat stored by the PCM will be too low in the daytime; if the melting temperature is too low, it is difficult to maintain the indoor air temperature at a comfortable level during the night.[11]

The exact value of the melting temperature should be selected according to the different conditions, such as buildings and climates. An analysis of a PCM wall in a passive solar house indicates that the optimal diurnal heat storage occurs with a melting temperature of 1–3°C above the average room temperature.[31]

The investigation of the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes revealed that the maximum diurnal energy storage occurs at a PCM melting point temperature that is close to the average comfort room temperature in most circumstances.[31] For wallboard installed on the building envelope, the optimal value of the melting temperature also depends on the outdoor temperature and the thermal resistance of the wall.[11] Based on these results, the set-point temperature schedules that are tested for the purposes of this study are in the range of 1-3°C above and below the melting temperature, respectively. Specifically, the cases that are examined for the cooling set-point temperature schedule are:

Case 1. Baseline case, no PCM, 25°C constant temperature
Case 1b. No PCM, 27°C constant temperature, in order to be in the same comfort level as the other cases.

Case 2a. 27°C from 8am-6pm and 24°C from 6pm-8am
Case 2b. 28°C from 8am-6pm and 23°C from 6pm-8am
Case 2c. 29°C from 8am-6pm and 22°C from 6pm-8am

Case 3a. 27°C from 8am-8pm and 24°C from 8pm-8am
Case 3b. 28°C from 8am-8pm and 23°C from 8pm-8am
Case 3c. 29°C from 8am-8pm and 22°C from 8pm-8am
Case 4a. 27°C from 8am-10pm and 24°C from 10pm-8am
Case 4b. 28°C from 8am-10pm and 23°C from 10pm-8am
Case 4c. 29°C from 8am-10pm and 22°C from 10pm-8am

Case 5a. 27°C from 10am-10pm and 24°C from 10pm-10am
Case 5b. 28°C from 10am-10pm and 23°C from 10pm-10am
Case 5c. 29°C from 10am-10pm and 22°C from 10pm-10am

A regression model based on the DOE-2.1E chiller models is developed to simulate the part load and off-design COP of the chiller in the examined operating schemes and finally calculate the total electric energy used in each case.[11]

The DOE2 model consists of the following three curves.

- CAPFT—a curve that represents the available capacity as a function of evaporator and condenser temperatures
- EIRFT—a curve that represents the full-load efficiency as a function of evaporator and condenser temperatures
- EIRFPLR—a curve that represents the efficiency as a function of the percentage of load.

In the case of the CAPFT and EIRFT, the model employs heat exchange fluid temperatures as a proxy for the refrigerant operating pressure in the evaporator and condenser. The chilled water supply temperature is used for the evaporator conditions of all electric chillers. The condenser water supply temperature is used for the condenser conditions of all water-cooled electric chillers. The outdoor dry-bulb temperature is used for the condenser conditions of all air-cooled electric chillers[30]. The format of the curves is as follows:

$$CPATF = a_1 + b_1 T_{CWS} + c_1 \cdot T_{CWS}^2 + \\ + d_1 \cdot T_{OA} + e_1 \cdot T_{OA}^2 + f_1 \cdot T_{CWS} \cdot T_{OA}$$

$$EIRFT = a_2 + b_2 T_{CWS} + c_2 \cdot T_{CWS}^2 + \\ + d_2 \cdot T_{OA} + e_2 \cdot T_{OA}^2 + f_2 \cdot T_{CWS} \cdot T_{OA}$$

$$EIRFPLR = a_3 + b_3 \cdot PLR + c_3 \cdot PLR$$

$$PLR = \frac{Q(\tau)}{Q_{NOMINAL} \cdot CPAFT}$$

$$P = P_{NOMINAL} \cdot CPAFT \cdot EIRFT \cdot EIRFPLR$$

where: T_{CWS} is the chilled water supply temperature (°C), T_{OA} is the outdoor air dry-bulb temperature (°C) for air-cooled equipment, Q is the the cooling power

(W), $Q_{NOMINAL}$ is the nominal cooling power (W), P is the electric consumption for the given cooling power (kW), $P_{NOMINAL}$ is the nominal electric consumption (kWh), PLR is a function representing the part-load operating ratio of the chiller, and a_i, b_i, c_i, d_i, e_i, and fi are the regression coefficients. The regression coefficients used for this model are presented in Fig. 68.

Finally, an investigation of the effect of material thickness, as well as the material placement is performed. Having the necessary thermal mass in the wall does not automatically mean that it is used. It takes a certain time to melt an amount of PCM with a given layer thickness. Phase change materials incorporated into a building in too thick layers will not melt and solidify completely by daily temperature variations. Then, part of the PCM is used only rarely or never, and thus is less economical. The amount of heat that can be stored and withdrawn daily from a wall was initially calculated. Subsequently, the total amount of PCM that can be effectively used is calculated. A calculation is performed on the effect of material thickness on the electric energy consumption. Finally, an investigation of the PCM thickness versus the surface area of the PCM is performed.

a_1	b_1	c_1	d_1	e_1	f_1
-0.09464899	0.0383407	-0.00009205	0.00378007	-0.00001375	-0.00015464
a_2	b_2	c_2	d_2	e_2	f_2
0.1354564	0.0229295	0.0001611	-0.002354	0.0001299	-0.000187
a_3	b_3	c_3			
0.909619	0.498962	0.274888			

Fig. 68 Regression coefficients for the calculation of electric consumption

6.5. Calculation of savings in electricity charges

After calculating the savings in electricity consumption, a calculation of the savings in electrical charges is performed. As previously mentioned, in order to level the electrical load, different pricing policies have been implemented in several countries, including the USA. Specifically, different prices are applied for on-peak and for off-peak hours and thus, effective energy management and economic benefit is achieved.

Based on this principle, the utility company of Austin; Austin Energy, has implemented a "Rider Time-of-Use (TOU) – Thermal Energy Storage" rate. This rate is applicable to any customer on the General Service - Demand, Primary Service, Large Primary Service (including Time-of-Use), Large Primary Special Contract Rider (including Time-of-Use), State General Service - Demand, State Primary Service, State Large Primary Service (including Time-of-Use), or Independent School Districts General Service - Demand (including Time-of-Use) rate who shifts to off-peak time periods no less than the lesser of 20% of the customer's normal on-peak "Summer Billed Demand" or 2,500 kW through the use of thermal energy storage technology. According to this rate, the on-peak hours are from 4:00 p.m. to 8:00 p.m., Monday through Friday; May 1 through October 31. Therefore, the off-peak hours are from 8:00 p.m. to 4:00 p.m., Monday through Friday; all day Saturday, Sunday, Memorial Day, Independence Day, and Labor Day; May 1 through October 31. Additionally, winter days; all day November 1 through April 30, are considered off-peak hours. One of the conditions of this particular service is that the on-peak load shall be shifted to off-peak; not eliminated or replaced by alternative fuels.

According to this rate, from

May through October, the summer billed demand shall be the highest fifteen-minute demand recorded during the on-peak period. The summer billed demand shall not be less than 50% of the normal on-peak summer billed demand. If more than 50% of the customer's load is attributable to cooling, the 50% floor will be waived. Additionaly, from November through April, the winter billed demand shall be the highest fifteen-minute demand recorded during the month, or 90% of the summer billed demand set in the previous summer; whichever is less.

For the purposes of this study, the savings on electric charges for cooling are calculated, since it is initially assumed that the heating system operates with gas. Therefore the potential savings of winter charges is not taken into account. A reasonable assumption, based on information provided from the city of Austin, is that an office building in Austin Texas is operated on the General Service - Demand. In this case, the demand rate for the on-peak hours is 14.03$/kW during the summer and 12.65$/kW during the winter. This rate is applied to the monthly peak load. The additional energy rate is 0.018$/kWh for the whole year. A "Fuel Adjustment Clause" of 0.03653$/kWh is applied during the whole year. The kilowatt demand during the fifteen-minute interval of greatest use during the current billing month as indicated or recorded by metering equipment installed by the City of Austin. When the power factor during the interval of greatest use is less than 85 percent, Billing Demand shall be determined by multiplying the indicated demand by 85 percent and dividing by the lower peak power factor. In order to calculate the annual savings in electric charges for cooling, the on-peak loads during the summer period are initially calculated based on this principle and thus, the total electrical charges. The percentage of savings achieved in each case is subsequently calculated.

6.6. Natural ventilation

Natural ventilation is the process of supplying and removing air through an indoor space by natural means. Natural ventilation systems rely on natural driving forces, such as wind and temperature difference between a building and its environment, to drive the flow of fresh air through a building. Both work on the principle of air moving from a high pressure to a low pressure zone. Natural ventilation systems are usually integrated into building systems where there is some mechanical support; these are called mixed mode or hybrid ventilation buildings.[Fig. 67]
Natural ventilation has the potential to significantly reduce the energy cost required for mechanical ventilation of buildings. These natural ventilation systems may reduce both first and operating costs compared to mechanical ventilation systems while maintaining ventilation rates that are consistent with acceptable indoor air quality. Also, some studies have indicated that occupants reported fewer symptoms in buildings with natural ventilation compared to buildings with mechanical ventilation.[Fig. 68] If natural ventilation can improve indoor environmental conditions, such improvements can also potentially increase occupant productivity by reducing absenteeism, reducing health care costs, and improving worker productivity. Because of these potential benefits, natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality within commercial buildings, particularly in the "green buildings" community. These proposals are often made without any engineering analysis to support the claimed advantages, e.g., without calculating expected ventilation rates or air distribution patterns. In addi-

tion, proven design approaches are not available in this country to incorporate natural ventilation into commercial building system designs.[Fig. 68] Natural ventilation strategies are less likely to reach the U.S. marketplace until design tools are made available and strategies are investigated and demonstrated for a variety of climates and construction types.[Fig. 68]

While natural ventilation is becoming more common in Europe, significant questions exist concerning its application in U.S. commercial buildings. These questions include the reliability of the outdoor air ventilation rates, distribution of this outdoor air within the building, control of moisture in naturally ventilated buildings, building pressurization concerns, and the entry of polluted air from outdoors without an opportunity to filter or clean it. One of the most important issues in determining the potential of natural ventilation systems is the suitability of the climate.[Fig. 68]

The climate of a location is affected by its latitude, terrain, altitude, ice or snow cover, as well as nearby water bodies and their currents. Climates can be classified according to the average and typical ranges of different variables, most commonly temperature and precipitation. The subtropics are characterized as the moist, subtropical, mid-latitude climates between the tropics and the moderated climates, immediately south and north of the tropics. It is important to note that for subtropical climates, there is no clear-cut division between hot-humid and moist-warm regions, which means that in a particular case the climatic parameters of a location need to be established and analyzed. Depending upon local conditions, the operation of cooling systems alone or combined systems for heating and cooling will be necessary.[1]

Austin has a humid subtropical climate, characterized by hot summers and mild winters. On average, Austin receives 853.4 mm of rain per year, with most of the precipitation in the spring, and a secondary maximum in the fall [42]. During springtime, severe thunderstorms sometimes occur, though tornados are rare in the city. Austin is usually at least partially sunny. Austin summers are usually hot and humid, with average temperatures of approximately 32°C from June until September. Temperatures above 38 °C are common. For the entire year, there is an average of 111 days above 32 °C and 198 days above 27 °C.[42] Winters in Austin are mild and dry. For the entire year, Austin averages 88 days below 7 °C and 24 days when the minimum temperature falls below freezing.[42] The hot and humid summers in Austin create a challenge for the effectiveness of natural ventilation in commercial buildings.

In order to assess the effectiveness of natural ventilation and night cooling in discharging the phase change materials, a simulation model with natural ventilation is created in addition to the PCM. The electric energy consumption is plotted and compared. The cases that are examined and compared for the purposes of this study are:
Case A: Best case of the above investigation (described in section 6.4)
Case B: Natural ventilation during the entire day and night
Case C: Night ventilation

7. Results

7.1. South orientation of facade

The simulation of the several cases of set-point temperature schedule for charging and discharging the phase change materials is performed because it is expected that the space cooling requirement will shift towards the night depending on the charging cycle. The contribution of the ideal cooling loads for three typical summer days is presented in Fig. 69, Fig. 70, Fig. 71 and Fig.

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 2a
27°C from 8am to 6pm
24°C from 6pm to 8am

Case 2b
28°C from 8am to 6pm
23°C from 6pm to 8am

Case 2c
29°C from 8am to 6pm
22°C from 6pm to 8am

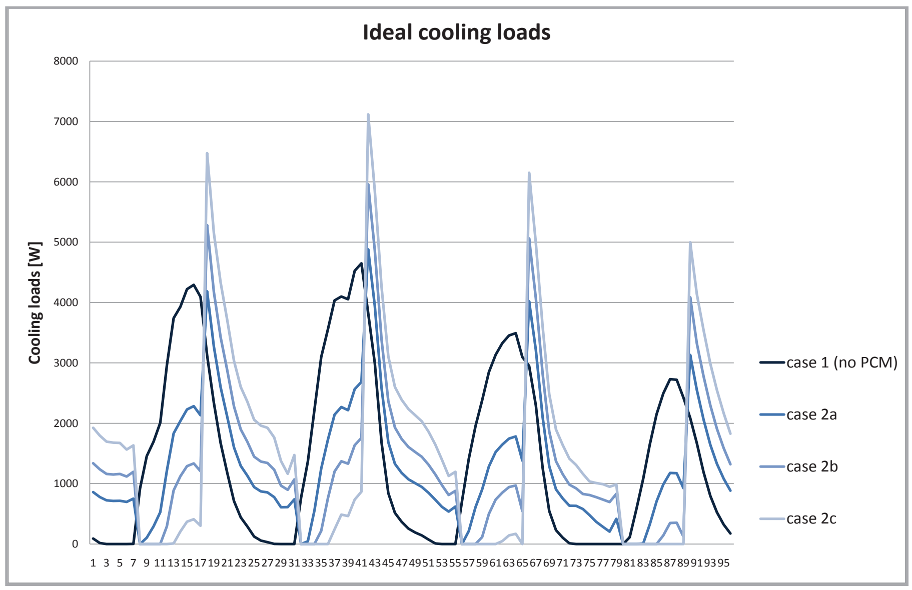


Fig. 69 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 2a, 2b and 2c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 3a
27°C from 8am to 8pm
24°C from 8pm to 8am

Case 3b
28°C from 8am to 8pm
23°C from 8pm to 8am

Case 3c
29°C from 8am to 8pm
22°C from 8pm to 8am

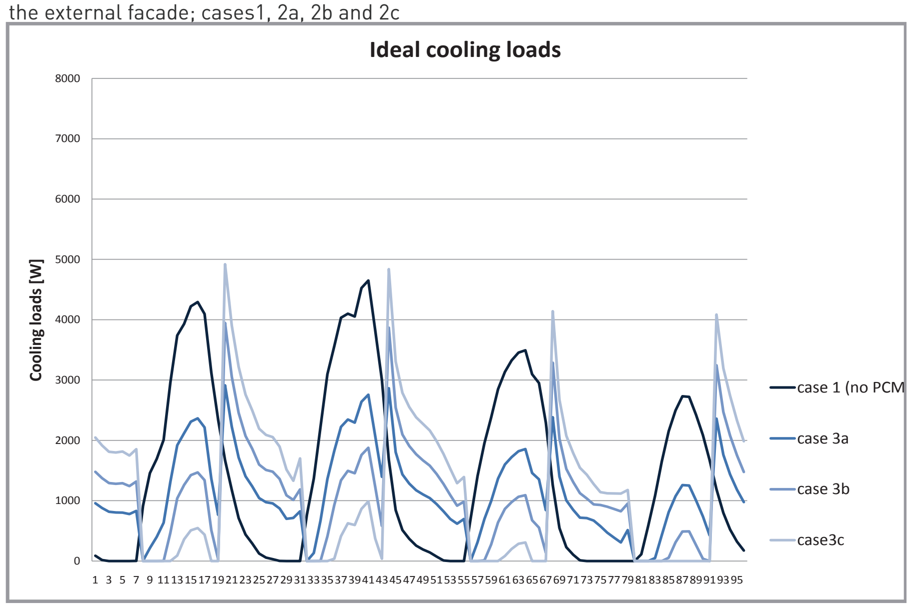


Fig. 70 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 3a, 3b and 3c

71, respectively, for the various set-point temperature schedules and different charging cycles. It is observed from the figures that while the shifting of the cooling demand depends on the charging cycle, the required peak load varies depending on the set-point temperature schedule that is assigned. A charging cycle of fourteen hours (cases 4a, 4b and 4c) leads to lower peak loads than

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 4a
27°C from 8am to 10pm
24°C from 10pm to 8am

Case 4b
28°C from 8am to 10pm
23°C from 10pm to 8am

Case 4c
29°C from 8am to 10pm
22°C from 10pm to 8am

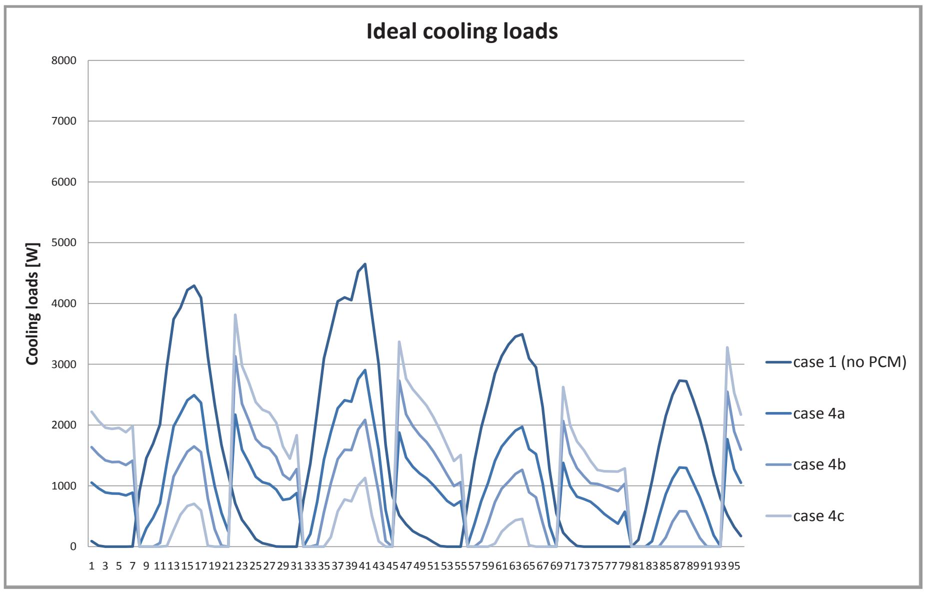


Fig. 71 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 4a, 4b and 4c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 5a
27°C from 10am to 10pm
24°C from 10pm to 10am

Case 5b
28°C from 10am to 10pm
23°C from 10pm to 10am

Case 5c
29°C from 10am to 10pm
22°C from 10pm to 10am

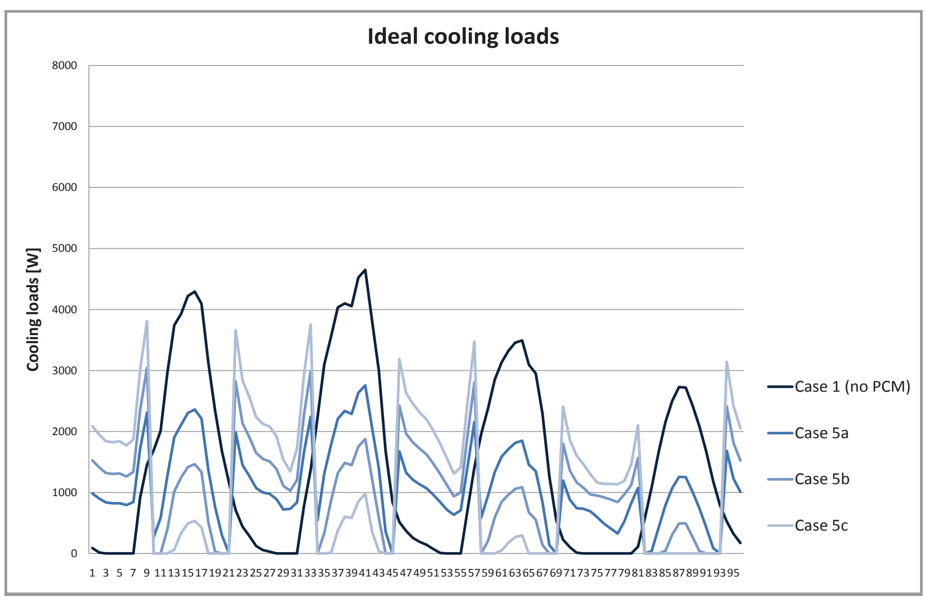


Fig. 72 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 5a, 5b and 5c

Case	Average chiller COP	Annual Electric consumption [kWh]	Saving in annual electricity consumption, compared to 25°C constant temperature %	Saving in annual electricity consumption compared to 27°C constant temperature %
1a	2,48	878,03		
1b	1,92	590,55	32,74%	
2a	2,74	768,26	12,50%	-30,09%
2b	2,50	942,53	-7,35%	-59,60%
2c	2,37	1088,13	-23,93%	-84,26%
3a	2,99	615,85	29,86%	-4,28%
3b	1,43	706,28	19,56%	-19,60%
3c	1,37	839,09	4,43%	-42,09%
4a	2,91	563,69	35,80%	4,55%
4b	2,67	579,64	33,98%	1,85%
4c	2,30	676,75	22,92%	-14,60%
5a	2,65	747,30	14,89%	-26,54%
5b	2,98	593,37	32,42%	-0,48%
5c	2,64	691,98	21,19%	-17,18%

Fig. 73 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

Case	Average chiller COP	Annual Electric consumption [kWh]	Savings in annual electricity consumption due to concrete construction %	Savings in annual electricity consumption due to PCM%
no PCM / no concrete: 24C-27C	2,33	734,42		
no PCM: 24C-27C	2,74	617,71	15,89%	
PCM: Case 4a	2,91	563,69		8,74%
no PCM / no concrete: 23C-28C	2,35	712,18		
no PCM: 23C-28C	2,72	610,52	14,27%	
PCM: Case 4b	2,67	579,64		5,06%
no PCM / no concrete: 22C-29C	2,39	716,97		
no PCM: 22C-29C	2,43	710,21	0,94%	
PCM: Case 4c	2,30	676,75		4,71%

Fig. 74 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

a twelve hour cycle (cases 3a, 3b and 3c), while a charging cycle of twelve hours leads to lower peak loads than a ten hour charging cycle (cases 2a, 2b and 2c). It is also observed in each of these figures that in cases that most of the cooling demand is shifted, the highest peak cooling load occurs. For example, in cases 2c, 3c, 4c and 5c almost all of the cooling load is shifted later during the day, but these cases seem to have 20-40% higher peak load requirement compared to cases 2b, 3b, 4b, 5b and2a, 3a, 4a, 5a, respectively.

The annual electricity consumption, as well as the savings in annual electricity consumption are presented in Fig. 73. In this figure, column 4 shows the percentage of savings in electric consumption when all the cases are compared to case 1 (no PCM, constant temperature 25°C). The examined case 4a, where the set-point temperature is 27°C from 8am to 10pm and 24°C from 10pm to 8am, appears to have the optimal energy performance. Additionally, it is observed that the average coefficient of performance is higher in this case, compared to the other examined cases. A reduction of almost 36% in electricity consumption is achieved with a fourteen hour charging cycle with the set-point temperature only 1°C above the melting point and below the solidification point, respectively, when a 2mm layer of encapsulated octadecane is used. Also, a reduction of almost 34% in electricity consumption is achieved with a fourteen hour charging cycle with the set-point temperature only 2°C above the melting point and below the solidification point, respectively, when a 2mm layer of encapsulated octadecane is used. It is also observed that there is a 32.5% reduction of annual electricity consumption when a ten hour charging cycle is applied; with set-point temperature 28°C from 10am to 10pm and 23°C from 10pm to 10am.

Since it would be more accurate to keep the same comfort level in all cases, the same calculation is performed with a constant temperature of 27°C (case 1b). Column 5 of Fig. 73 shows the total savings of each case, when they are compared to case 1b, which has the same thermal comfort level. As expected, case 4a has the optimal performance, achieving 4.5% reduction in electric consumption. Additionaly, 1.85% reduction of the electric consumption is achieved when case 4b is applied. In this comparison, it seems that all the other cases have a negative effect in the electric energy consumption.

Shifting of the daily cooling requirement in the performed experiments can be partly explained, either by the concrete construction of the floor and ceiling, or simply by the various set-point temperature schedules assigned to the space. The effect of these parameters is investigated and the additional savings achieved by the addition of phase change materials is calculated. Specifically, a set-point temperature schedule similar to the one assigned in the examined cases 4a, 4b and 4c, where the set-point temperature is 27°C, 28°C and 29°C from 8am to 10pm and 24°C, 23°C and 22°C from 10pm to 8am, respectively, is used for this test. These schedules are assigned to the initial baseline case, where there are no PCMs. The ideal cooling loads of each case is subsequently compared to the respective case with PCM construction, as well as with a respective case without PCM and without concrete of the floor and ceiling. The comparison of the average COP and the annual electricity consumption of these cases are presented in Fig. 74. The total savings achieved only by the addition of PCM are 8.7% for case 4a, 5% for case 4b and 4.7% for case 4c.

The amount of PCM used is critical for the design of a thermal energy storage system, since the energy stored daily depends on the specific mass of the phase change material. Additionally, the surface area of the PCM is critical for the design, since the energy stored daily depends on the surface area of the material. A simulation of various material thicknesses is performed in order to evaluate the effect of material thickness to the thermal performance of the chamber. In order to investigate the effect of the material surface area versus its thickness, the same experiment is performed for several cases of PCM placement. Specifically, three cases of material placement are examined:

1. PCM on the floor and ceiling of the chamber
2. PCM on the walls of the chamber
3. PCM on all the internal surfaces of the chamber

The comparison of the average COP and the annual electricity consumption for the various cases is presented in Fig. 75. Additionally, the savings in electricity consumption is only 2% when PCMs are located on the ceiling and the floor of the chamber, while the respective savings when PCM are applied on all the internal surfaces are 10%. Apart from the small surface area of the floor and ceiling, a possible explanation for this fact is that phase change materials are located behind 3mm acoustic tiles that do not allow free convection on the chamber floor and ceiling. The simulation of various material thicknesses has not revealed a significant change in the system's operating efficiency and therefore the observed savings in electricity demand are minimal.

Additionally, the electric consumption per surface area of PCM is presented in the same figure. It seems that the placement of the material can create a significant difference in the energy performance of the building. Specifically, when the PCM

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [KW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,74	617,71		
ceiling-floor / 1mm	2,77	607,10	25,30	1,72%
ceiling-floor / 2mm	2,77	606,35	25,26	1,84%
ceiling-floor 3mm	2,77	605,85	25,24	1,92%
ceiling-floor / 5mm	2,79	605,17	25,22	2,03%
ceiling-floor/ 10mm	2,81	605,09	25,21	2,04%
walls / 1mm	2,94	567,37	7,47	8,15%
walls / 2mm	2,92	564,27	7,42	8,65%
walls / 3mm	2,91	562,37	7,40	8,96%
walls / 5mm	2,89	559,79	7,37	9,38%
walls / 10mm	2,86	555,81	7,31	10,02%
all surfaces / 1mm	2,94	567,00	5,56	8,21%
all surfaces / 2mm	2,91	563,69	5,67	8,74%
all surfaces / 3mm	2,90	561,92	5,64	9,03%
all surfaces / 5mm	2,89	559,36	5,62	9,45%
all surfaces / 10mm	2,87	555,54	5,59	10,06%

Fig. 75 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

is placed on the floor and ceiling the average electric consumtion is 25.25kWh/m^2 . Subsequently, when the PCM is placed on the surrounding walls or on all the surrounding surfaces of the space the electric energy consumption is 7.3kWh/m^2 and 5.5kW/m^2, respectively. The results of this experiment reveal that the material placement is far more important than the material thickness.

In order to better evaluate the effect of material placement and thickness, the total amount of PCM needed to absord the excess heat is calculated. The average daily cooling load is E_{daily}=1500W, based on the contribution of cooling loads of case 1 (Fig. 69). The energy stored daily in the PCM is: $E_{daily}=m_{cp}\cdot h_{fg}$,

where m_{cp} is the specific mass of material and h_{fg} is the enthalpy of the material.

As mentioned earlier, octadecane has latent heat storage capacity h_{fg}=245kJ/kg and density p=790kg/m^3. Therefore, the required mass of PCM and subsequently the required PCM volume is:

$$m_{pcm} = \frac{130 \cdot 10^6 J}{245 \cdot 10^3 J/kg} = 530kg$$

$$V = \frac{m}{\rho} = \frac{530kg}{790kg/m^3} = 0.67m^3$$

In order to place this amount of material to various surfaces, different material thicknesses should be applied. The required material thickness for each surface is calculated.

1. PCM on the floor and ceiling of the chamber - total surface area A=24m^2.
Thickness=Volume/area=28mm

2. PCM on the walls of the chamber - total surface area A=76m^2.
Thickness= Volume/area=9mm

3. PCM on all the surrounding surfaces of the chamber - total surface area A=100m^2.
Thickness= Volume/area=7mm

The results of this investigation are presented in Fig. 76. It is observed from the results that placing PCM in a large thickness on the floor and ceiling has a negative effect on the electric consumption of the space. On the other hand, when a smaller material thickness is placed on a larger surface area, there is a reduction of almost 7% in the electric consumption. The electric energy consumption per surface area is similar to the above experiment. When the PCM is placed on the floor and ceiling, it is 26.09kWh/m^2, while it drops to 7.57kWh/m^2 and 5.78kWh/m^2, when it is placed into the walls or into all the surounding building surfaces respectively.

The electrical charges for the various cases of set-point temperature schedules, as well as the percentage of saving in electrical charges in each case are calculated and presented in Fig. 77. The cases that appear to have the largest savings in electrical charges are different than those that have the largest reduction in electic energy consumption. This seems to be the effect of shifting the daily electric energy requirement towards the off-peak hours. As already mentioned, in this cases the required peak load is higher compared to the other cases. This peak load occurs during off-peak hours and therefore it is not included in the calculation of electrical charges. When comparing the examined cases with case 1b -constant temperature 27C in order to have the same comfort level- the largest percentage of savings in electrical charges reaches 39.14% and it is observed for case 4c, when there is a twelve hour charging cycle with set-point temperature schedule is 22°C during the office hours and 29°C during the night. Another interesting observation is

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,74	617,71		
floor-ceiling / 28mm	2,82	606,35	25,26	1,84%
walls / 9mm	2,87	555,79	7,31	10,02%
all surfaces / 7mm	2,89	558,23	5,58	9,63%

Fig. 76 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

Case	On-peak electrical charges $	Saving in annual electrical charges compared to 25°C constant temperature %	Saving in annual electrical charges compared to 27°C constant temperature %
1	821235,66		
1b	570270,86	30,56%	
2a	657944,95	19,88%	-15,37%
2b	766440,39	6,67%	-34,40%
2c	896592,6025	-9,18%	-57,22%
3a	516028,98	37,16%	9,51%
3b	599638,28	26,98%	-5,15%
3c	705436,73	14,10%	-23,70%
4a	471144,42	42,63%	17,38%
4b	400857,67	51,19%	29,71%
4c	347076,4046	57,74%	39,14%
5a	476515,28	41,98%	16,44%
5b	411269,96	49,92%	27,88%
5c	365862,71	55,45%	35,84%

Fig. 77 Calculation of the amount of savings in electrical charges for each of the examined cases

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption %
no ventilation	2,76	613,38	
ventilation all day/night	2,73	608,27	0,01
night ventilation 22pm-8am	2,73	608,27	0,01

Fig. 78 Calculation of the amount of saving in electricity consumption when natural ventilation is used as a cooling strategy

that case 2a, 2b and 2c appear to have higher electric charges that case 1b. The set-point temperature schedule assigned on the space in combination with phase change materiasls seems to be an important factor in minimizing the electrical charges. The addtion of PCM in the building components leads to a shifting of energy demand, which leads to this significant amount of savings. Controlling the charging and discharging of the PCM can, therefore, control the time-shifting of the peak energy demad.

The addition of natural ventilation to the model does not seem to have an important effect, as expected. The hot and humid climate of Austin creares a major disadvantage in the efectiveness of natural ventilation. Fig. 78 shoes the comparison of the average COP and the electrical consumtion of the examined cases; without ventilation, with ventilation for the whole day and with night ventilation. Specifically, the addition of night ventilation, from 22:00pm to 08:00am, leads to a reduction of the electricity consumption of only 0.1%. The same reduction in electricity consumption is achieved when the natural ventilation is allowed for the whole day.

7.2. East orientation of facade

A similar performance is expected when the chamber is simulated with the external facade oriented to the east. The contribution of the ideal cooling loads is presented in Fig. 79, Fig. 80, Fig. 81 and Fig. 82, respectively, for the various

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 2a
27°C from 8am to 6pm
24°C from 6pm to 8am

Case 2b
28°C from 8am to 6pm
23°C from 6pm to 8am

Case 2c
29°C from 8am to 6pm
22°C from 6pm to 8am

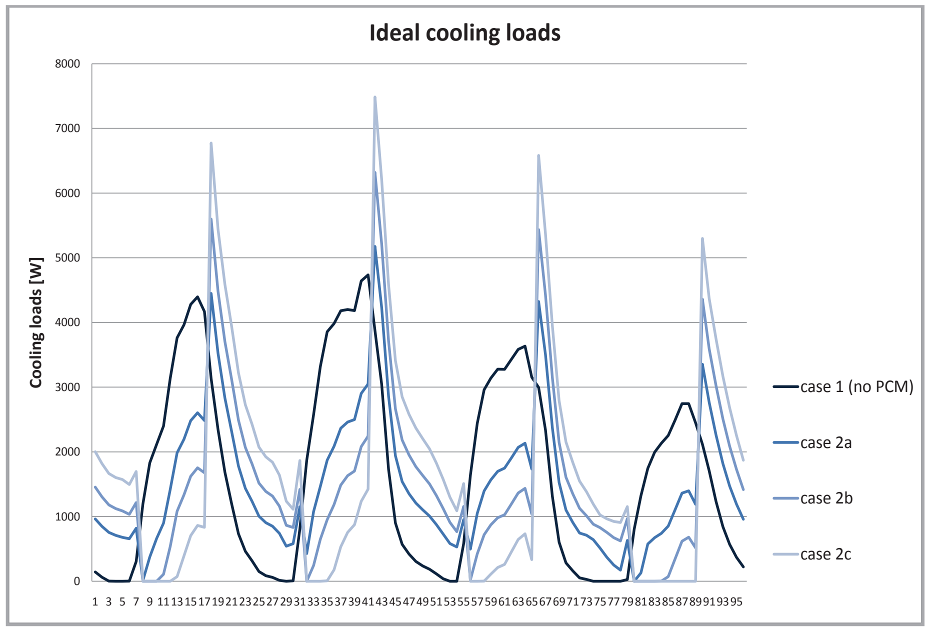


Fig. 79 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 2a, 2b and 2c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 3a
27°C from 8am to 8pm
24°C from 8pm to 8am

Case 3b
28°C from 8am to 8pm
23°C from 8pm to 8am

Case 3c
29°C from 8am to 8pm
22°C from 8pm to 8am

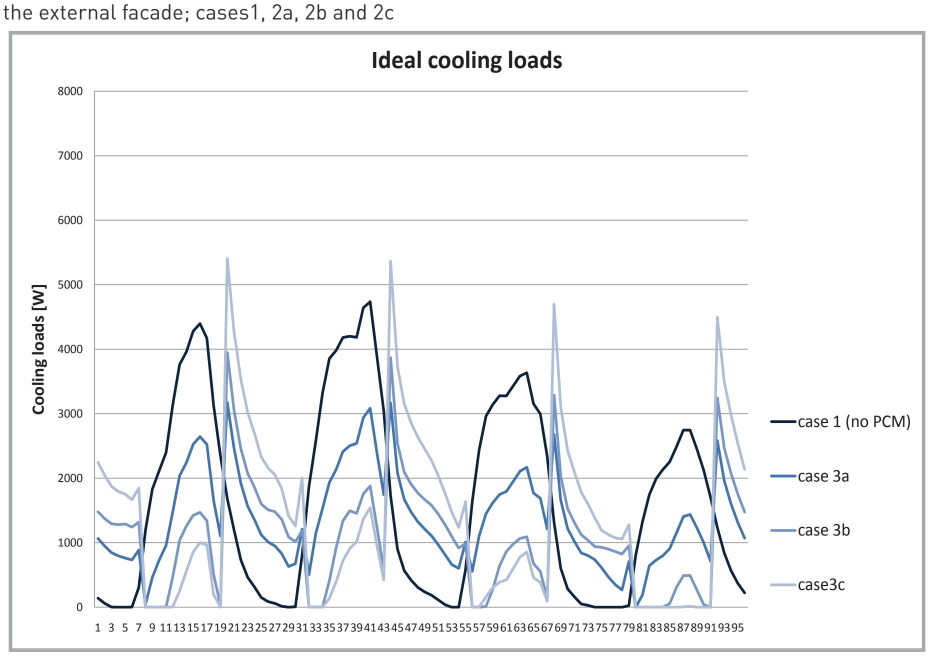


Fig. 80 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 3a, 3b and 3c

set-point temperature schedules and different charging cycles. It is observed from the figures that while the shifting of the cooling demand depends on the charging cycle, the required peak load varies depending on the set-point temperature schedule that

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 4a
27°C from 8am to 10pm
24°C from 10pm to 8am

Case 4b
28°C from 8am to 10pm
23°C from 10pm to 8am

Case 4c
29°C from 8am to 10pm
22°C from 10pm to 8am

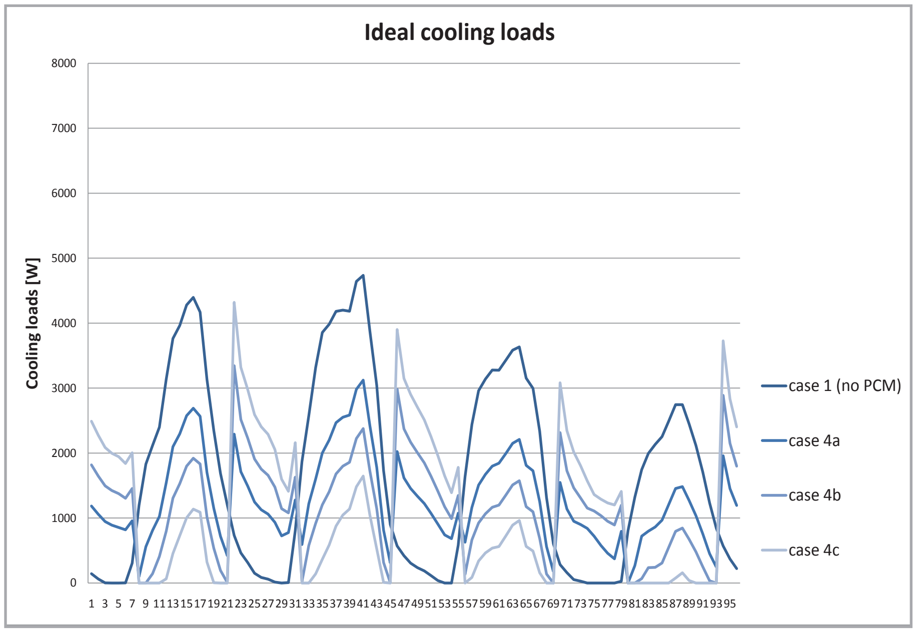


Fig. 81 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 4a, 4b and 4c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 5a
27°C from 10am to 10pm
24°C from 10pm to 10am

Case 5b
28°C from 10am to 10pm
23°C from 10pm to 10am

Case 5c
29°C from 10am to 10pm
22°C from 10pm to 10am

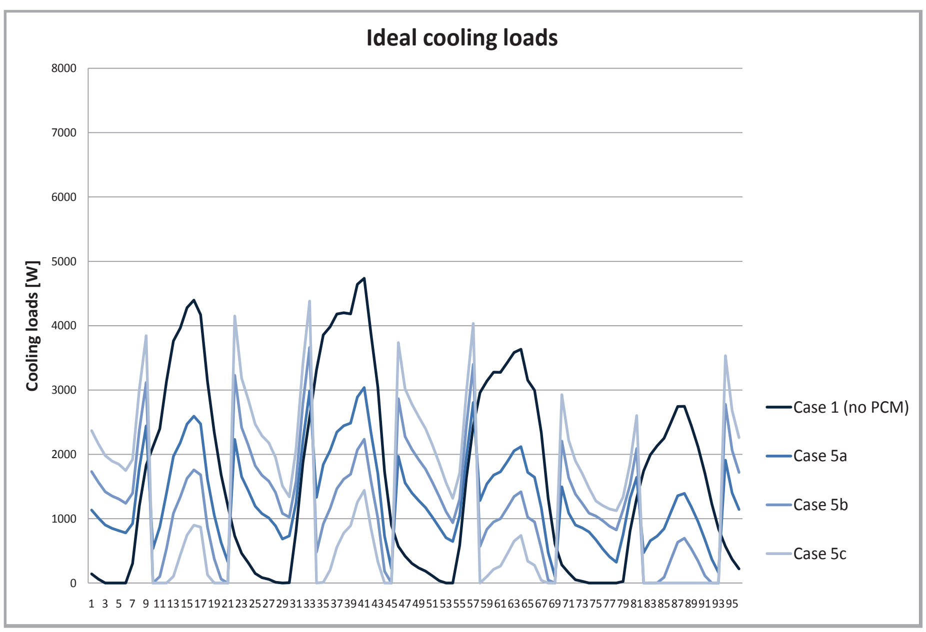


Fig. 82 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 5a, 5b and 5c

is assigned. A charging cycle of fourteen hours (cases 4a, 4b and 4c) leads to lower peak loads than a twelve hour cycle (cases 3a, 3b and 3c), while a charging cycle of twelve hours leads to lower peak loads than a ten hour charging cycle (cases 2a, 2b and 2c). It is also observed in each of these figures that in cases that most of the cooling demand is shifted, the highest peak cooling load occurs. For example, in cases 2c, 3c, 4c and 5c almost all of the cooling load is shifted later during the day, but these cases seem to have 20-40% higher peak load requirement compared to cases 2b, 3b, 4b, 5b and2a, 3a, 4a, 5a, respectively.

The annual electricity consumption, as well as the savings in annual electricity consumption are presented in Fig. 83. In this figure, column 4 shows the percentage of savings in electric consumption when all the cases are compared to case 1 (no PCM, constant temperature 25°C). The examined case 4a, where the set-point temperature is 27°C from 8am to 10pm and 24°C from 10pm to 8am, appears to have the optimal energy performance achieving a 31% reduction in electricity consumption. Additionally, it is observed that the average coefficient of performance is higher in this case, compared to the other examined cases. A reduction of almost 30% in electricity consumption is achieved with a fourteen hour charging cycle with the set-point temperature only 2°C above the melting point and below the solidification point, respectively, when a 2mm layer of encapsulated octadecane is used. It is also observed that there is a 29% reduction of annual electricity consumption when a twelve-hour charging cycle is applied; with set-point temperature 28°C from 10am to 10pm and 23°C from 10pm to 10am.

As in the south orientation case, in order to keep the same comfort level in all cases, the same calculation is performed with a constant temperature of 27°C (case 1b). Column 5 of Fig. 83 shows the total savings of each case, when they are compared to case 1b, which has the same thermal

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption, compared to 25°C constant temperature %	Saving in annual electricity consumption, compared to 27°C constant temperature %
1	2,61	895,61		
1b	1,87	717,05	19,94%	
2a	2,80	788,65	11,94%	-9,99%
2b	2,52	955,37	-6,67%	-33,24%
2c	2,42	1096,12	-22,39%	-52,87%
3a	3,07	637,41	28,83%	11,11%
3b	1,37	765,91	14,48%	-6,81%
3c	1,33	921,67	-2,91%	-28,54%
4a	2,96	616,35	31,18%	14,04%
4b	2,76	619,74	30,80%	13,57%
4c	2,36	722,41	19,34%	-0,75%
5a	2,71	778,93	13,03%	-8,63%
5b	2,91	672,37	24,93%	6,23%
5c	2,62	756,29	15,56%	-5,47%

Fig. 83 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

comfort level. As expected, case 4a has the optimal performance, achieving 14% reduction in electric consumption. Additionaly, 13.5% reduction of the electric consumption is achieved when case 4b is applied and 6.5% when case 5b is applied. It is observed from the results that in the east orientation the savings in electric consumption are significantly higher that in the south orientation case.

The effect of the concrete construction of the floor and ceiling, as well as the effect of different set-point temperature schedule is subsequently investigated. The additional savings achieved by the addition of phase change materials is calculated. Fig. 85 shows the comparison of the average COP and the annual electricity consumption of the examined cases. The total savings achieved only by the addition of PCM are 1.5% for case 4a, 1.25% for case 4b and 0.4% for case 4c. It is observed that the effect of phase change materials is not significant in an east oriented space.

A simulation of various material thicknesses is performed in order to evaluate the effect of material thickness to the thermal performance of the chamber. The comparison of the average COP and the annual electricity consumption for the various cases is presented in Fig. 86. The savings in electricity consumption is minimal; only 0.5% when PCMs are located on the ceiling and the floor of the chamber, while the respective savings when PCM are applied on all the internal surfaces are almost 7%. The simulation of various material thicknesses has not revealed a significant change in the system's operating efficiency in this case as well, and therefore the observed savings in electricity demand are minimal.

The effect of the material placement to the electric consumption per surface area of PCM is also similar to the south orientation case and it presented in Fig. 86. It seems that the placement of the material can create a significant

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption due to concrete construction %	Savings in annual electricity consumption due to PCM %
no PCM / no concrete: 24C-27C	2,33	734,42		
no PCM: 24C-27C	2,98	626,20	14,74%	
PCM: Case 4a	2,96	616,35		1,57%
no PCM / no concrete: 23C-28C	2,35	712,18		
no PCM: 23C-28C	2,91	627,61	11,88%	
PCM: Case 4b	2,76	619,74		1,25%
no PCM / no concrete: 22C-29C	2,39	716,97		
no PCM: 22C-29C	2,58	725,10	-1,13%	
PCM: Case 4c	2,36	722,41		0,37%

Fig. 84 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

difference in the energy performance of the building. Specifically, when the PCM is placed on the floor and ceiling the average electric consumtion is 26.7kWh/m^2 . Subsequently, when the PCM is placed on the surrounding walls or on all the surrounding surfaces of the space the electric energy consumption is 7.95kWh/m^2 and 6.0kWh/m^2, respectively. The results of this experiment reveal that the material placement is far more important than the material thickness. The electric energy consumption per surface area of the PCM is a little higher in this case compared to the south oriented external facade.

In order to better evaluate the effect of material placement and thickness, the total amount of PCM needed to absorb the excess heat and subsequently the material thickness required for each surface is calculated. The examined PCM placement is similar to the south orientation case.

1. PCM on the floor and ceiling of the chamber - total surface area A=24m^2.
Thickness=Volume/area=28mm

2. PCM on the walls of the chamber - total surface area A=76m^2.
Thickness= Volume/area=9mm
3. PCM on all the surrounding surfaces of the chamber - total surface area A=100m^2.
Thickness= Volume/area=7mm

The results of this investigation are also very similar to the south orientation case and they are presented in Fig. 86. It is observed from the results that placing PCM in a large thickness on the floor and ceiling has a negative effect on the electric consumption of the space. On the other hand, when a smaller material thickness is placed on a larger surface area, there is a reduction of almost 7% in the electric consumption. The electric energy consumption per surface area is similar to the above experiment. When the PCM is placed on the floor and ceiling, it is 26.4kWh/m^2, while it drops to 8.21kWh/m^2 and 6.04kWh/m^2, when it is placed into the walls or into all

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,92	646,08		
floor-ceiling / 1mm	2,90	645,75	26,91	0,05%
floor-ceiling / 2mm	2,90	645,43	26,89	0,10%
floor-ceiling / 3mm	2,90	645,20	26,88	0,14%
floor-ceiling / 5mm	2,89	644,53	26,86	0,24%
floor-ceiling / 10mm	2,88	643,10	26,80	**0,46%**
walls / 1mm	3,03	608,31	8,00	5,85%
walls / 2mm	3,00	606,70	7,98	6,09%
walls / 3mm	2,98	605,81	7,97	6,23%
walls / 5mm	2,97	604,32	7,95	6,46%
walls / 10mm	2,93	602,40	7,93	**6,76%**
all surfaces / 1mm	3,02	608,18	6,08	5,87%
all surfaces / 2mm	2,99	606,41	6,06	6,14%
all surfaces / 3mm	2,97	605,34	6,05	6,31%
all surfaces / 5mm	2,96	604,26	6,04	6,47%
all surfaces / 10mm	2,91	601,35	6,01	**6,92%**

Fig. 85 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

the surounding building surfaces respectively.

The electrical charges for the various cases of set-point temperature schedules, as well as the percentage of saving in electrical charges in each case are calculated and presented in Fig. 86. The cases that appear to have the largest savings in electrical charges are different to those that have the largest reduction in electic energy consumption, as in the south oriented facade. When comparing the examined cases with case 1b -constant temperature 27°C in order to have the same comfort level- the largest percentage of savings in electrical charges reaches 35.12% and it is observed for case 4c, when there is a twelve hour charging cycle with set-point temperature schedule is 22°C during the office hours and 29°C during the night. In general terms, the savings in electrical charges are similar to the case of south orientated external facade. This experiment supports the notion that controlling the charging and discharging of the PCM can control the time-shifting of the peak energy demand.

The addition of natural ventilation to the model does not seem to have an important effect, as expected. The hot and humid climate of Austin creares a major disadvantage in the effectiveness of natural ventilation. Specifically the results are the same as in the south orientation case. Fig. 88 shows the comparison of the average COP and the electrical consumtion of the examined cases; without ventilation, with ventilation for the whole day and with night ventilation. Specifically, the addition of night ventilation, from 22:00pm to 08:00am, leads to a reduction of the electricity consumption of only 0.1%. The same reduction in electricity consumption is achieved when the natural ventilation is allowed for the whole day.

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,92	646,08		
floor-ceiling / 28mm	2,87	633,61	26,40	1,93%
walls / 9mm	2,97	624,29	8,21	3,37%
all surfaces / 7mm	2,95	603,55	6,04	6,58%

Fig. 86 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

Case	On-peak electrical charges $	Savings in electrical charges, compared to 25°C constant temperature %	Savings in electrical charges, compared to 25°C constant temperature %
1	813.521,68		
1b	563.907,01	30,68%	
2a	685.954,91	15,68%	-21,64%
2b	791.978,97	2,65%	-40,44%
2c	918.779,18	-12,94%	-62,93%
3a	516.028,98	36,57%	8,49%
3b	599.638,28	26,29%	-6,34%
3c	736.202,41	9,50%	-30,55%
4a	488.313,85	39,98%	13,41%
4b	419.016,88	48,49%	25,69%
4c	365.886,91	**55,02%**	**35,12%**
5a	494.276,06	39,24%	12,35%
5b	429.527,68	47,20%	23,83%
5c	381.616,08	**53,09%**	**32,33%**

Fig. 87 Calculation of the amount of savings in electrical charges for each of the examined cases

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption %
no ventilation	2,76	613,38	
ventilation all day/night	2,73	608,27	0,01
night ventilation 22pm-8am	2,73	608,27	0,01

Fig. 88 Calculation of the amount of saving in electricity consumption when natural ventilation is used as a cooling strategy

7.3. West orientation of facade

A similar performance is expected when the chamber is simulated with the external facade oriented to the east. The contribution of the ideal cooling loads is presented inFig. 89, Fig. 90, Fig. 91 and Fig. 92, respectively, for the various set-point temperature schedules and different charging cycles. It is observed from the figures that while the shifting of the cooling demand depends on the

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 4a
27°C from 8am to 10pm
24°C from 10pm to 8am

Case 4b
28°C from 8am to 10pm
23°C from 10pm to 8am

Case 4c
29°C from 8am to 10pm
22°C from 10pm to 8am

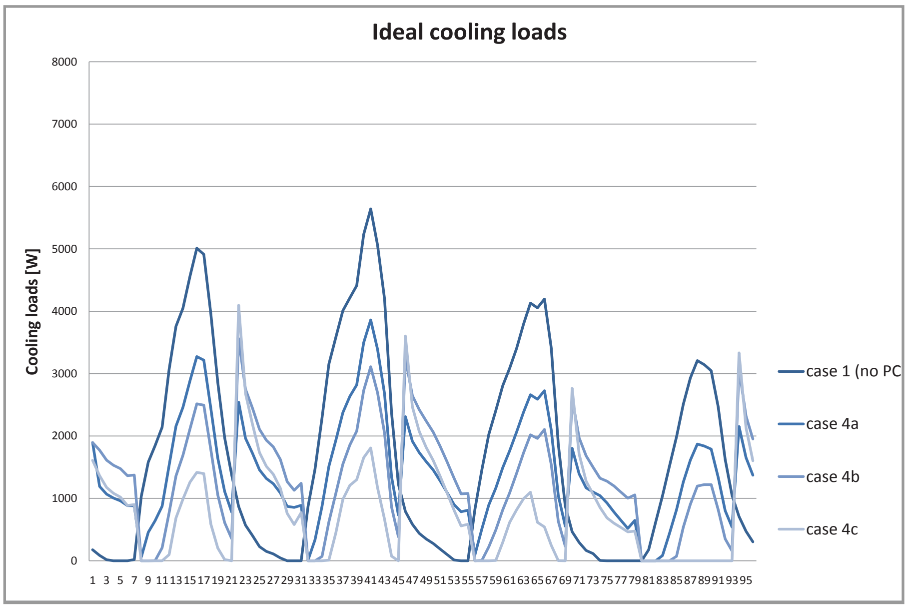


Fig. 89 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 2a, 2b and 2c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 5a
27°C from 10am to 10pm
24°C from 10pm to 10am

Case 5b
28°C from 10am to 10pm
23°C from 10pm to 10am

Case 5c
29°C from 10am to 10pm
22°C from 10pm to 10am

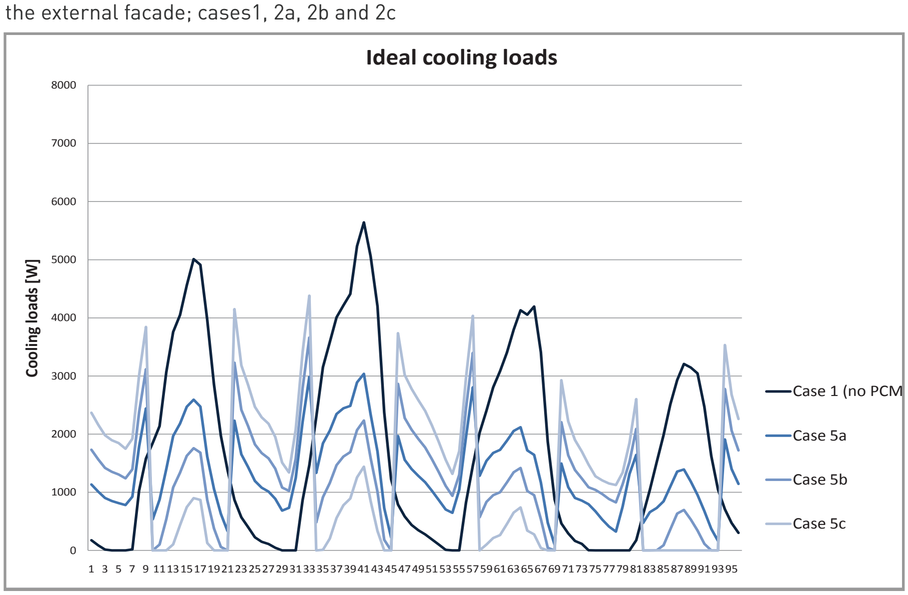


Fig. 90 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 3a, 3b and 3c

charging cycle, the required peak load varies depending on the set-point temperature schedule that is assigned. A charging cycle of fourteen hours (cases 4a, 4b and 4c) leads to lower peak loads than a twelve hour cycle (cases 3a, 3b and 3c), while a charging cycle of twelve hours leads to lower peak loads than a ten hour charging cycle (cases 2a, 2b and 2c). It is also observed in each of these figures that in cases that most of the cooling demand is shifted, the

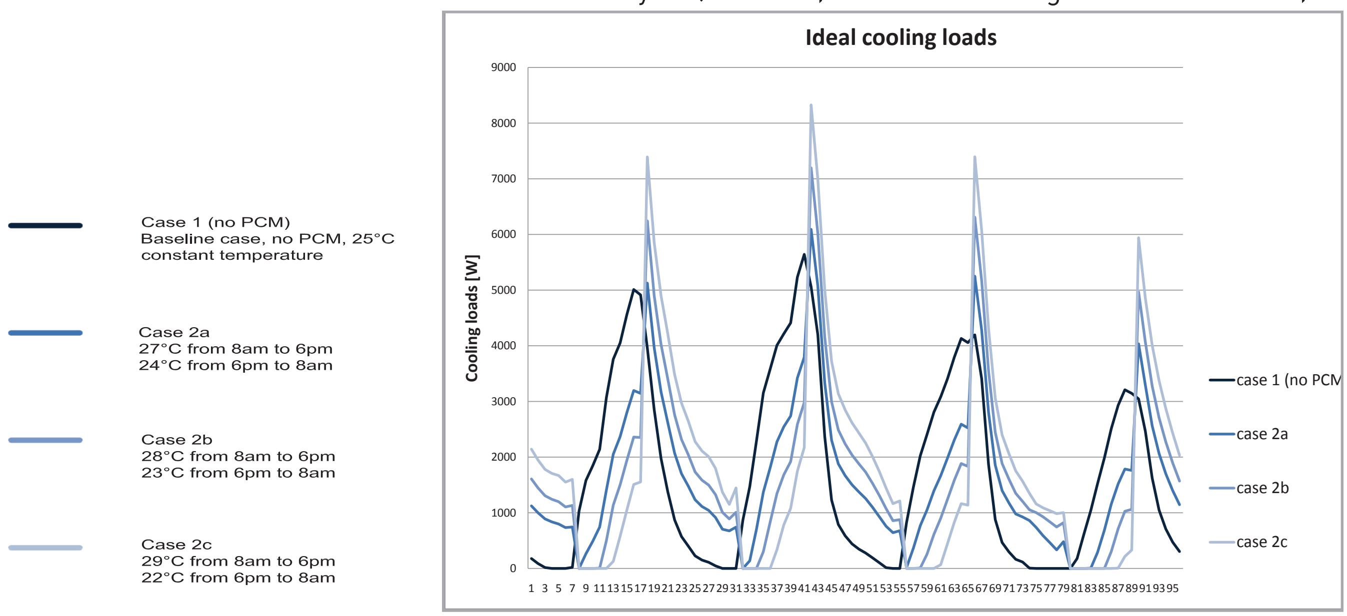


Fig. 91 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 4a, 4b and 4c

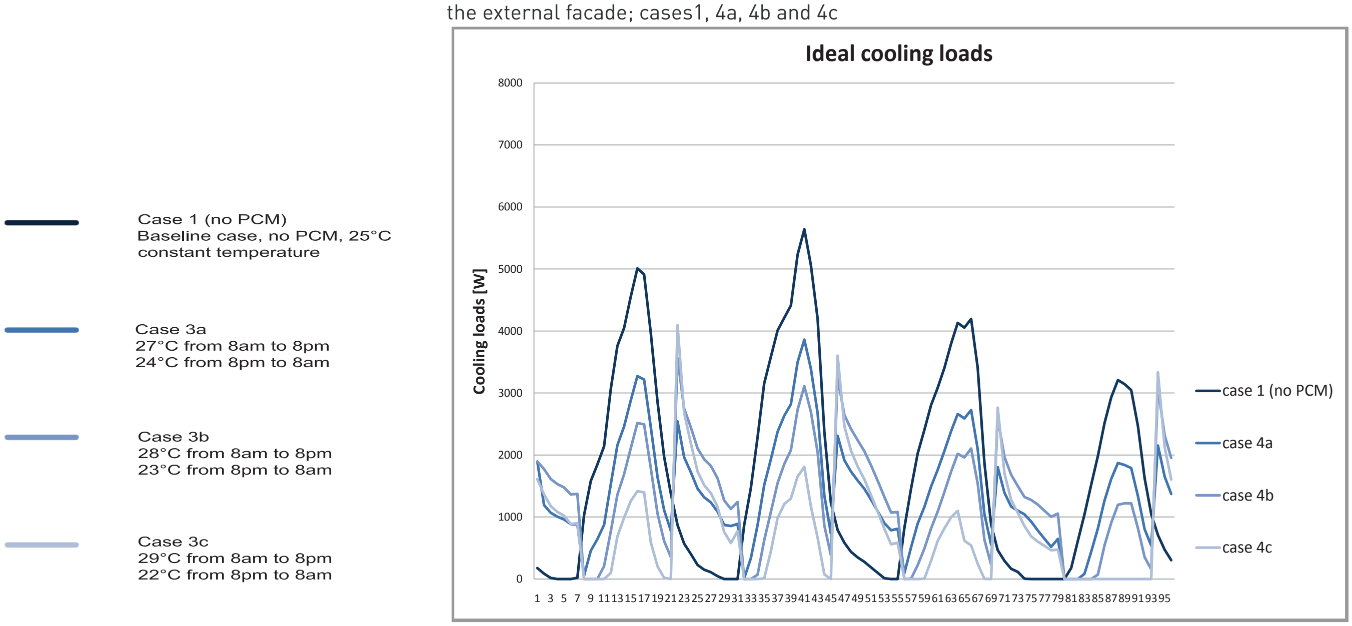


Fig. 92 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 5a, 5b and 5c

highest peak cooling load occurs. For example, in cases 2c, 3c, 4c and 5c almost all of the cooling load is shifted later during the day, but these cases seem to have 20-40% higher peak load requirement compared to cases 2b, 3b, 4b, 5b and2a, 3a, 4a, 5a, respectively.

The annual electricity consumption, as well as the savings in annual electricity consumption are presented in Fig. 93. The examined case 4a, where the set-point temperature is 27°C from 8am to 10pm and 24°C from 10pm to 8am, appears to have the optimal energy performance achieving a 24% reduction in electricity consumption. Additionally, it is observed that the average coefficient of performance is higher in this case, compared to the other examined cases. A reduction of almost 23% in electricity consumption is achieved with a fourteen hour charging cycle with the set-point temperature only 2°C above the melting point and below the solidification point, respectively, when a 2mm layer of encapsulated octadecane is used. It is also observed that there is a 18% reduction of annual electricity consumption when a twelve-hour charging cycle is applied; with set-point temperature 28°C from 10am to 10pm and 23°C from 10pm to 10am. The comparison of the average COP and the annual electricity consumption of the examined cases without PCM are presented in Fig. 93.

As in the south orientation case, in order to keep the same comfort level in all cases, the same calculation is performed with a constant temperature of 27°C (case 1b). Column 5 of Fig. 93 shows the total savings of each case, when they are compared to case 1b, which has the same thermal comfort level. As expected, case 4a has the optimal performance, achieving 12% reduction in electric consumption. Additionaly, 11.7% reduction of the electric consumption is achieved when case 4b is applied and 10.9% when case 4c is applied. It is observed from the results that in the west orientation the savings in electric consumption are significantly higher that in the south orientation case.

The effect of the concrete con-

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption, compared to 25°C constant temperature %	Saving in annual electricity consumption, compared to 27°C constant temperature %
1a	2,45	867,22		
1b	1,93	748,24		
2a	2,94	832,16	4,04%	-11,22%
2b	2,57	1051,48	-21,25%	-40,53%
2c	2,58	1145,95	-32,14%	-53,15%
3a	3,19	700,43	19,23%	6,39%
3b	1,44	765,91	11,68%	-2,36%
3c	1,43	921,67	-6,28%	-23,18%
4a	3,16	658,51	24,07%	11,99%
4b	2,93	660,49	23,84%	11,73%
4c	2,12	666,80	23,11%	10,88%
5a	3,30	692,41	20,16%	7,46%
5b	3,12	713,67	17,71%	4,62%
5c	2,80	828,18	4,50%	-10,68%

Fig. 93 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

struction of the floor and ceiling, as well as the effect of different set-point temperature schedule is subsequently investigated. The additional savings achieved by the addition of phase change materials is calculated. Fig. 94 shows the comparison of the average COP and the annual electricity consumption of the examined cases. The total savings achieved only by the addition of PCM are negative for case 4a, 1.5% for case 4b and 11.4% for case 4c. It is observed that in the west orientation a fourteen hour cycle set-point schedule, from 8am to 10 pm, is more effective given the movement of the sun. The amount of solar radiation late during the day leads to higher internal gains and therefore keeping the PCM melted during that time is more energy efficient.

A simulation of various material thicknesses is performed in order to evaluate the effect of material thickness to the thermal performance of the chamber. The comparison of the average COP and the annual electricity consumption for the various cases is presented in Fig. 95. The savings in electricity consumption is minimal; only 0.5% when PCMs are located on the ceiling and the floor of the chamber, while the respective savings when PCM are applied on all the internal surfaces are almost 7.2%. The simulation of various material thicknesses has not revealed a significant change in the system's operating efficiency in this case as well, and therefore the observed savings in electricity demand are minimal.

The effect of the material placement to the electric consumption per surface are of PCM is also also similar to the south orientation case and it presented in Fig. 95. Specificcaly, when the PCM is placed on the floor and ceiling the average electric consumtion is 29.8kWh/m^2 . Subsequently, when the PCM is placed on the surrounding walls or on all the surrounding surfaces of the space the electric energy consumption is 8.8kWh/m^2 and 6.7kWh/m^2, respectively. The results of this experiment reveal that the material placement is far more important than the material thickness. The electric energy consumption per surface area of the PCM is

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption due to concrete construction %	Savings in annual electricity consumption due to PCM %
no PCM / no concrete 24C-27C	2,33	734,42		
no PCM: 24C-27C	2,94	668,48	8,98%	
PCM: Case 4a	3,16	658,51		1,49%
no PCM / no concrete 23C-28C	2,35	712,18		
no PCM: 23C-28C	2,93	655,72	7,93%	
PCM: Case 4b	2,93	660,49		-0,73%
no PCM / no concrete 22C-29C	2,39	716,97		
no PCM: 22C-29C	2,65	749,58	-4,55%	
PCM: Case 4c	2,12	666,80		11,04%

Fig. 94 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

higher in this case compared to the south and the east oriented external facade.

In order to better evaluate the effect of material placement and thickness, the total amount of PCM needed to absord the excess heat and subsequently the material thickness required for each surface is calculated. The examined PCM placement is similar to the south orientation case.

1. PCM on the floor and ceiling of the chamber - total surface area A=24m^2.
Thickness=Volume/area=28mm

2. PCM on the walls of the chamber - total surface area A=76m^2.
Thickness= Volume/area=9mm

3. PCM on all the surrounding surfaces of the chamber - total surface area A=100m^2.
Thickness= Volume/area=7mm

The results of this investigation are also very similar to the south orientation case and they are presented in figure Fig. 96. It is observed from the results that placing PCM in a large thickness on the floor and ceiling has a negative effect on the electric consumption of the space. On the other hand, when a smaller material thickness is placed on a larger surface area, there is a reduction of almost 7% in the electric consumption. The electric energy consumption per surface area is similar to the above experiment. When the PCM is placed on the floor and ceiling, it is 26.4kWh/m^2, while it drops to 8.21kWh/m^2 and 6.04kWh/m^2, when it is placed into the walls or into all the surounding building surfaces respectively.

The electrical charges for the various cases of set-point temperature schedules, as well as the percentage of saving in electrical charges in each case are calculated and presented in Fig. 97. When comparing the examined cases with case 1b -constant temperature 27^{o}C in order to have the same comfort level- the largest percentage of savings in electrical charges reaches 46% and it is observed for case 4c, when there is a fourteen hour charging cycle with set-point tempera-

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,94	668,48		
floor-ceiling / 1mm	2,91	667,86	27,83	0,09%
floor-ceiling / 2mm	2,91	667,41	27,81	0,16%
floor-ceiling / 3mm	2,91	667,23	27,80	0,19%
floor-ceiling / 5mm	2,90	666,56	27,77	0,29%
floor-ceiling / 10mm	2,90	665,22	27,72	**0,49%**
walls / 1mm	3,18	665,59	8,76	0,43%
walls / 2mm	3,16	663,77	8,73	0,70%
walls / 3mm	3,13	662,04	8,71	0,96%
walls / 5mm	3,10	659,26	8,67	1,38%
walls / 10mm	3,08	656,55	8,64	**1,78%**
all surfaces / 1mm	3,15	663,48	6,63	0,75%
all surfaces / 2mm	3,15	663,48	6,63	0,75%
all surfaces / 3mm	3,10	660,81	6,61	1,15%
all surfaces / 5mm	3,10	659,14	6,59	1,40%
all surfaces / 10mm	3,05	655,08	6,55	**2,00%**

Fig. 95 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

ture schedule is 22°C during the office hours and 29°C during the night. As already mentioned, in the case of west oriented external facade a fourteen hour cycle seems to have the best performance. Controlling the charging and discharging of the PCM can control the time-shifting of the peak energy demand and therefor the required savings in electric energy and in electric charges can be achieved.

The addition of natural ventilation to the model does not seem to have an important effect, as expected. The hot and humid climate of Austin creares a major disadvantage in the efectiveness of natural ventilation. Specifically the results are the same as in the south orientation case. Fig. 98 shoes the comparison of the average COP and the electrical consumtion of the examined cases; without ventilation, with ventilation for the whole day and with night ventilation. Specifically, the addition of night ventilation, from 22:00pm to 08:00am, leads to a reduction of the electricity consumption of only 0.1%. The same reduction in electricity consumption is achieved when the natural ventilation is allowed for the whole day.

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,33	668,48		
floor-ceiling / 28mm	2,90	664,92	27,70	0,53%
walls / 9mm	3,11	652,58	8,59	2,38%
all surfaces / 7mm	3,07	650,65	6,51	2,67%

Fig. 96 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

Case	On-peak electrical charges $	Savings in annual electrical charges, compared to 25°C constant temperature %	Savings in annual electrical charges, compared to 27°C constant temperature %
1	665627,42		
1b	631586,08		
2a	772067,03	-15,99%	-22,24%
2b	879463,28	-32,13%	-39,25%
2c	1007870,38	-51,42%	-59,58%
3a	603230,14	9,37%	4,49%
3b	687343,81	-3,26%	-8,83%
3c	793251,12	-19,17%	-25,60%
4a	562150,90	15,55%	10,99%
4b	493163,23	25,91%	21,92%
4c	334963,31	49,68%	46,96%
5a	568918,66	14,53%	9,92%
5b	505040,19	24,13%	20,04%
5c	461446,03	30,68%	26,94%

Fig. 97 Calculation of the amount of savings in electrical charges for each of the examined cases

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption %
no ventilation	2,76	613,38	
ventilation all day/night	2,73	608,27	0,01
night ventilation 22pm-8am	2,73	608,27	0,01

Fig. 98 Calculation of the amount of saving in electricity consumption when natural ventilation is used as a cooling strategy

7.4. North orientation of facade

A similar performance is expected when the chamber is simulated with the external facade oriented to the north. The contribution of the ideal cooling loads is presented in Fig. 99, Fig. 100, Fig. 101 and Fig. 102, respectively, for the various set-point temperature schedules and different charging cycles. It is observed from the fig-

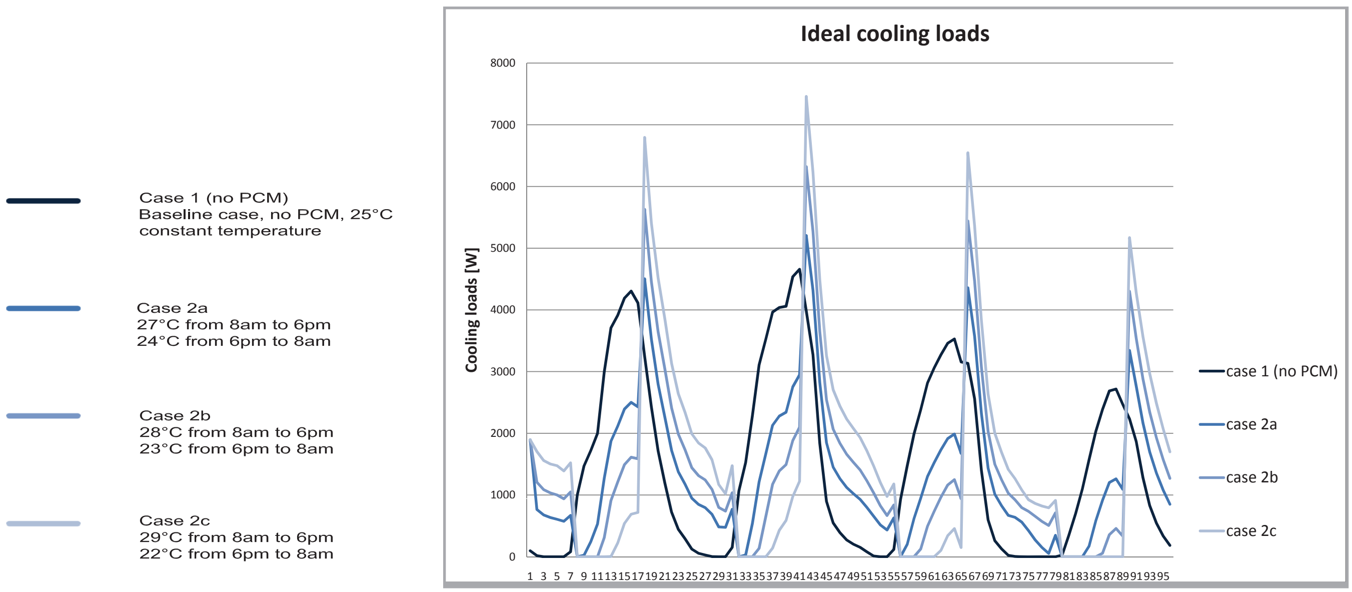


Fig. 99 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 2a, 2b and 2c

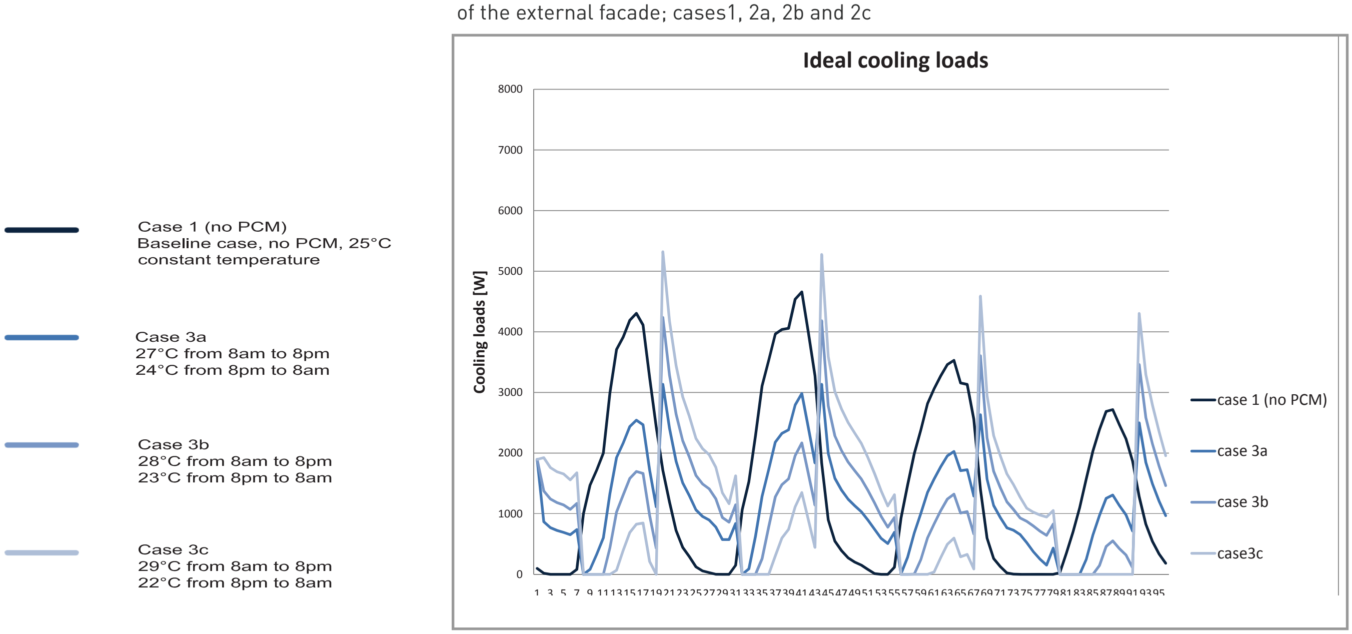


Fig. 100 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 3a, 3b and 3c

ures that while the shifting of the cooling demand depends on the charging cycle, the required peak load varies depending on the set-point temperature schedule that is assigned. A charging cycle of fourteen hours (cases 4a, 4b and 4c) leads to lower peak loads than a twelve hour cycle (cases 3a, 3b and 3c), while a charging cycle of twelve hours leads to lower peak loads than a ten hour charging

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 4a
27°C from 8am to 10pm
24°C from 10pm to 8am

Case 4b
28°C from 8am to 10pm
23°C from 10pm to 8am

Case 4c
29°C from 8am to 10pm
22°C from 10pm to 8am

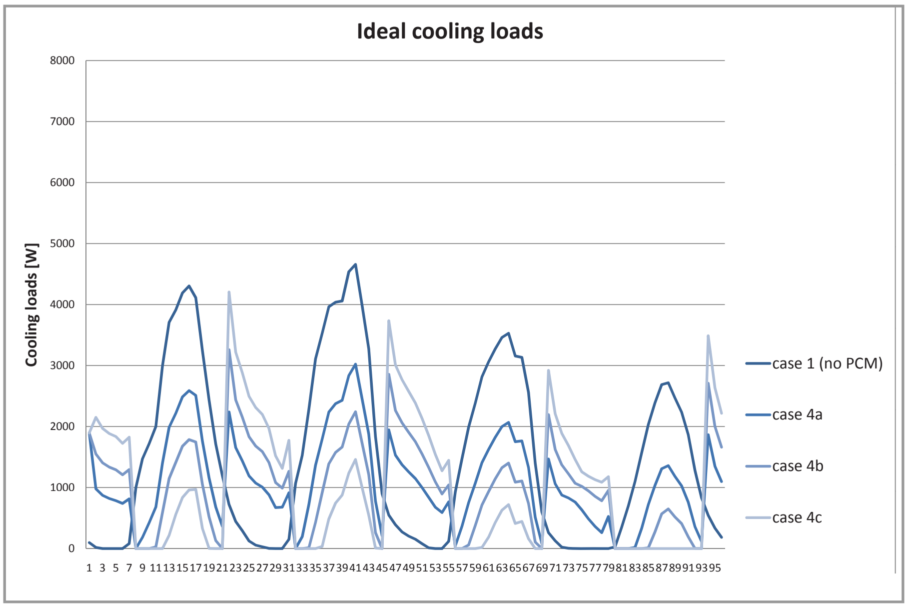


Fig. 101 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 4a, 4b and 4c

Case 1 (no PCM)
Baseline case, no PCM, 25°C constant temperature

Case 5a
27°C from 10am to 10pm
24°C from 10pm to 10am

Case 5b
28°C from 10am to 10pm
23°C from 10pm to 10am

Case 5c
29°C from 10am to 10pm
22°C from 10pm to 10am

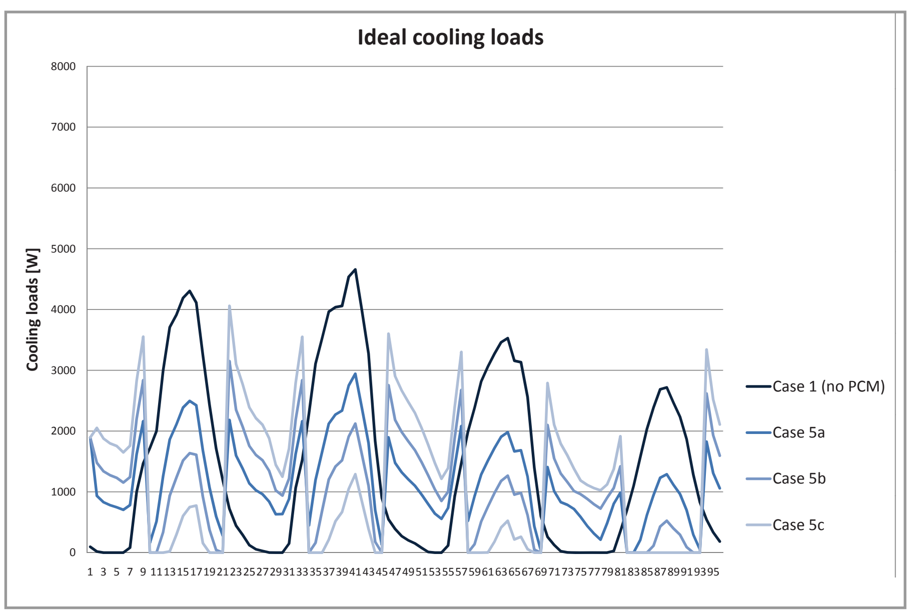


Fig. 102 Contribution of ideal cooling loads for three typical summer daysfor south orientation of the external facade; cases1, 5a, 5b and 5c

cycle (cases 2a, 2b and 2c). It is also observed in each of these figures that in cases that most of the cooling demand is shifted, the highest peak cooling load occurs. For example, in cases 2c, 3c, 4c and 5c almost all of the cooling load is shifted later during the day, but these cases seem to have 20-40% higher peak load requirement compared to cases 2b, 3b, 4b, 5b and2a, 3a, 4a, 5a, respectively.

The annual electricity consumption, as well as the savings in annual electricity consumption are presented in Fig. 103. The examined case 4a, where the set-point temperature is 27°C from 8am to 10pm and 24°C from 10pm to 8am, appears to have the optimal energy performance achieving a 32% reduction in electricity consumption. Additionally, it is observed that the average coefficient of performance is higher in this case, compared to the other examined cases. A reduction of almost 30% in electricity consumption is achieved with a fourteen hour charging cycle with the set-point temperature only 2°C above the melting point and below the solidification point, respectively, when a 2mm layer of encapsulated octadecane is used. It is also observed that there is a 25% reduction of annual electricity consumption when a twelve-hour charging cycle is applied; with set-point temperature 28°C from 10am to 10pm and 23°C from 10pm to 10am. The comparison of the average COP and the annual electricity consumption of the examined cases without PCM are presented inFig. 103.

As in the other orientation cases, in order to keep the same comfort level in all cases, the same calculation is performed with a constant temperature of 27°C (case 1b). Column 5 of Fig. 103 shows the total savings of each case, when they are compared to case 1b, which has the same thermal comfort level. As expected, case 4a has the optimal performance, achieving 2.3% reduction in electric consumption.

The effect of the concrete construction of the floor and ceiling, as well as the effect of different set-point temperature schedule is subsequently investigated. The additional savings achieved

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption, compared to 25°C constant temperature %	Saving in annual electricity consumption, compared to 27°C constant temperature %
1	2,52	814,48		
1b	1,86	568,44		
2a	2,50	755,70	7,22%	-32,94%
2b	2,32	926,67	-13,77%	-63,02%
2c	2,29	1074,65	-31,94%	-89,05%
3a	2,69	624,81	23,29%	-9,92%
3b	1,37	724,94	10,99%	-27,53%
3c	1,34	848,48	-4,18%	-49,26%
4a	2,73	554,91	31,87%	2,38%
4b	2,54	570,52	29,95%	-0,37%
4c	2,23	667,88	18,00%	-17,49%
5a	2,49	736,64	9,56%	-29,59%
5b	2,75	611,74	24,89%	-7,62%
5c	2,47	731,49	10,19%	-28,68%

Fig. 103 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

by the addition of phase change materials is calculated.Fig. 104 shows the comparison of the average COP and the annual electricity consumption of the examined cases. The total savings achieved only by the addition of PCM are 1.5% for case 4a, 1.5% for case 4b and 4.5% for case 4c. It is observed that in the west orientation a fourteen hour cycle set-point schedule, from 8am to 10 pm, is more effective given the movement of the sun. The amount of solar radiation late during the day leads to higher internal gains and therefore keeping the PCM melted during that time is more energy efficient.

A simulation of various material thicknesses is performed in order to evaluate the effect of material thickness to the thermal performance of the chamber. The comparison of the average COP and the annual electricity consumption for the various cases is presented in Fig. 104. The savings in electricity consumption are negative, when PCMs are located on the ceiling and the floor of the chamber, while the respective savings when PCM are applied on all the internal surfaces are almost 2.5%. The simulation of various material thicknesses has not revealed a significant change in the system's operating efficiency in this case as well, and therefore the observed savings in electricity demand are minimal.

The effect of the material placement to the electric consumption per surface are of PCM is also also similar to the south orientation case and it presented inFig. 105. Specificcaly, when the PCM is placed on the floor and ceiling the average electric consumtion is 24.7kWh/m^2 . Subsequently, when the PCM is placed on the surrounding walls or on all the surrounding surfaces of the space the electric energy consumption is 7.3kWh/m^2 and 5.5kWh/m^2, respectively. The results of this experiment reveal that the material placement is far more important than the material thickness. The electric energy consumption per surface area of the PCM is a higher in this case compared to the south and the east oriented external facade.

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption due to concrete construction %	Savings in annual electricity consumption due to PCM %
no PCM / no concrete: 24C-27C	2,73	585,30		
no PCM: 24C-27C	2,54	563,08	3,80%	
PCM: Case 4a	2,73	554,91		1,45%
no PCM / no concrete: 23C-28C	2,60	579,83		
no PCM: 23C-28C	2,68	578,71	-1,43%	
PCM: Case 4b	2,54	570,52		1,41%
no PCM / no concrete: 22C-29C	2,46	644,98		
no PCM: 22C-29C	2,34	699,34	-4,71%	
PCM: Case 4c	2,23	667,88		4,50%

Fig. 104 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for each of the examined cases

In order to better evaluate the effect of material placement and thickness, the total amount of PCM needed to absord the excess heat and subsequently the material thickness required for each surface is calculated. The examined PCM placement is similar to the south orientation case.

1. PCM on the floor and ceiling of the chamber - total surface area $A=24m^2$.
Thickness=Volume/area=28mm
2. PCM on the walls of the chamber - total surface area $A=76m^2$.
Thickness= Volume/area=9mm
3. PCM on all the surrounding surfaces of the chamber - total surface area $A=100m^2$.
Thickness= Volume/area=7mm

The results of this investigation are also very similar to the south orientation case and they are presented in Fig. 106. It is observed from the results that placing PCM in a large thickness on the floor and ceiling has a negative effect on the electric consumption of the space. On the other hand, when a smaller material thickness is placed on a larger surface area, there is a reduction of almost 2.3% in the electric consumption. As expected,- the effect of PCMs in the annual electricity consumption is significantly lower in the north orientation, compared to the south, east and west orientations. The electric energy consumption per surface area is similar to the above experiment. When the PCM is placed on the floor and ceiling, it is $24.68kWh/m^2$, while it drops to $7.24kWh/m^2$ and $5.51kWh/m^2$, when it is placed into the walls or into all the surounding building surfaces respectively.

The electrical charges for the various cases of set-point temperature schedules, as well as the percentage of saving in electrical charges in each case are calculated and presented in Fig. 107. When comparing the examined cases with case 1b -constant temperature 27°C in order to have the same comfort level- the largest percentage of savings in electrical charges reaches 35.8% and it is observed for case 4c, when there is a fourteen hour charging cycle with set-point tempera-

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,54	563,08		
floor-ceiling / 1mm	2,68	589,68	24,57	-4,72%
floor-ceiling / 2mm	2,68	589,48	24,56	-4,69%
floor-ceiling / 3mm	2,68	589,21	24,55	-4,64%
floor-ceiling / 5mm	2,65	587,44	24,48	-4,33%
floor-ceiling / 10mm	2,66	586,91	24,45	**-4,23%**
walls / 1mm	2,77	556,69	7,32	1,13%
walls / 2mm	2,74	555,03	7,30	1,43%
walls / 3mm	2,73	553,82	7,29	1,64%
walls / 5mm	2,73	553,08	7,28	1,78%
walls / 10mm	2,86	555,81	7,31	**1,29%**
all surfaces / 1mm	2,76	556,52	5,57	1,16%
all surfaces / 2mm	2,73	554,91	5,55	1,45%
all surfaces / 3mm	2,73	554,88	5,55	1,46%
all surfaces / 5mm	2,71	552,43	5,52	1,89%
all surfaces / 10mm	2,69	550,45	5,50	**2,24%**

Fig. 105 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

ture schedule is 22°C during the office hours and 29°C during the night. As already mentioned, in the case of west oriented external facade a fourteen hour cycle seems to have the best performance. Controlling the charging and discharging of the PCM can control the time-shifting of the peak energy demand and therefor the required savings in electric energy and in electric charges can be achieved.

The addition of natural ventilation to the model does not seem to have an important effect, as expected. The hot and humid climate of Austin creares a major disadvantage in the efectiveness of natural ventilation. Specifically the results are the same as in the south orientation case. Fig. 108 shoes the comparison of the average COP and the electrical consumtion of the examined cases; without ventilation, with ventilation for the whole day and with night ventilation. Specifically, the addition of night ventilation, from 22:00pm to 08:00am, leads to a reduction of the electricity consumption of only 0.2%. The same reduction in electricity consumption is achieved when the natural ventilation is allowed for the whole day. The natural ventilations has a little larger impact on the north orientation, compared to the others.

Placement / Thickness [mm]	Average chiller COP	Annual Electric consumption [kW]	Electric consumption per surface area of PCM [kW/m2]	Saving in annual electricity consumption %
no PCM: temperature schedule 24C-27C	2,54	563,08		
floor-ceiling / 28mm	2,66	592,43	24,68	-5,21%
walls / 9mm	2,69	550,32	7,24	2,27%
all surfaces / 7mm	2,69	550,65	5,51	2,21%

Fig. 106 Comparison of average COP, annual electric consumption and percentage of saving in annual electricity consumption for various material thicknesses and placement

Case	On-peak electrical charges $	Savings in electrical charges, compared to 25°C constant temperature %	Savings in electrical charges, compared to 27°C constant temperature %
1	777711,5504		
1b	529186,5984		
2a	659831,5243	15,16%	-24,69%
2b	768134,5048	1,23%	-45,15%
2c	893686,0562	-14,91%	-68,88%
3a	515474,7642	33,72%	2,59%
3b	603823,3034	22,36%	-14,10%
3c	712284,7307	8,41%	-34,60%
4a	459691,5364	40,89%	13,13%
4b	391034,2242	49,72%	26,11%
4c	339800,387	**56,31%**	**35,79%**
5a	465189,9178	40,18%	12,09%
5b	400918,9699	48,45%	24,24%
5c	356701,8437	**54,13%**	**32,59%**

Fig. 107 Calculation of the amount of savings in electrical charges for each of the examined cases

Case	Average chiller COP	Annual Electric consumption [kW]	Saving in annual electricity consumption %
no ventilation	2,71	551,89	
ventilation all day/night	2,71	543,38	0,02
night ventilation 22pm-8am	2,71	543,38	0,02

Fig. 108 Calculation of the amount of saving in electricity consumption when natural ventilation is used as a cooling strategy

7.5. Discussion

The results that are presented in sections 7.1-7.4 give a detailed idea of the performance of phase change materials in different orientations.

As mentioned in section 2.2, the applications of latent heat thermal energy storage in buildings have the ability to narrow the gap between the peak and off-peak loads of electricity demand, and thus reduce the total annual consumption, when they are used effectively. Additionally, they can save operative fees by shifting the electrical consumption from peak periods to off-peak periods since the cost of electricity at night is lower of that during the day. They utilize solar energy continuously, storing it during the day and releasing it at night, particularly for space heating in winter thus improving the degree of thermal comfort and finally, they can store natural cooling by ventilation at night in summer and release it to decrease the room temperature at night, thus reducing the cooling load of air conditioning.[11]

It is revealed from these results that effectively charging and discharging the phase change materials is very important in achieving the required shifting of the electrical consumption from on-peak to off-peak periods, as well as decreasing the total energy consumption. Fig. 109 shows a comparison of the ennual electricity consumption and the annual electric charges for all four orientations. Specifically, the optimum case is compared for each orientation. It is observed from the graphs that the highest reduction in electricity consumption is not achieved at the same schedule scenario, as the highest reduction in electrical charges. As already mentioned, in cases that most of the cooling demand is shifted, the highest peak cooling load occurs. For example, in cases 2c, 3c, 4c and 5c almost all of the cooling load is shifted later during the day, but these cases seem to have 20-40% higher peak load requirement compared to cases 2b, 3b, 4b, 5b and2a, 3a, 4a, 5a, in all orientations respectively. Therefore, the cases that have the highest peak loads are those that appear to have higher electricity consumption. These peak loads occur durind off-peak hours, therefore they are not included in the calculation of electrical charges. This explains the fact that these cases appear to have lower electrical charges. Specifically, case 4a has the optimal performance in terms of electric energy consumption in all orientations, while case 4c has the lowest annual electrical charges. Looking at the contribution of electrical charges of these cases in sections 7.1-7.4, it is observed that in case 4a a smaller portion of the cooling loads is shifted towards the night compared to case 4c, therefore has higher annual electrical charges. Additionally, in case 4a the required peak load is lower than in case 4c, therefore the annual electric energy consumption is lower. It would be safe to say the electricity consumption is mostly affected by the set-point temperature of the space, while the electrical charges are mostly affected by the schedule applied in the operating system. The optimal solution can be found in combining those two variables; finding the set-point temperature with the lowest electricity consumption, and applying a schedule that shifts the energy requirements as needed.

Fig. 110 and Fig. 111 graphically show the achieved savings in electricity consumption and in electrical charges, respectively, in each orientation, when the optimum case is applied. Comparing the scedule scenarios examined in this case and their outcome, it is observed that the maximum amount of electricity saving is achieved when the external facade is oriented to the south, while the lowest saving is achieved in the west orientation. It is important to mention that the optimum case scenario for all four orientations is when the set-point temperature is 27°C from 8am to 10pm and 24°C from 10pm to 8am. This can be explained by the fact that these temperature are closer to the outside conditions, during these times of day. Therefore, the additional cooling requirement is minimized. In this case, the electricity consumption is 36% lower in the south orientation and 24% lower in the west orientation, compared to the baseline case of 25°C constant temperature. The solar movement and the amount of solar radiation that enters the space is significantly higher for the west orientation, later in the evening. Therefore, the additional

comparison	South	East	West	North
annual electircity consumption [kWh]				
optimum schedule scenario	4a	4a	4a	4a
no PCM	878,03	895,61	814,48	814,48
PCM - optimum scenario	563,69	616,35	554,91	554,91
savings %	**35,80%**	**31,18%**	**24,07%**	**31,87%**

comparison	South	East	West	North
annual electrical charges [$]				
optimum schedule scenario	4c	4c	4c	4c
no PCM	821.235,66	813.521,68	665.627,42	777.711,55
PCM - optimum scenario	347.076,40	365.886,91	334.963,31	339.800,39
savings %	**57,74%**	**55,02%**	**49,68%**	**56,31%**

Fig. 109 Comparison of annual electricity consumption and annual electrical charges for all orientations

cooling required to reach the 24°C at night is higher than in the other orientations.

On the other hand, the maximum amount of savings in electrical charges are achieved when the external facade in oriented to the east and the smallest saving is achieved in the north orientation. This fact can also be explained by the geometry of the sun. In the east orientation, the cooling requirement during the on-peak hours is lower and therefore the electrical charges drop significantly.

As explained in detail in sections 7.1-7.4, the savings in electricity consumption can be achieved due to many different parameters, such as the specific set-point temperature schedule, the concrete construction and the addition of PCM. Fig. 112 and Fig. 113 show the savings in electricity consumption achieved only by the addition of PCM in all orientations, for the examined cases 4a, 4b and 4c. It is observed from the graphs that there is a reduction of 8.8 % in electricity consumption, achieved only by the addition of PCM, in the south orientation. The orientation, in combination with the set-point temperature schedule of the space are important in the effective discharging of PCM, and thus for their perfor-

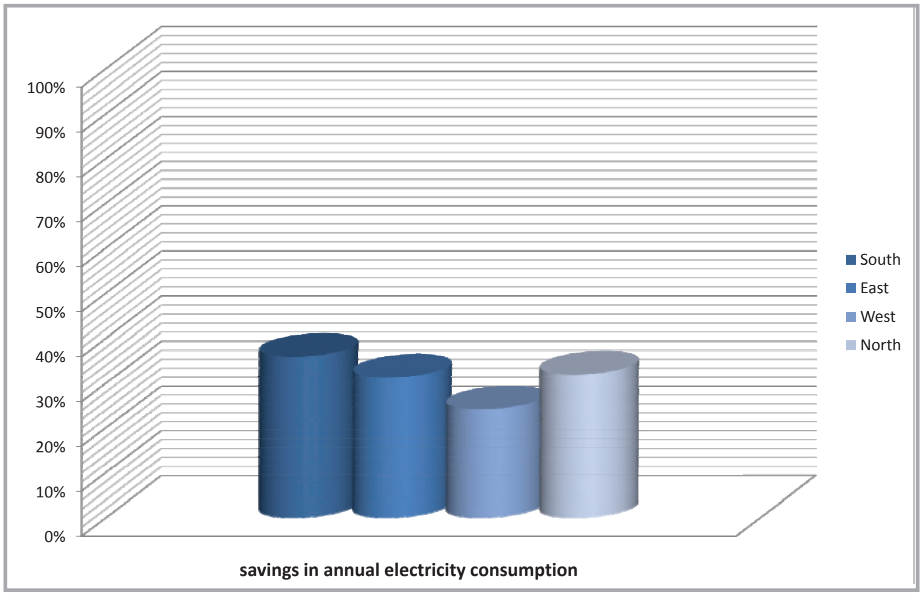


Fig. 110 Percentage of savings in annual electricity consumption in all orientations

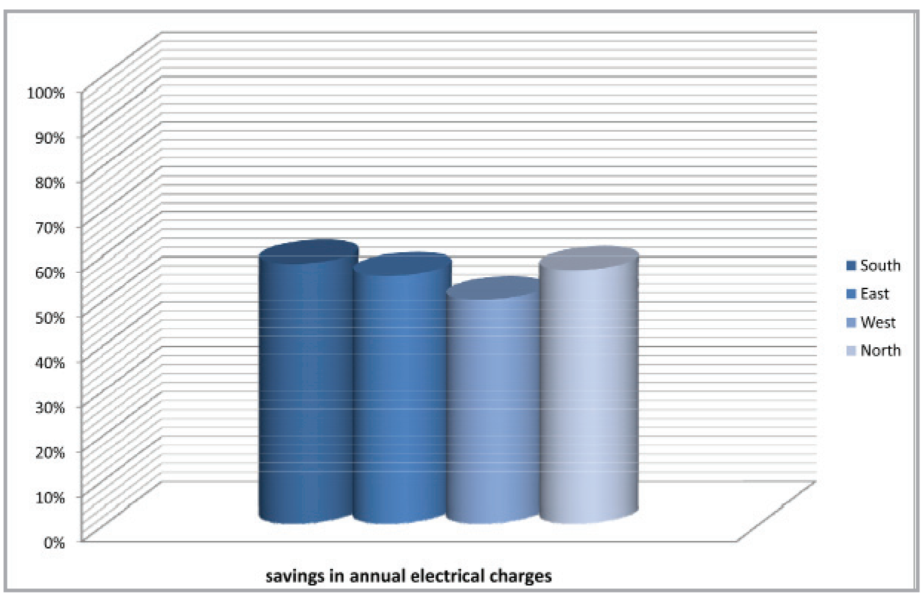


Fig. 111 Percentage of savings in annual electrical charges in all orientations

mance.

Considering the amount and the placement of PCM, this study shows that the surface area of PCM should be maximized, while the thickness of the material does not have a significant effect in the material's performance. Fig. 114 shows a comparison of the electricity consumption per surface area of PCM for all the examined orientations. Specifically, in the compared case the volume of PCM needed to absord the daily heat is located on the floor and ceiling, on the walls and on all the surrounding surfaces of the space. The volume of PCM in all these case is the same, and it equally dispersed on the examined surfaces. The results of this study reveal that the larger the surface area of the material, the better performance the material shows. This is explained by the fact that Phase change materials incorporated into a building in too thick layers will not melt and solidify completely by daily

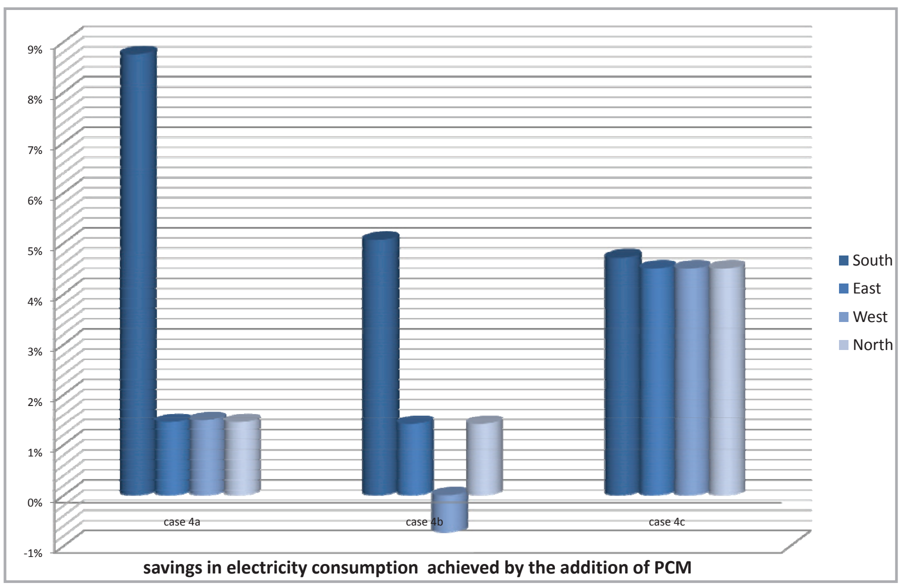


Fig. 112 Percentage of savings in annual electricity consumption achieved only by the addition of PCM

comparison	South	East	West	North
Savings in electricity consumption due to the addition of PCM [kWh]				
case 4a	8,74%	1,45%	1,49%	1,45%
case 4b	5,06%	1,41%	-0,73%	1,41%
case 4c	4,71%	4,50%	4,50%	4,50%

Fig. 113 Percentage of savings in annual electricity consumption achieved only by the addition of PCM

temperature variations. Having the necessary thermal mass in the wall does not automatically mean that it is used. It takes a certain time to melt an amount of PCM with a given layer thickness. Therefore, it is preferable to have a small material thickness spread in large surface area. The same results are in effect for all orientations. The north and the south orientations have lower electricity consumption per surface area compared to the east and west orientations, but the difference is not significant.

Finally, according to the performed experiments the effect of natural ventilation is minimal in all orientations. It is worth mentioning that both case of natural ventilation -all day ventilation and night ventilation- have the same performance. The additional savings in electric energy consumption due to natural ventilation is only 1% for the south, east and west orientation, while it is almost 2% for the north orienta-

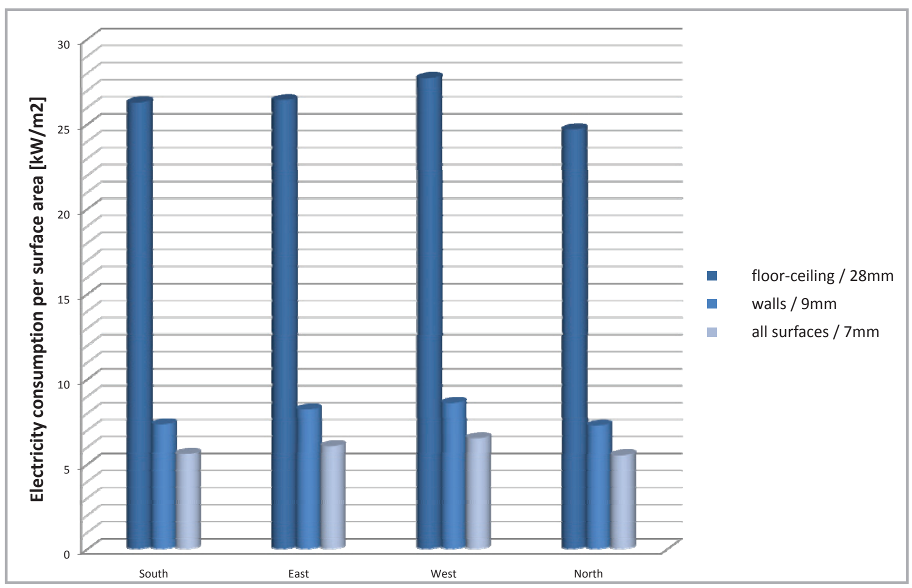


Fig. 114   Comparison of electricity consumption per surface area of PCM for all orientations

PCM placement	South	East	West	North
Electricity consumption per surface area of PCM [kWh/m2]				
floor-ceiling / 28mm	26,26	26,4	27,7	24,68
walls / 9mm	7,31	8,21	8,59	7,24
all surfaces / 7mm	5,58	6,04	6,51	5,51

Fig. 115   Comparison of electricity consumption per surface area of PCM for all orientations

tion (fig. 116). This fact can be explained by the warm and humid climate of Austin, as presented in fig. 117. The area in the blue circle is the area of the psychrometric chart where natural ventilation would be effective. Austin, as already mentioned is a got and humid climate, therefore it is found in the red area of the psychrometric chart (fig.117) which is not in the circle. It is therefore expected that natural ventilation is not an effective strategy for the climate of Austin.

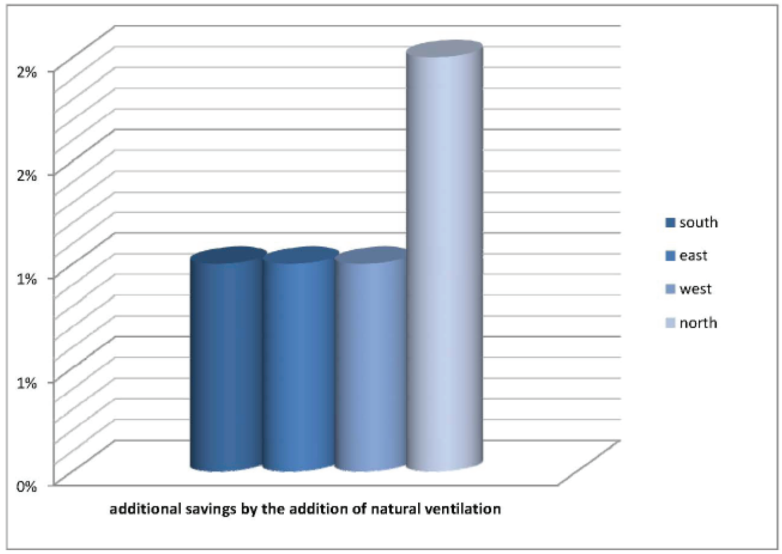


Fig. 116 Comparison of additional savings in electricity consumption due to natural ventilation for all orientations

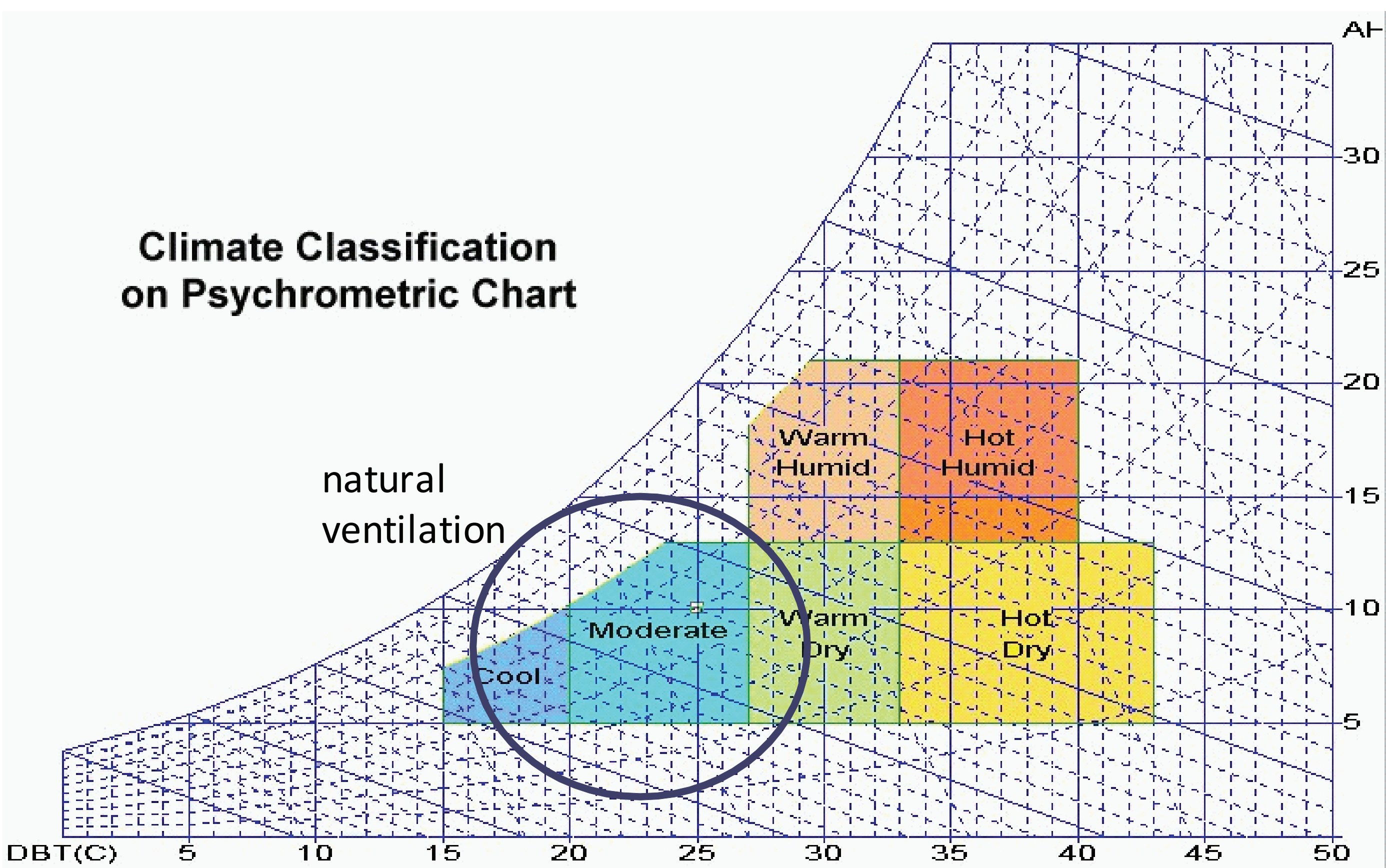


Fig. 117 Comparison of electricity consumption per surface area of PCM for all orientations

8. Conclusions

The use of thermal energy storage for thermal applications has received much attention during the past decades; a variety of thermal energy storage techniques have been developed as industrial countries have become highly electrified. Such thermal energy storage systems have an enormous potential to make the use of thermal energy equipment more effective and for facilitating large scale energy substitutions from an economic perspective. Many types of energy storage play an important role in energy conservation. Thermal storage in a building may be decisive for the reduction of cooling loads and the reduction of temperature increases. External surfaces of building envelopes show higher or lower temperatures not only as a function of ambient air temperature, intensity of solar radiation and the radiation physics of the envelope itself, but also dependent on their own thermal properties. Additionally, the transmission of external temperature fluctuations through a building envelope is a function of the capacity of the envelope and the building structures to store heat.

As explained in detail in this study, the applications of latent heat thermal energy storage in buildings have the ability to narrow the gap between the peak and off-peak loads of electricity demand and to save operative fees by shifting the electrical consumption from peak periods to off-peak periods since the cost of electricity at night is lower of that during the day. Additionally, they utilize solar energy continuously, storing it during the day and releasing it at night, particularly for space heating in winter thus improving the degree of thermal comfort and finally, they have the ability to store natural cooling by ventilation at night in summer and to release it to decrease the room temperature at night, thus reducing the cooling load of air conditioning.

Significant research has been performed on the application of latent heat storage systems for temperature control of buildings. Applications for thermal inertia and thermal protection focus on temperature regulation and not on the amount of heat supplied and they are the ones where phase change materials have achieved a higher penetration in the market[Fig. 116]. Problems that still need to be resolved include the effective charging and discharging of phase change thermal storage, as well as their integration with other building systems. This study focuses on the energy storage strategies integrated within the building envelope in order to regulate indoor temperature swings and enhance thermal comfort. Phase change materials that have a melting point near room temperature can replace thermal mass without the bulk of large masonry structures. In theory, this can lead to a significant reduction of the building energy consumption, as well as reduction of conventional structure materials. This study focuses on examining the effect of integrated phase change materials on the thermal performance of buildings in shifting the typical daily cooling requirements to night time. Furthermore, it investigates if controlling the thermal storage can lead to a significant reduction in equipment cycling frequency and thus achieve a noticeable increase in operating efficiency. More specifically, the objective of this study is to investigate the performance of phase change materials in applications for temperature control, and to identify their effect in the energy performance of the space when the charging cycle of the materials is controlled.

An in depth analysis of phase change materials is initially performed; different types of materials, their advantages and drawbacks, possible problems and their solutions, their implementation in and integration in various materials. After acquiring the basic knowledge in the specific materials, several applications for temperature control of buildings are researched and a typology of applications of PCM in buildings is created and analyzed.

Subsequently, an investigation based on computer software simulations is performed, on the efficiency and the energy performance of the space when phase change materials are applied. The goal of this research is to examine the performance of phase change materials when the charging cycle of the materials is controlled. This way, the cooling energy demand is shifting towards the off-peak period. Several cases are examined, considering the effective charging and discharging the PCM, by applying various set-point temperature schedules. Subsequently, a regression model based on the DOE-2.1E chiller models is developed to simulate the part load and off-design COP of the chiller in the examined operating schemes and finally calculate the total electric energy used in each case. Finally, an investigation of the effect of material thickness, as well as the material placement is performed. The savings in electrical charges achieved in all the examined cases are also calculated.

The simulation of the several cases of set-point temperature schedule for charging and discharging the phase change materials is initially performed because it is expected that the space cooling requirement will shift towards the night depending on the charging cycle. It is observed from the results that while the shifting of the cooling demand depends on the charging cycle, the required peak load varies depending on the set-point temperature schedule that is assigned. A charging cycle of fourteen hours (cases 4a, 4b and 4c) leads to lower peak loads than a twelve hour cycle (cases 3a, 3b and 3c), while a charging cycle of twelve hours leads to lower peak loads than a ten hour charging cycle (cases 2a, 2b and 2c).

It is revealed from this investigation that effectively charging and discharging the phase change materials is important in achieving the required shifting of the electrical consumption from on-peak to off-peak periods, as well as decreasing the total energy consumption. Specifically, the electric energy consumption can be decreased up to 36% in the south orientation, 31% in the east orientation, 24% in the west orientation and 32% in the north orientation. Additionally, the electrical charges can be reduced by 60%, 55%, 50% and 56% in the south, east, west and north orientation respectively.

The electricity consumption is mostly affected by the set-point temperature of the space, while the electrical charges are mostly affected by the schedule applied in the operating system. The optimal solution can be found in combining those two variables; finding the set-point temperature with the lowest electricity consumption, and applying a schedule that shifts the energy requirements as needed.

Considering the amount and the placement of PCM, this study shows that the surface area of PCM should be maximized, since a specific thickness of material can be effectively charged and discharged on a daily basis. Specifically, the volume of PCM that can absorb the daily energy loads is calculated and distributed to various surfaces. The electric energy consumption is 26.3kWh/m^2 when the PCM is placed only on the floor and ceiling, 7.3kWh/m^2 when it is placed on the walls of the chamber and 5.6kWh/m^2 when it is placed on all the internal surfaces.

Finally, the addition of natural ventilation does not have a significant effect in reducing the energy consumption of the space. Specifically, the additional savings due to natural ventilation are only 1% in the south, east and west orientation, and 2% in the north orientation.

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