Platform voor mens en techniek

PRELIMINARY STUDY OF THE POTENTIAL APPLICATIONS OF PHASE CHANGE MATERIALS IN BUILDINGS

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Contents

Summary

This preliminary study gives an overview of the possibilities of using phase change materials (PCMs) to reduce the energy consumption of climate control systems in buildings. The results and conclusions in this report are based on test measurements carried out or verified by the authors, or on the basis of testing done at Delft University of Technology under the supervision of Prof. A.H.C. van Paassen. Data originating from the suppliers of PCM products has not been used unless this data has been experimentally verified by the authors, by students of the faculty Energy in the Built Environment at Delft University of Technology, or by other independent research.

From an economic perspective PCMs are best used for supplying additional cooling capacity during hot weather. Savings can be made on the mechanical cooling system and more use can be made of free (night time) cooling.

There are various ways of making use of the heat accumulation capacity of PCMs. This study covers three options that are either commercially available or are in an advanced stage of development.

PCMs can be used to cool buildings in the summer. The economic potential is created by the possibility of making savings on mechanical cooling equipment and by making use of free cooling at night to make cooling capacity available during the day. In practice the possibility is created of lowering the capacities/usage peaks or of damping them. The realistically achievable cooling capacity per square metre of floor area lies between 10 and 40 W/m². This depends on the design of the system (the manner of heat transfer). Higher cooling capacities are technically possible, but then additional measures must be taken to regenerate the PCMs.

The costs of PCM systems are currently still too high to make them competitive with existing techniques, although the situation is improving. More PCM suppliers have become active in the market, leading to a slight reduction in price to approximately 4 to 8 €/kg, depending on the design. Based on a potential increase in demand, the prices of PCMs in the future could possibly drop to 1 to 2 €/kg.

A promising application for PCMs is in the renovation of existing heating, ventilating, and air conditioning systems (HVAC systems). A building with a system based on the supply of centrally cooled air as the only means of cooling can be improved by the use of PCMs in the rooms, thus increasing the accumulation capacity. This enables more cold to be buffered at night, so that during the day a greater supply of cooling can be achieved and over a longer operating period, minimising temperature rises above the desirable setting.

CHAPTER 1 Introduction

The purpose of this study is to provide an insight into the manner in which phase change materials (PCMs) can be used for controlling room temperatures in buildings.

The expertise compiled in this document is a result of investigations carried out by the Energy in the Built Environment section (Prof. A.H.C. van Paassen) of the Process and Energy department of the 3ME faculty at Delft University of Technology. The investigation was initiated in 2001 by A. H. H. Schmitz, at that time active as Director of ARCADIS Bouw and Vastgoed in The Hague. ARCADIS provided financial support for the investigation up until 2006 under the responsibility of A.H.H. Schmitz.

The experimental work and the modelling of PCM and PCM applications was carried out by J. E. van Dorp under the supervision of Prof. A.H.C. van Paassen and A. H. H. Schmitz with the assistance of several graduate students, including I. Bouwman who refined the validation of the models using experiments with a PCM baffle ceiling and a water tank for PCM enthalpy measurements.

1.1 OBJECTIVES

Questions that will be answered in this preliminary study are:

- What are the physical properties of PCMs, which types of PCMs are there and at which temperatures do they operate? What are their specific accumulating properties? Over which time span is the heat released? Which products are currently on the market and what developments are taking place?
- How can PCMs be made suitable for use without reacting with the local environment and how can they be protected against mechanical damage?
- In which way can PCMs be used in buildings?
- Estimation of the achievable cooling capacity, depending on the temperature difference.
- Influence on room acoustics when fitted to ceiling surfaces.
- What costs are involved?
- Brief list of projects in which PCM has been used.
- What is the expected service life of PCMs (ageing, separation of emulsions etc) and what are the environmental implications?

1.1.1 SUMMARY OF CONTENTS

This chapter will cover the physical properties of PCMs. The packaging and application of PCMs will be covered in chapter 2, based on three different application types. The consequences of the use of PCMs for user comfort are examined in chapter 3. The cooling capacity that can be achieved and the associated measures for regeneration are handled in chapter 4. The control of PCM systems, in particular considering the necessary regeneration, is handled separately in chapter 5. In chapter 6 the operation of the various types of PCM systems is demonstrated by means of simulation. Chapter 7 contains a calculation of the financial feasibility of PCM-based cooling systems for climate control. Chapter 8 handles the calculation algorithm used in this report for the thermal behaviour of PCMs. Chapter 9 contains a list of suppliers of PCM products and services. Finally chapter 10 contains a list of project references.

1.2 OPEN QUESTIONS

Subjects outside the scope of this report, which require additional study:

- The possibility of simulating PCM applications in popular building simulation software, such as VA114;
- Surveying the experiences of people working in an environment where PCM is use for climate control;
- The cost/benefit analysis of PCM applications in practice;
- The more specific application of PCMs in underfloor heating systems (p. 2.1);
- The possibility of further reducing the costs of PCM products by the use of improved production techniques and economies of scale;
- Which PCM applications may potentially qualify for subsidies?

1.3 MOTIVATION FOR THE USE OF PCMS

Phase change materials have a higher heat capacity than materials used in construction, such as water or concrete. This makes a variety of applications for the climate control of buildings possible, where the heat accumulating capacity of the mass of the building plays a role. Specific applications of PCMs in buildings are economically interesting, or will be in the future.

In the first place the application of PCMs offers benefits comparable with those of concrete core activation. In addition there are applications in installation technology. The sustainability aspect is found in the transfer of cooling demands to the 24 hour cycle, so that more effective use can be made of night cooling and cheaper night time electricity for the climate control of buildings during the day. Also the peak cooling demand is reduced during day time, so that the additional mechanical cooling system required can have a smaller capacity.

The use of PCMs combines well with other existing sustainable climate control concepts and techniques, including natural (night time) ventilation, intelligent building control systems and (very) low temperature heating or (very) high temperature cooling systems.

1.4 SELECTION OF PCMS AND THEIR PHYSICAL PROPERTIES

Various types of PCMs are commercially available. A list of suppliers of PCMs materials and their properties is included in the appendix. The differences between the PCMs involve:

- Their chemical compositions and the available types.
- The temperature ranges within which melting and solidifying of the PCMs occurs.
- The heat capacity of the phase change.
- The expansion during the phase change.
- The thermal conductivity.
- The tendency towards under cooling or the (temporary) undesirable under cooling of the liquid phase during regeneration.
- The toxicological and fire safety characteristics.

The selection of the correct PCM based on the desired thermal characteristics is very important for the optimum functioning of the application. Although water for example melts and freezes exactly at 0°C, PCMs melt and solidify over temperature *ranges*. These ranges also differ for the melting and solidification processes. This generally has a negative effect on the performance of PCM systems. The non-ideal thermal behaviour of PCMs cannot be neglected, because often only small temperature differences are available for the heat transfer in PCM systems. The behaviour of PCMs can be reasonably well modelled using computer simulations.

In addition to suitable thermal characteristics, the following criteria apply to the applicability of PCMs in buildings:

- The flammability and toxicity must comply with the regulations.
- During use, PCMs exist in a liquid phase and may react with moisture present in the air and/or they may be corrosive. Therefore once mounted the PCM elements must not be drilled through and they must not leak. (An exception to this is micro-encapsulated PCM, which can be incorporated into plasterboard, plaster or concrete).

Nowadays the thermal properties of PCMs area part of the installation design. The various suppliers of PCMs offer a number of product variants, each having different thermal behaviour. Some suppliers can even supply custom-made PCMs, enabling the client to determine at which temperatures the phase change must occur.

The potential heat storage capacity of a PCM cannot be increased in an unlimited manner, but it is a variable that depends on the chosen melting and solidification temperatures. This is because additives (antifreeze) are used to modify the melting and solidification that make the proportion of active PCM relatively smaller.

PCMs generally have the highest heat storage capacity and the most well-defined phase transitions when they are used in their original, pure condition. Additives are added to PCMs to increase the service life or cycle stability and to reduce the degree of under cooling.

1.5 THERMAL PROPERTIES OF PCMS

The thermal properties of PCMs vary from product to product. The differences involve the quality of the phase transition, the average temperatures at which the melting and the solidification take place, and the total enthalpy difference between the molten state and the solid state.

By the quality of the phase transition is meant the breadth of the temperature range within which the phase transition takes place. For an ideal PCM, such as water, this range is 0^oK, i.e. the phase transitions take place at a constant temperature, but in the case of 'synthetic' phase change materials this range is often several degrees Kelvin.

This phase change temperature range for PCMs is a function of the heat flux. The greater the heat flow, the greater the measured range. The range that must be worked with in practice is the range that is measured under heat fluxes that are to be expected in practice. Therefore in Delft University of Technology's laboratory the properties of the PCMs are measured during exposure to an environmental temperature that rises and then falls at 2 to 3^oK per hour. The maximum temperature rise or fall in the PCM is then approximately 100 mK/min (milliKelvin per minute). The temperature ranges found during solidification and melting under these circumstances are indicative for applications in buildings.

To determine the cooling capacity of a PCM plate, the quantity of air in m^3/s needed to flow alongside the surface of the plate (m), the specific heat of the air (c) and the temperature difference between the air and the PCM plate (ΔT) are required.

$$Q_{cooling} = mc\Delta T$$

Another quality aspect of PCMs is temperature hysteresis. During experiments it has been shown that the mean temperature of the PCM during solidification, and the mean temperature during melting are not the same. There is a significant temperature hysteresis that cannot be explained by measurement errors or by internal temperature gradients in the PCM. The hysteresis for the tests on PCMs in Delft is in the order of 2 to 3^oK.

The quality of the phase transition plays a significant role for most applications in buildings, because the design temperature differences between the sources of heat or cooling and the PCM are generally small, i.e. in the order of a few degrees Kelvin. The temperature hysteresis is important for the determination of the heat removal temperature of the medium for the regeneration phase, once a suitable mean melting temperature has been chosen.

This report makes use of a fictitious PCM with properties chosen to be conservative, based on experimental data collected during investigations at Delft University of Technology. The properties are based on the behaviour of the Rubitherm product SP22a17 PCM. This PCM was developed between 2002 and 2004 by ARCADIS and Delft University of Technology in cooperation with Rubitherm for suspended ceiling applications. This PCM has a melting phase transition between approximately 22°C and 24°C and a solidification phase transition between 22°C and 20°C. There is therefore a temperature hysteresis of 2^oK. The enthalpy difference between these temperature levels is 100 kJ/kg minimum. This is the storage capacity that will be used in the rest of this report.

CHAPTER 2 The application of PCMs

In this chapter various applications of PCMs for space cooling are described qualitatively. The calculation of the thermal behaviour and the dimensioning are handled in chapter 4.

There are various ways of using PCM in buildings. A number of categories can be differentiated:

- As ceiling, wall or floor in the room to be air conditioned.
- As a buffer/central buffer in the hot/cold water cooling or heating system.
- In the air handling or distribution system as central or decentral buffer.

Each application has specific consequences for the building design, the system concept, and the control strategy. The energy-related and economic advantages and disadvantages vary per application, as does the effect on the temperature of the indoor climate.

2.1 PCM FOR APPLICATION IN HEATING SYSTEMS

The use of PCM in heating system applications has limited potential in the Netherlands. It is possible to use PCM systems to increase the heat storage capacity of solar heating systems while maintaining the same volume and weight. PCM heat buffers have been developed for buildings that are heated electrically. These store heat at 450°C by making use of solid state phase transitions in metals. This enables the use of cheaper night time electricity tariffs to supply a heating system during the day.

In the past an examination was made of the potential of the application of PCMs, in the form of granulate, in in-situ poured-in under-floor heating systems. The idea was that due to the buffering of heat a smaller boiler could be used, which could provide heat to the building on the basis of a longer operating period. However in the first instance energy savings and economic benefits appeared to be small.

PCMs as a heat source/buffer for hot water heating systems (and/or cooling systems) will not be considered further in this preliminary study.

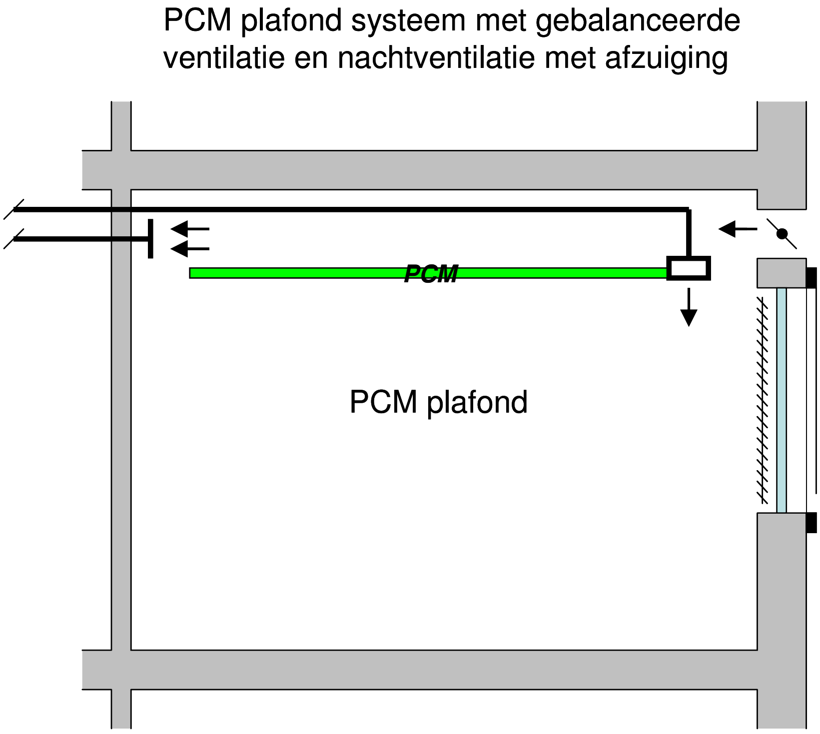
In the types of systems to be discussed, PCMs can be used in both new building and existing buildings. When using PCMs in existing buildings, account must be taken of aspects that may change due to the use of a different material in the ceiling or the walls. An example is the sound absorption properties of surfaces.

2.2 PCMS USED AS A BUFFER IN ROOMS

PCMs can be used as a buffer in a suspended ceiling to reduce the temperature rise in a room.

The PCM complements the natural damping effect of the building mass. Part of the cooling demand in the building is therefore shifted to night time. This enables the utilisation of free cooling by the cool night air, and use to be made of lower cost electricity at night. The damping effect during the day reduces the maximum mechanical cooling capacity required.

Figure 2.1 PCM ceiling system



As well as for suspended ceilings, PCM can also be used in walls, floors or can be mounted directly to concrete ceilings. For use on large surface areas account must be taken of the acoustics and the presence of other fittings and equipment such as light fittings, grilles, ducts, piping and cables.

The cooling capacity of a PCM ceiling is determined in the same way as that of a climate ceiling or a concrete core activation system. The heat transfer takes place by convection of air in the room along the PCM, and by radiation. The prevailing temperature difference between the (PCM) ceiling surface and the room counts as a measure of the cooling capacity.

The difference between a PCM ceiling and a climate ceiling (or activated concrete layer) is that the temperature of the PCM during the day is not constant when cooling capacity is being supplied. This is because the PCM temperature slowly but surely rises, also during the phase change. Therefore the cooling capacity of a PCM ceiling always reduces slowly at constant room temperature, in contrast with the cooling capacity of a climate ceiling. Account must be taken of this during the design by anticipating an increasing room temperature.

The condition of the PCM at the end of the working day is a determining factor. This condition can be predicted if the amount of cooling capacity that the PCM must supply during the day to meet the cooling demands in the room is known, and if it is known what the condition of the PCM is at the start of the day. From this can be calculated what the end temperature of the PCM will be, and thus how high the room temperature will be based on the required cooling capacity.

The cooling capacity of a horizontal ceiling as a function of the temperature difference between the room and the PCM can be increased by increasing the surface area of the PCM surface compared to the surface area of the floor. This can be done by fitting the PCM plates as a series of vertically mounted baffles, instead of as a flat, horizontal ceiling. In this case account must be taken of the finishing of the PCM plates to compensate for the loss of sound absorbent material in the ceiling.

A critical aspect of this and other PCM applications is the discharge of the heat at night. When it is excessively warm at night in the summer, night ventilation will not remove all the heat stored, even at a high ventilation rate. The following day the PCM may then be at a higher than ideal temperature and thus have a lower cooling capacity. The behaviour of this application has been investigated experimentally at room-scale by Delft University of Technology.

One or more warm nights can be bridged by using extra PCM. On the other hand a small mechanical cooling system could be deployed at night if it is not cool enough outside for free cooling. Finally the user could accept the limitation of the PCM system for just a few days a year. Computer simulations can be used to show how the PCM functions during such hot periods.

2.3 PCMS AS BUFFER IN VENTILATION SYSTEMS

Finally PCMs can be used as air-side cooling buffers. This can be in the air handling unit to cool or pre-cool the primary air flow, or in the rooms to cool the air via air induction or ventilation over a PCM package. When required, very warm summer outside air can first be precooled in a heat exchanger by (humidified) return air.

Figure 2.2 PCM buffer in air handling unit

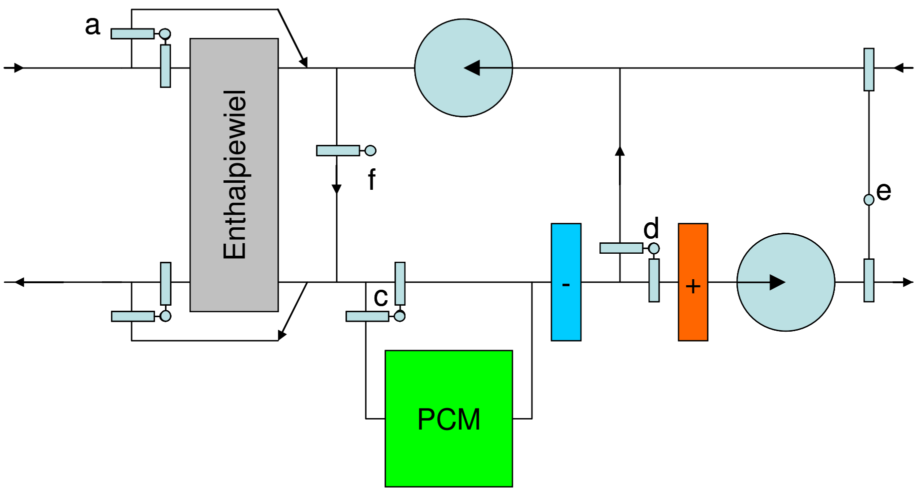
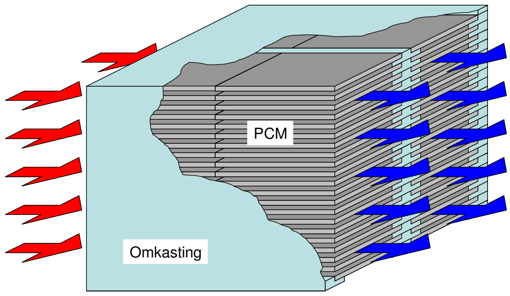


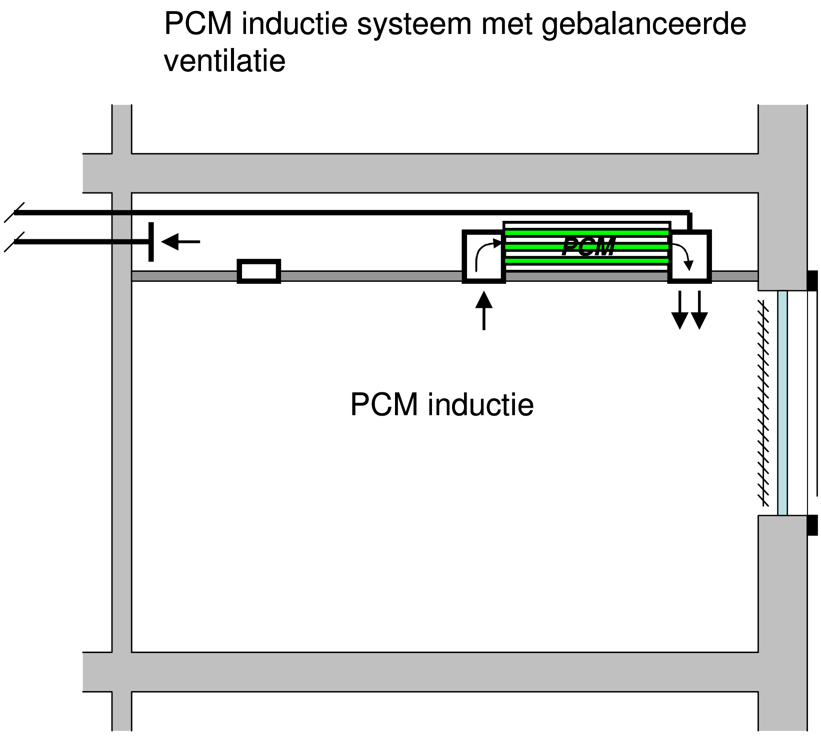
Figure 2.3 PCM unit

Additional cooling capacity can be supplied by the correct installation of an extra package of PCM elements in the central air handling system. This enables the system to cope with peak cooling demand, and free cooling – stored during the night – can be exploited during the day.



PCM can also be used as a cooling source from a stand-alone air cooler (mobile if required). During the cooling operation a fan circulates warm room air over PCM plate package. The fan also operates at night while the room is ventilated with cold outdoor air, so that the PCM in the air cooler solidifies again. In place of a fan, air induction can also be used in combination with a central mechanical ventilation system.

Figure 2.4 PCM induction system



The PCM induction system works during the day by inducing (warm) room air over a number of PCM plates. The room air is cooled by the PCM and mixed with fresh supply air (cooled if required). The cooling capacity of the system is then the sum of the cooling capacity of the fresh air and the cooling capacity of the induced room air, just as in the case of a conventional water filled induction unit.

The difference between a conventional induction unit and a PCM induction unit is that the temperature of the cooling surface of an induction grid is much lower than that of the PCM plates in a PCM induction unit. For example, an induction unit can be fed by water at between 14 and 18°C, as a result of which at a room air temperature of 26°C, a temperature difference of 10°K prevails between the air and the cooling surface in the unit. In a PCM induction unit the PCM temperature during melting will generally lie between the 20 and

22°C, depending on the PCM selected. Then there is just 5°K available as the driving force for the heat transfer.

A PCM induction unit will therefore need a larger heat exchanging surface area than a conventional induction unit. Because the pressure difference across the PCM plates cannot be excessively high due to the induction process, the air flow rate between the PCM plates will be lower than between the plates of a conventional induction unit, as a result of which the heat transfer is even less than in the case of a conventional unit.

Intelligently designed PCM induction units do allow the induction flow rate to be optimised. This has resulted in the development of very high quality PCMs, enabling efficiently operating equipment to be designed. Various suppliers already have or are busy developing PCM induction units that are competitive with conventional alternatives.

When existing HVAC units based on just cooled supply air have to be upgraded, PCM induction units are the cheapest and/or the best solution, particularly because no additional cold water circulation system needs to be fitted in the building and because no additional cooling generation capacity needs to be added. In this case the PCM induction unit works as a ‘peak-shaver’ for the cooling system of the building, as a result of which a higher total cooling capacity can be achieved in the rooms during the day.

CHAPTER

3 User comfort

The use of PCM as a separate (additional) cooling buffer in the air handling system or the water cooling system need not have any comfort consequences. When the PCMs are used as passive surface elements or as local cooling buffers in rooms, this does have comfort consequences.

The thermal inertia of a PCM ceiling enables temperature variations in a room to be reduced. A relatively large amount of the cooling capacity is supplied in the form of radiative cooling. These characteristics have a favourable effect on thermal comfort.

If savings are made on mechanical air cooling in favour of passive PCM ceiling cooling, then the individual controllability of the cooling system is no longer available. If PCM is used as a cooling source for a controllable air cooler locally in one room then a degree if individual controllability can be achieved.

The cooling capacity of a PCM ceiling is a function of the temperature in a room. A consequence of this is that the temperature in the room must first rise before the cooling effect of the PCM becomes noticeable. Therefore even if the maximum temperature setting is not exceeded it can frequently become rather warm in a room cooled by PCM.

If PCM is installed in a closed metal ceiling this may have adverse effects on the acoustics, particularly in rooms larger than a single office cell. This is because, unlike a system ceiling, the PCM ceiling has no sound damping effect. The surface is often metallic which maximises heat transfer by convection. The sound absorption characteristics of PCM plates were not investigated for this report.

CHAPTER 4 Cooling capacity

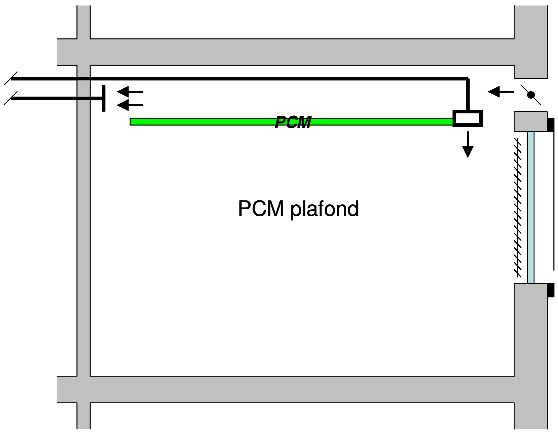
In this chapter the practically and economically feasible cooling capacities are calculated for three different applications.

- PCM used in ceilings and suspended ceilings.
- PCM as cooling buffer in an air handling system
- PCM as cooling buffer in a room air cooler

These applications are possible with the PCM products available now and have a reasonable potential for economically viable energy saving applications.

For the discussion of these three applications a typical office situation is assumed, where a maximum cooling capacity of approximately 40 W/m² is needed, for a maximum room temperature of 25.5°C to handle the cooling demand caused by people, equipment, lighting and solar gain. In a conventional office this cooling capacity is supplied by cooled ventilation air in combination with additional induction cooling, fan coil units, cooling ceilings and/or concrete core activation.

4.1 PCMS IN SUSPENDED CEILINGS



PCMs can be installed in the form of horizontal or vertical plates in a suspended (system) ceiling. The heat is then absorbed from the room by means of radiation and convection, as long as the surface temperature of the PCM remains lower than the room temperature.

4.1.1 PCM THERMAL PROPERTIES REQUIRED

To be used directly in a room as a PCM ceiling passive heat buffer, the melting and solidifying temperatures of the PCM must be chosen very carefully. The melting temperature must be as low as possible, so that as big a temperature difference as possible exists between the room temperature and the PCM surface temperature during the cooling operation. However the melting temperature must not be too low because in that case undesirable heat storage may start at lower (but normal) room temperature levels. In addition account must be taken of the uppermost air in a room generally being somewhat warmer that air in the living zone.

Moreover a lower melting temperature also implies a lower solidification temperature, and if it is the intention to regenerate the PCMs at night using outdoor air, as high a solidification temperature as possible is desirable. Also if the PCM is regenerated with mechanically cooled ventilation air it is more beneficial for the efficiency of the entire system if the PCM solidifies at as high a temperature as possible.

Considering the above, a PCM for this application should melt between 22.5°C and 23.5°C and solidify between 20.5 and 21.5°C. Rubitherm has developed a PCM that meets the above stated criteria very closely - the PCM SP22a17. During solidification this PCM absorbs approximately 100 kJ/kg of heat between 22°C and 24°C and has a density of 1400 kg/m³.

4.1.2 COOLING CAPACITY

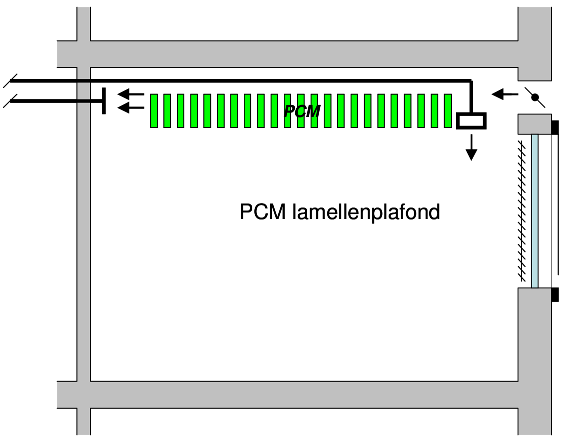
Assuming a radiant heat transfer coefficient of 5.5 W/m²K and a convective heat transfer coefficient of 2.5 W/m²K, the total heat transfer coefficient for a horizontal cooling surface in a room is approximately 8 W/m²K. Heat transfer above the suspended PCM ceiling can therefore be neglected. The thermal resistance in the PCM plate is not included because the thermal resistance in the material is negligible compared to the heat transfer coefficient and has no significant effect on the temperature gradient in the material.

If 80% of the suspended ceiling is clad with PCM plates and the PCM has an average melting temperature of 23°C then at a room temperature of 25.5°C the cooling capacity of the ceiling averages 20 W/m². This cooling capacity has been confirmed by experiments carried out in the climate chamber at Delft University of Technology. The cooling capacity of a PCM ceiling at constant room temperature drops a little during operation, because the PCM temperature rises slowly during the solidification process.

Therefore in a typical office room this cooling capacity of 20 W/m² represents approximately half the total maximum cooling capacity of 40 W/m² required. The remaining 20 W/m² must therefore be supplied by the intake of cooled ventilation air or by cooling capacity mounted in the room.

PCM lamella ceilings

The cooling capacity of a PCM ceiling can be increased by fitting a large series of vertical PCM plates (also called lamella or baffles) instead of a horizontal ceiling. This increases the convective cooling capacity of the ceiling construction due to the increase in surface area of the PCM plates. Experiments with this PCM ceiling have shown that the cooling capacity can easily be doubled compared to a flat, horizontal PCM ceiling, with which a cooling capacity of 40 W/m² or more can be achieved at 25.5°C.



With such a high cooling capacity additional cooling during the day by chilled air for example is no longer necessary. Extra attention must be paid to the regeneration of the PCMs at night. All the stored heat must of course be removed.

4.1.3 PCM MASS REQUIRED

The mass of PCM to be installed in a flat, horizontal PCM ceiling must be at least sufficient to absorb all heat assimilated during an operational period without undergoing a complete phase change. If the PCM were to fully melt during an operational period then the temperature of the ceiling would rise much faster and the cooling capacity would reduce. Depending on the potential heat capacity of the PCM and the cooling demand and operating time of the building, between 5 and 15 kg/m² of PCM per m² of floor area must be installed to absorb the heat of a single day.

The installation of more PCM than the minimum leads to a small improvement in the average capacity during operation, because the PCM remains at a lower temperature level because a smaller proportion of the PCM changes phase. Also the installation of more PCM makes it possible to omit complete regeneration of the PCM on one occasion in the case of an excessively high outdoor night time temperature or a system malfunction. The use of a more generous quantity of PCM also makes control of the system easier, because the control system does not have to be so closely tied to the state of the PCM. In practice, for the above reasons, it would seem advisable to install at least 10 kg/m² (kg PCM per m² floor area), or 0.5 kg/W/m² (kg PCM per Watt/m² cooling capacity).

PCM lamella ceiling

More PCM per m² of floor surface is needed for the PCM lamella ceiling discussed in section 4.1.2, because the cooling capacity is higher than that of a horizontal ceiling. A PCM lamella ceiling with a cooling capacity of 40 W/m² at 25.5°C room temperature must contain between 15 and 25 kg PCM per m² of floor area.

4.1.4 REGENERATION OF THE PCM

The efficient and energy-conserving regeneration of the PCM is the most critical aspect of a PCM ceiling system. The heat absorbed during the day must be removed from the PCM during the night. This can be done in various ways, e.g. abundant ventilation with outside air via natural transverse ventilation, supported by central mechanical air extraction, or ventilating with mechanically cooled ventilation air, or cooling by means of water piping mounted on the PCM, as with a chilled ceiling.

Regeneration using water

Cooling the PCM with water piping mounted on the PCM plates is technically the best solution, but the costs of such a system turn out to be so high that it is preferable to abandon the PCM and just used a chilled ceiling. To lower the PCM investment costs to a level that makes the systems competitive with other concepts, the heat must be dispersed as cheaply as possible, and the use of water piping is then not practical. The viability of PCM applications in the building industry depends on reducing the investment needed in other HVAC system components or eliminating this investment altogether.

Regeneration with natural night time ventilation

The regeneration of the PCM with outdoor air via natural (transverse) ventilation is easily possible for most of the year. There are only a few nights in the year during the summer in the Netherlands when it is too warm outside to fully remove the heat stored in the PCM. A room with a PCM ceiling can be fitted with grilles in the walls so that outdoor air flushes the building under the influence of normal and transverse ventilation when the grilles are opened. The cooling effect is optimised (maximised) by constructing the grilles so that the outside air is directed at the ceiling instead of just into the room. In the case of transverse ventilation the ventilation openings must be situated above the (open island) PCM ceiling so that warm air above the ceiling can be efficiently extracted.

By selecting a sufficiently large ventilation grille area, or automatically opening the windows at night, an air change rate of 10 times can be achieved. If night time ventilation is programmed between 20:00 and 6:00 then 10 hours are available for regeneration. If the ventilation air enters the building at an average temperature of 17°C and leaves the building at an average of 21°C then at least 25,000 kJ will be removed from the room; sufficient to extract all the heat from the PCM. In the climate reference year 1964-65 there were 6 nights in the year when the average outside temperature between 20:00 and 06:00 was higher than 17°C.

The night time ventilation can be boosted mechanically or guaranteed by installing a central extraction system that brings the outside air through the rooms and the corridor via a central shaft. To make sure that all rooms are adequately ventilated, despite potentially difficult wind pressure differences at the various external walls, the ventilation opening between the rooms and the hall can be fitted with a constant volume damper.

Regeneration with mechanically cooled ventilation air

The regeneration of the PCMs in the ceilings with the assistance of a mechanical ventilation system is easy to set up, but it does have its limitations. Firstly the supply of cooled air must be directed at the PCMs, so that the energy is extracted from the PCM plates. In addition the now warmed-up air must no longer be directed along the PCM plates. It must be sent removed directly.

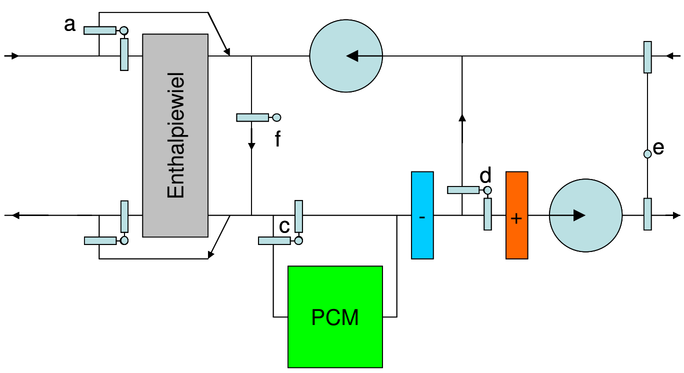
We saw from the example with natural ventilation that to solidify all PCM, an air change rate of n=10 over a 10 hour period at a temperature of 17°C must take place. Mechanical regeneration provides the certainty that that this period will be used effectively. The ventilation system must however be designed to have a greater capacity than would normally be used. Typical ventilation systems in the market have an air change rate of n=2 – 4.

For example a mechanical ventilation system with 4 air changes per hour will be able to regenerate the PCM package as follows. To remove all the heat stored in the PCM, air must be supplied for a period of 10 hours at an average of 12°C, assuming a return air temperature of 21°C. This means that the ventilation system must operate throughout the entire night!

If the PCM will be regenerated in this way it is best to use a ventilation system with plenty of capacity so that large air volumes can be moved. Then the air supplied for the regeneration does not need to be cooled as much and the pressure drop over the ventilation system will be smaller, in spite of the large air flow rate.

4.2 PCM AS COOLING BUFFER IN AN AIR HANDLING SYSTEM

Instead of installing the PCM in the rooms it can also be incorporated in the central air handling unit as an air-side cooling buffer. The PCM is then used during the day to lower the supply air temperature using the cold stored during the night, or if needed cold uploaded during the night using a lower capacity



mechanical cooling unit. The PCM ensures an increase of the effective maximum cooling capacity of the air handling unit and makes the use of stored night time cooling possible. The mechanical cooling unit can therefore be smaller and in the summer can operate part of the time at night, as a result of which the use of cheaper night electricity is possible for generating cooling for use during the day.

4.2.1 REQUIRED THERMAL PROPERTIES OF PCM

The selection of the optimum thermal properties of the PCM for use in a central air-side cooling buffer is subject to the same constraints and limitations as for use in rooms, as described in section 4.1.1. In addition the selection depends on the way in which the cooling buffer is used and on the functions available in the air handling unit.

Air handling unit without mechanical cooling

If the air handling unit does not have a cooling coil, but does have heat recovery facilities, then the PCM buffer can be added at the end of the supply air handling, after the fan.

The average melting temperature of the PCM must be lower than the required supply air temperature of the ventilation air, but (taking account of the temperature hysteresis) high enough so that the heat can be extracted to the outside air as often as possible at night. It is therefore a balance between a higher cooling capacity during the day and better regeneration at night.

Based on the above considerations, the optimum average melting temperature will be somewhere between 20 and 22°C, with an average solidification temperature between 18 and 20°C. A PCM cooling buffer can be dimensioned so that the exhaust air temperature remains constant for a relatively long period and in the region of the lowest melting temperature of the PCM, because the PCM in the buffer will melt first at the air inlet and gradually over the entire buffer. The heat transfer between the air and the PCM is much higher than is the case with an application without a forced air flow in a room, so that the exhaust temperature of the air can lie close to the PCM temperature at the outlet.

If a PCM with a melting range of 20°C to 22°C is chosen, an exhaust air temperature at a constant 21°C is easily achievable. The climate control concept of the building must then be designed to operate on the basis of this 21°C exhaust air temperature. Without additional cooling facilities in the room the ventilation flow rate must then be around 6 to 8 air changes per hour to prevent excessive temperature rises to 28°C. A relative large quantity of air for which a large system of air ducts is needed in combination with larger– or more – grilles in the rooms. On the other hand no mechanical cooling capacity is needed in the building and the air quality is extra high as a result of the higher air flow rate.

Dehumidification is not possible with such a PCM buffer, because the surface temperature of the PCM is too high for this.

Air handling unit with mechanical cooling

An air handling unit with mechanical cooling can operate with a PCM with a lower melting temperature than a unit without mechanical cooling, because if needed during hot summer nights the PCM can be regenerated with the assistance of the mechanical cooling system. The PCM buffer must be installed before the cooling coil and after the heat/cold recovery unit if present. The PCM buffer takes care of the first stage of the air cooling and the air cooler handles the second stage, where dehumidification can also take place if required.

Therefore the PCM relieves the mechanical cooling system, while use is made of cooling from outside stored during the night, or cooling supplied by the mechanical cooling system at a lower night electricity tariff.

The capacity of the PCM buffer to take over the task of the mechanical cooling system is increased by the choice of a lower melting temperature. It will however then be necessary to deploy the mechanical cooling system more frequently at night for the regeneration. Therefore a balance must be found between optimum energy savings as a consequence of the effective use of free cooling at night and the reduction of the mechanical cooling capacity that can be achieved during the day.

In the summer, condensation will form on the PCM at lower PCM melting temperatures than approximately 16°C. Account must therefore be taken of this.

4.2.2 COOLING CAPACITY

The cooling capacity of a PCM buffer with forced air flow is dependent on the airflow speed between the PCM plates and the prevailing local temperature difference between the PCM and the air flowing over it.

Assuming PCM plates of 1 cm thickness, as they are usually available commercially, and minimising the volume of the buffer, limiting the internal air flow rate to 12 m/s, the average capacity of the PCM buffer over one operating cycle will only be limited by the heat storage capacity of the PCM present in the buffer. The heat storage capacity must be sufficiently large to supply the capacity demanded during the operating cycle (a day).

4.2.3 REQUIRED PCM MASS

The exhaust air temperature of an air-side PCM buffer is fairly constant during the entire operating cycle, due to the melting of the PCM at the inlet initially and gradually shifting towards the outlet. The heat transfer in the unit will be very good if standard PCM plates of 1 cm thickness are used. The cooling capacity is then dependent on the temperature difference between the supply air and the exhaust air.

The PCM mass required can be determined by the quantity of cooling to be calculated during one operating cycle on a warm reference day. 26 August 1964 was such a day in the climate reference year 1964-65. The cooling demand can be determined based on the air flowing along the surface and its characteristics. Assuming an exhaust air temperature of 21°C and an average supply air temperature of 25.3°C, on this day per 100 m^3/h air flow rate approximately 2500 Wh, or 9000 kJ of storage capacity storage capacity was needed. Assuming a PCM with 100 kJ/kg storage capacity, 90 kg PCM would be needed. An air handling unit with an air flow rate of 30,000 m^3/h would then need a 27,000 kg PCM buffer. Such a buffer would have a volume of approximately 30 m^3, assuming air slits of 5 mm between 1 cm thick PCM plates. This would therefore be a very large component in relation to the dimensions of the air handling unit.

By choosing a higher exhaust air temperature for the buffer the required capacity and size of the buffer can be reduced.

If the air handling unit has good heat recovery provisions (combined with adiabatic humidification of the return air if required) the PCM buffer can be made even smaller. The

PCM buffer then forms the second stage in the air cooling system, therefore after the indirect adiabatic cooling and before an air cooler/dehumidifier if required.

4.2.4 REGENERATION OF THE PCM

The regeneration of the PCM buffer takes place by flushing the unit with cool outside air. A fan from the air handling unit is used for this purpose and suitable duct and damper system must be provided. Due to the high heat transfer the regeneration of a PCM buffer can be designed to be efficient and easily controlled. A smaller temperature difference is required between the outside air and the PCM than in the case of the regeneration of a PCM ceiling. If the air handling unit has two fans, or fans that can be speeded up, then less time is needed to carry out the regeneration. The end of the regeneration cycle can easily be recognised by a sharp drop in the exhaust temperature when almost all the PCM has solidified.

Regeneration with mechanically cooled air

It the air handling unit contains a cooling coil then during excessively warm summer nights the mechanical cooling can be switched in. Then there must be a provision in the ducts and damper system that makes it possible for circulation of the air to take place through the coil and the air cooler.

4.3 PCM AS COOLING BUFFER IN A ROOM AIR COOLER

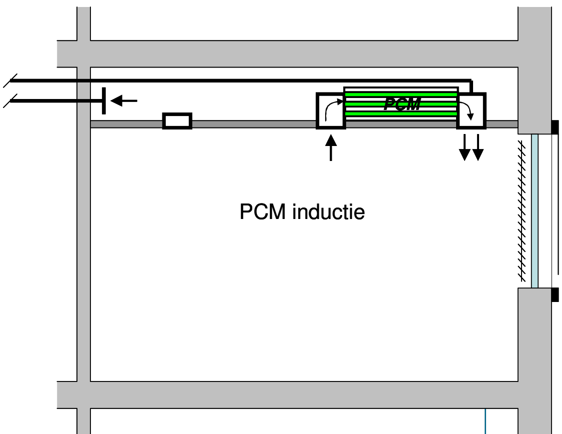
In place of the use of PCM in a central buffer at the air handling unit the PCM can also be used in a buffer in the room to be air conditioned, in combination with a suitable system for passing air through the buffer. There are a number of possible designs.

The buffer can be flushed with mechanically supplied air to cool this air before it enters the room. The buffer can be flushed with room air to cool this air independently of the supply air. Or room air can be induced through the PCM buffer with the assistance of the supply air flow.

- PCM buffer in the supply air flow.
- PCM buffer with a fan for cooling room air.
- PCM buffer with room air induction, powered by the central ventilation system.

There are also a numbers of options for the location of the PCM buffer in the room. The buffer can be mounted above the suspended ceiling. Or the buffer can be fitted standing on the floor as an air cooler (possibly mobile). Also the buffer can be mounted in or against the outer wall as part of an individual ventilation facility in the wall, where other provisions such as heat recovery, heating or air cooling can be included (EMCO).

A commercially available PCM application is the PCM induction unit. This device is connected to the central ventilation system and consists of a PCM buffer, an induction grille and a damper to switch between day and night time operation (regeneration). During the day, room air is drawn over the PCM buffer by induction. For night time operation the damper is switched over so that the cool air flows over the PCM buffer



into the room in the opposite direction, thus regenerating the PCM.

During the day the cooling capacity of the PCM induction device is the sum of the cooling capacity of the mechanically cooled supply air and the cooling capacity of the PCM buffer over which the room air is induced. The total volume of airflow through the device is the sum of the primary supply air flow and the secondary air flow that is induced over the PCM buffer. The device is dimensioned so that the total cooling capacity is approximately twice as large as the primary cooling capacity of the supply air. The supply air is mechanically cooled because the induction unit cannot always supply sufficient cooling capacity to satisfy the total cooling demand. This does reduce the cooling capacity required for the air handling unit.

The induction flow rate of the device, i.e. the quantity of room air drawn in by induction, expressed as a multiple of the supply air flow rate, is a function of the efficiency of the induction grille, the pressure available in the supply air duct and the resistance of the PCM buffer. In practice an induction rate of between 1.5 and 5 is achievable.

The discussions in this section will focus on this type of equipment.

4.3.1 REQUIRED PCM THERMAL PROPERTIES

The optimum average melting temperature of the PCM in the PCM induction device is chosen in accordance with the considerations discussed in section 4.2 for the central PCM buffer. The difference is that a PCM induction unit is only used in combination with mechanical cooling to direct the air along the PCM surface to achieve heat transfer. The selection of the melting temperature of the PCM is therefore dependent on the desired combined supply air temperature and the desired cooling capacity of the PCM. The lower the melting temperature, the higher the cooling capacity that can be achieved and the lower the supply air temperature. The optimum melting temperature is 18°C minimum. A low PCM melting temperature means that use can be made of free cooling less often (also due to a low solidification temperature) and mechanical cooling will be needed more frequently. The optimum average melting temperature of the PCM will lie somewhere between 21 and 23°C; an average solidification temperature between 19 and 21°C.

4.3.2 COOLING CAPACITY AND REQUIRED PCM MASS

For determining the cooling capacity a PCM induction unit, a room with a floor surface area of 20 m^2 and two people are assumed. The primary supply air flow rate is 100 m^3/h. The supply air is mechanically cooled to 16°C during day time operation.

The supply air supplies a cooling capacity of 400 W at a room air temperature of 28°C, or 20 W/m^2. Then 400 W cooling will still be needed, which must be supplied by the PCM buffer over which the room air is induced. Use is made of a PCM with an average melting temperature of 22°C. At a room air temperature of 28°C approximately 250 m^3/h of induced air is then needed – an induction air change rate of 2.5 – that is cooled to 23°C in the buffer. The total cooling capacity of the PCM induction unit is then 450 W.

The surface area of PCM plate needed in the buffer can now be determined. Assuming a convective heat transfer coefficient of 14 (standard for a heat exchanger with an airflow of 1 m/s) and a radiant heat transfer coefficient of 5.5 W/m2K prevails between the PCM plates and the air flowing along them, a heat transfer coefficient of approximately 20 W/m^{2}K.

Assuming an average PCM temperature of 22°C and an average air temperature of (28+23)/2=25.5°C, a PCM surface area of approximately 6 m² is needed. This can be provided by using 10 square metres of PCM plates with 0.55 m fins. The PCM plates can be fitted horizontally above each other with an air slit.

To supply 400 W cooling capacity over an 8 hour period, 11,500 kJ of storage capacity is required, thus approximately 115 kg PCM. Therefore 28 mm thick PCM plates are needed. This is not a standard size. If standard 1 cm thick plates are used then 8.5 m² PCM plate will be needed.

4.3.3 REGENERATION OF THE PCM

The regeneration of the PCM in the induction unit takes place at night by using a damper to allow the cooled supply air to flow through the PCM buffer instead of flowing into the room through the induction grille. The PCM used in section 4.3.2 has an average melting temperature of 21°C and thus an average solidification temperature of 19°C. To regenerate this PCM with an air flow rate of 100 m³/h, the supply air temperature must be less than 9°C over a period of 10 hours. This is very low. Therefore it is better to use a somewhat higher air temperature in combination with a higher air flow rate, which also improves the heat transfer. By using an air flow rate of 200 m³/h, an inlet temperature of approximately 13°C is sufficient to fully regenerate the PCM. This does mean doubling the required air flow rate in the central ventilation system compared to the air flow rate during the day.

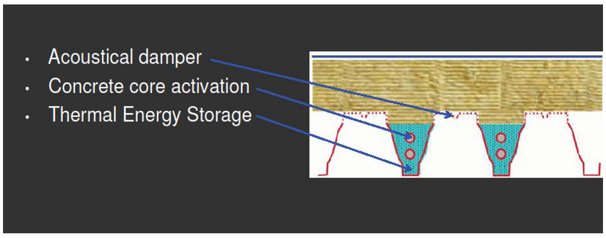
4.3.4 DISADVANTAGES OF REGENERATION

As shown in the above sections, it is important that the PCM is 'reset' and returned to its original condition outside the operational period. Various principles and methods of regeneration have been discussed. Not mentioned, but certainly important for regeneration, is that additional measures must often be taken to enable regeneration to take place. Examples include ventilating in the night situation, ventilating with larger that normal air quantities etc.

These measures will have an impact on the investment required for a situation where PCMs are used and the reference situation with a conventional system or another solution.

Also the energy savings can be largely negated by the extra energy needed for regeneration. Consider here the night time ventilation, while in the normal situation the ventilation is switched off after the operational period. Power use for ventilation is generally one of the greatest energy costs in a building.
When night time ventilation is in use in a building it is always advisable to check whether the ventilation system can supply just as much or even more cooling capacity by circulating outside air as by regeneration of the PCM.

Particularly interesting in this respect is a project carried out by R.I. Deerns, where regeneration is done using a chilled water pipe running through the material in which the PCM is incorporated. This pipe is fed from an aquifer



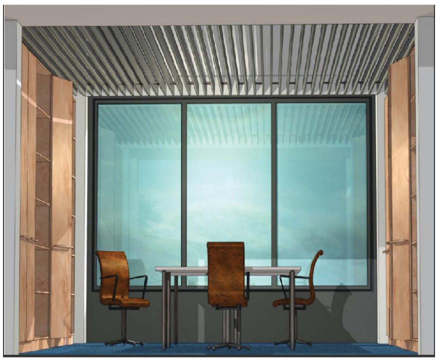
thermal energy storage system (ATES), which brings about the regeneration. This is the WILO building in Westzaan. This building has a lightweight structure with a number of concrete components in which PCM forms an integral part.

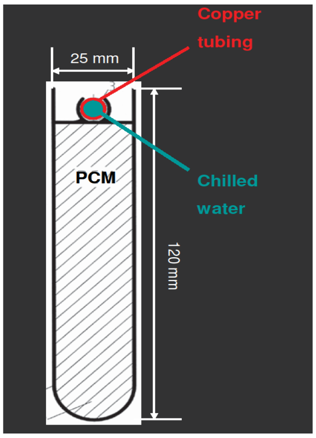
The figure shows a cross section of a steel roof profile with Rockwool insulation. The lowest part of the steel sheet profiles are filled with concrete incorporating a percentage of PCM, significantly improving the heat capacity. The figure also shows two poured-in pipes that are used to regenerate the PCM and also to provide extra cooling in the day time situation. These all form part of a sustainable aquifer system.

Figure 4.1 Impression of WILO building

Another example that takes advantage of this is the Caverion Climate Ceiling. This is a baffle ceiling with a chilled water pipe mounted in it for regeneration and also for the partial supply of primary cooling.

Figure 4.2 Impression and cross-section of PCM ceiling





In the left hand figure indicates the appearance of this type of ceiling. The right hand figure illustrates a cross-section of a single baffle. These are metal baffles filled with PCM. The strong, closed construction guarantees safety (from fire and leakage). The metal casing also ensures efficient energy transfer to the surroundings, and to the metal pipes that are filled with chilled water.

CHAPTER 5 Control

The control of PCM applications would seem in principle to be similar to the control of concrete core activation and also to that of night time ventilation, in as far as an attempt is made to make optimum use of the thermal storage capacity in the building. Here the cooling demand during the day is kept in balance as effectively as possible using the supply of (cheap or free) cooling during the night.

The application of PCMs makes the use of a smaller cooling installation possible. When efficiently controlled, these will be almost continuously in operation during hot summer periods. The cooling generated during the night then benefits the cooling demand during the day. Effective control is essential to prevent overshooting, or the excessive cooling of the room or of the PCM. In this situation, consideration can be given to predictive control on the basis of weather forecasts and user behaviour.

Several different control strategies apply to the various PCM applications discussed in previous chapters. The control system for each of the applications will be described in general terms in this chapter.

The control of the passive PCM systems, where PCM is continuously in thermal contact with the room to be air conditioned, such as the PCM ceiling, is the most complex and requires the most infrastructure. The control of PCM systems that are switched in or switched out during operation, such as the central PCM buffer and the PCM induction unit, is the simplest and require the least infrastructure.

Control systems for PCM applications must be designed so that they can be optimised based on experience gained with the building and by individual users.

5.1 PCM USED IN SUSPENDED CEILINGS

The heat stored in a PCM ceiling system must be removed at night using ventilation by cool outside air or by the supply of mechanically cooled air from the mechanical ventilation system. Therefore PCM ceilings rarely need to be supported by controlled, mechanised ventilation equipment.

Control of the regeneration is easiest if the PCM ceiling is designed with a separate provision to guide the cool air over the PCM plates. If the PCM is used in a simple (island) ceiling system, such a provision will not be available, and in practice the regeneration of the PCM means the night time ventilation of the entire room. Not only is the heat in the PCM then removed, but also the heat from floors, walls and the ceiling. Part of the heat from the

PCM is indirectly removed by radiation of the PCM surfaces to other surfaces in the room that cool faster under the influence of the night ventilation. This means that PCMs are primarily used in light structures that have limited mass for heat accumulation.
Control of night time ventilation is possible in various ways. The best is individual control per room on the basis of temperature measurement directly on a representative part of the PCM surface. The cheapest is central control using a timer and a seasonal program.

5.1.1 CONTROL ON THE BASIS OF PCM SURFACE TEMPERATURE

Optimum control to enable effective regeneration without overshooting can be based on temperature measurements on the surface of a representative part of the PCM ceiling, e.g. in the centre of the room. Motorised outside wall openings or the dampers in the mechanical ventilation system are then separately controlled per room on the basis of the temperature measured on the PCM.

The optimum setting point for this is around the lowest temperature of the melting temperature range of the PCM. In practice this will be around 20°C for a PCM ceiling. The ventilation will continue as long as the temperature measured on the PCM surface is above the setting point. The temperature measurement must be accurate though!

The heat flow from the PCM to the cooling ventilation air is driven by the temperature difference that occurs, thus the air temperature in the room during the regeneration process will be a few degrees lower than 20°C. These reasons explain the risk of overshooting, e.g. the room will be too cold in the morning when the user arrives after an intensive night ventilation programme. If the night ventilation is stopped in time the temperature in the room will increase a few degrees due to inertia in the system and also depending on the thermal mass present. Effective control ensures that the temperature in the room rises to a comfortable level of 20°C in time. This can be achieved through the selection of a suitable setting point and a suitable finishing time for the night ventilation programme.

5.1.2 INDIVIDUAL CONTROL BASED ON ROOM TEMPERATURE MEASUREMENTS

If the temperature measurement does not take place on the PCM, but somewhere in the room, e.g. as part of an individual thermal comfort control system, then a lower setting point must be chosen. In the case of air temperature measurements taken in the room, a setting point of 20°C would probably lead to the night ventilation programme stopping too early. The optimum setting point depends on the location of the temperature sensor, the ventilation flow pattern, and the thermal mass in the room.

5.1.3 CENTRAL CONTROL BASED ON SEASON-DEPENDENT TIMING PROGRAMMES AND WEATHER DATA

A simpler control system makes no (or only limited) use of individual temperature sensors in the rooms, but works with a central, season-dependent time programme, possibly in combination with data or the building's weather station. Each evening a night ventilation programme is established and implemented, depending on the time of the year and possibly the weather conditions during the day. The system parameters are optimised during the first year of operation based on user experience, in particular for the prevention of overshooting after night ventilation.

CHAPTER 6 Simulation of PCM applications

This chapter uses simulation techniques to investigate the effect of various PCM applications on the temperature in a room.

The simulations use an algorithm to determine the PCM temperature as well as experimental data about the heat transfer concerned. The simulation of the office rooms is done in accordance with the usual simplification of the lumped mass model where the room is modelled as a collection of point masses that exchange heat between each other by radiation and/or convection. To serve a 15-25 kg/m^2 floor area a PCM plate of 10-17 mm thickness is needed, where the internal thermal resistance may be neglected because the thickness of the plate remains limited and the thermal resistance is negligible compared to the heat transfer to the room air.

The simulations are limited to a one room office. The simulation period is 10 days in a summer period with climate data from the reference year 1964 - from 22 August 1964 up to and including 1 September 1964. The control is based on air conditioning in the summer. The winter is not considered, because the PCM application under consideration has no function at that time and conventional control is applicable.

By varying the amount of ventilation, temperature, degree of heating and cooling with time, various control settings can be demonstrated. The thermal comfort as a function of the operative temperature is used to assess the quality of the systems.

6.1 WHY SIMULATION?

Simulation of temperature changes in a room over time is the only clear-cut way to calculate the performance of a PCM application over a longer period. This is necessary because the functioning of PCM applications is dependent on the condition of the PCM, which is variable over time. Besides the control and the dimensioning of the ventilation system and the heating and cooling system are of importance to the behaviour over time.

The cooling capacity of a PCM ceiling is different at the start of a working day compared to at the end of the day. The cooling capacity at the start of the following day is different again, because it is dependent on the success of the regeneration of the PCM during the night. Using simulation over a number of days and nights, an examination can be made of whether the various process phases of the PCM application function effectively enough to provide the desired performance, and whether they are compatible. This enables design guidelines to be developed.

6.2 ASSUMPTIONS

The simulation is of an office with the following characteristics:

Table 1: Assumptions for reference room

Office		
Length	5.4	m
Width	3.6	m
Height to suspended ceiling	2.7	m
Height of storey	3.3	m
Floor surface area	19.44	m^2
Volume	52	m^3
Floor thickness	160	mm
Floor type	Concrete	
Partition wall thickness	100	mm
Partition wall type	System wall	
Outside wall type (from outside to inside)	Half-brick skin-insulation-metal stud	
Thermal resistance of outer wall Rc	2.58	m^2K/W
Window area percentage	30%	
Orientation	south	
Window area	3.56	m^2
Window U value	1.2	-
Window SHGC	0.7	-
Window + outside awning SHGC	0.15	-
Internal heat sources during working hours		
Working times	every day from 08:30 to 17:30	
Lighting	8	W/m^2K
People	8	W/m^2K
Equipment	6	W/m^2K
Fresh air flow rate during the day	2x ref. rate ventilation = 100	m^3/h

The control of the thermal climate in the room was carried out and simulated in various ways, working from the above basic information.

Explanation of the assumptions:
It was decided to simulate a standard office for one person. This person does not carry out active work, but just works on a laptop. An LED system was chosen for calculating the lighting, so that the effective power could be set to 8W/m2 over the entire day. The power required for equipment was only that needed for a laptop. The office was to be a light construction. The PCM has significant influence in this situation. Also an awning was used to provide shade from the sun. The Rc value of the external wall conforms with legally required standards.

Of course these assumptions can an issue for discussion. However they clearly illustrate what can be achieved by PCMs in buildings and this matches the objectives of this report.

6.2.1 PCM CONDITION SIMULATION – THE PCM CALCULATION ALGORITHM

The PCM used in the simulation of the ceiling systems is the PCM (code SP22a17) from Rubitherm. This is a PCM based on calcium chloride hexahydrate ($CaCl\ 6H_2O$). The properties of this PCM have been established experimentally by Delft University of Technology. The (characteristic) thermal behaviour of this PCM was later confirmed independently by investigators at the Fraunhofer Institute and The Bavarian Centre for Applied Energy Research (ZAE Bayern).

The thermal behaviour is illustrated in the following graph, where it can be seen how the enthalpy of the PCM changes during a complete thermal cycle.

Figure 6.1 Specific enthalpy of melting and solidification process

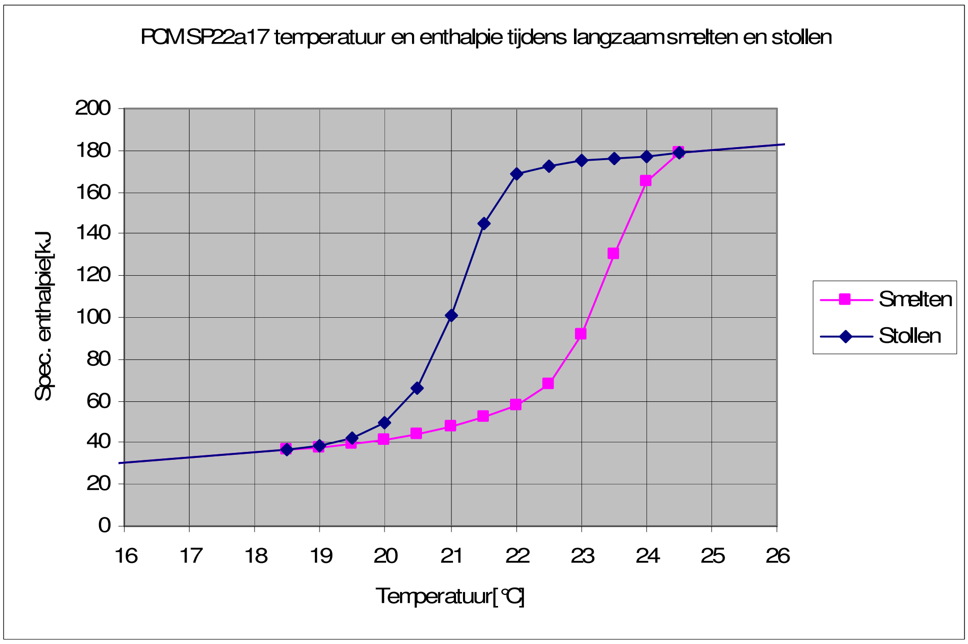


Figure 1: Enthalpy of PCM

To obtain the data, the PCM in macroscopic form (PCM plate from the factory), was exposed to a very slowly rising environmental temperature of not more than 2°K per hour, as would be expected in practice. The enthalpy increase of the PCM was calculated from the difference between the measured surface temperature of the PCM and the environmental temperature. After the complete phase change – indicated by the levelling out of the enthalpy curve at high specific enthalpy – a cooling process was started, once again with a slow cooling rate. This generated two curves as seen in the graph.

When the behaviour of PCMs is simulated under the influence of varying heat flows, the temperature and enthalpy will move along the curves *or in the area between the curves*. This is the main assumption on the basis of which an effective algorithm can be formulated. This algorithm has been used for the simulations described in this chapter. The algorithm was validated by several experiments at Delft University of Technology.

The principle used is that the temperature of the PCM is calculated depending on the increase or decrease of the enthalpy divided by the **specific heat** of the PCM. The temperature the PCM so calculated is however limited by the two empirically determined curves in the graph. Should the temperature of the PCM deviate from one of the curves then the algorithm corrects the calculated temperature so that it falls on the relevant curve. I.M. Bouwman's graduation thesis [3] confirms that this approach leads to very good correlation between the simulations and reality; much better than was the case using earlier algorithms for PCM.

In the following sections two reference simulations are presented of two frequently encountered HVAC systems with 2x air change rate (night) ventilation and with chilled and non-chilled supply air.

6.3 REFERENCE CASE SIMULATED ROOM

Before the simulations of PCMs in the rooms were carried out, a number of reference situations were first done to make the effect of the PCM clear. The first simulation was carried out for a reference case with a conventional HVAC system.

6.3.1 REFERENCE CASE 1 – BALANCED MECHANICAL VENTILATION WITH COOLING

This conventional system has the following characteristics:

Table 2: Reference for simulation

HVAC system Conventional		
Fresh air flow rate during the day	100	m^3/h
Supply air temperature during the day	Minimum 16	°C
	Only heating coil in AHU	
Operational	Between 07:00 and 19:00	
Night ventilation	100	m^3/h
Supply air temperature at night	Outside air temperature	
Operational	When outside air is colder than inside air: Between 20:00 and 07:00 Setting point for inside temperature 16°C	

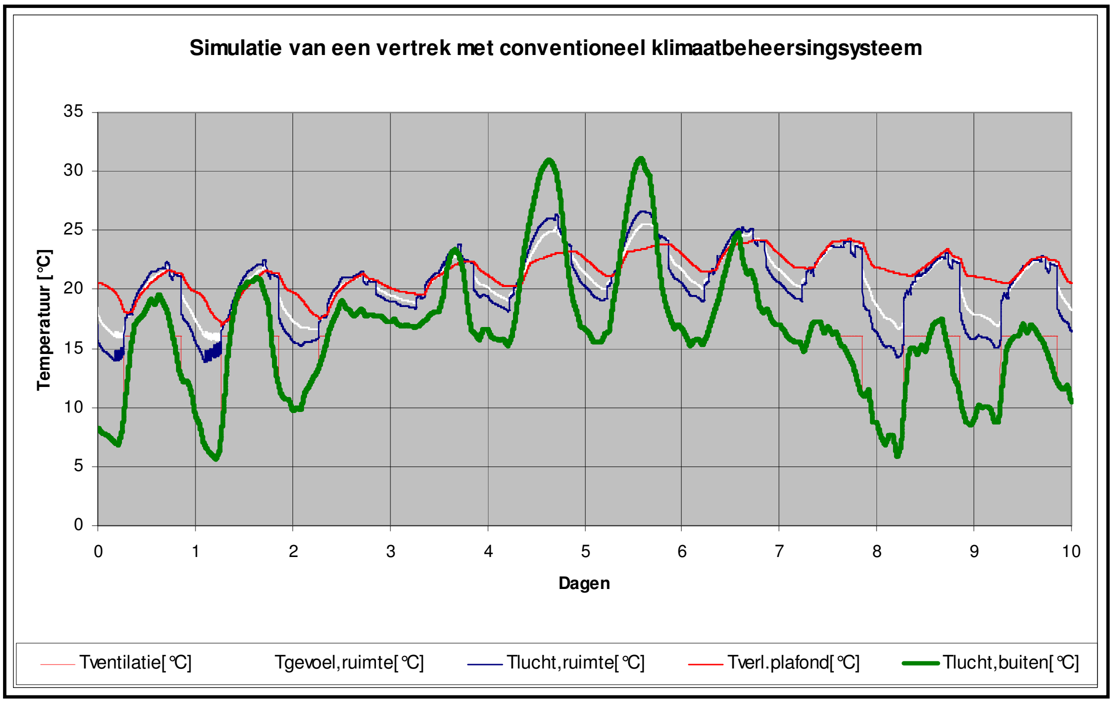
The simulation results are illustrated graphically. The horizontal axis shows the time period of 10 days and the vertical axis the relevant variables.

The following graph shows the air temperature in the room, the outside air temperature, the effective temperature, the temperature of the suspended ceiling and the supply air temperature as a function of time. The lower graph shows solar radiation and ventilation.

The effective temperature (white line) is the operative temperature. This is defined as follows:

$$T_{operative} = T_{air} / (4*(2+T_{susp.ceiling})(8+T_{floor})(8+T_{wall}))$$

N.B. The temperatures of the floor and the walls are not included in the graphs.



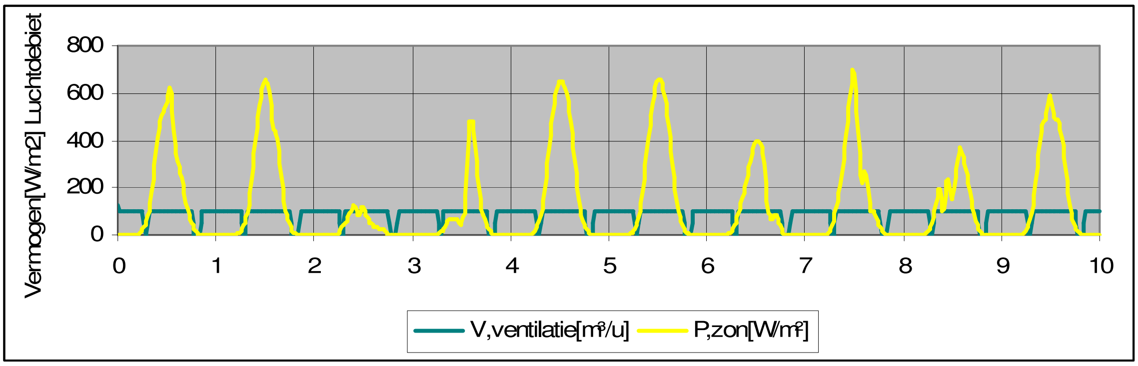


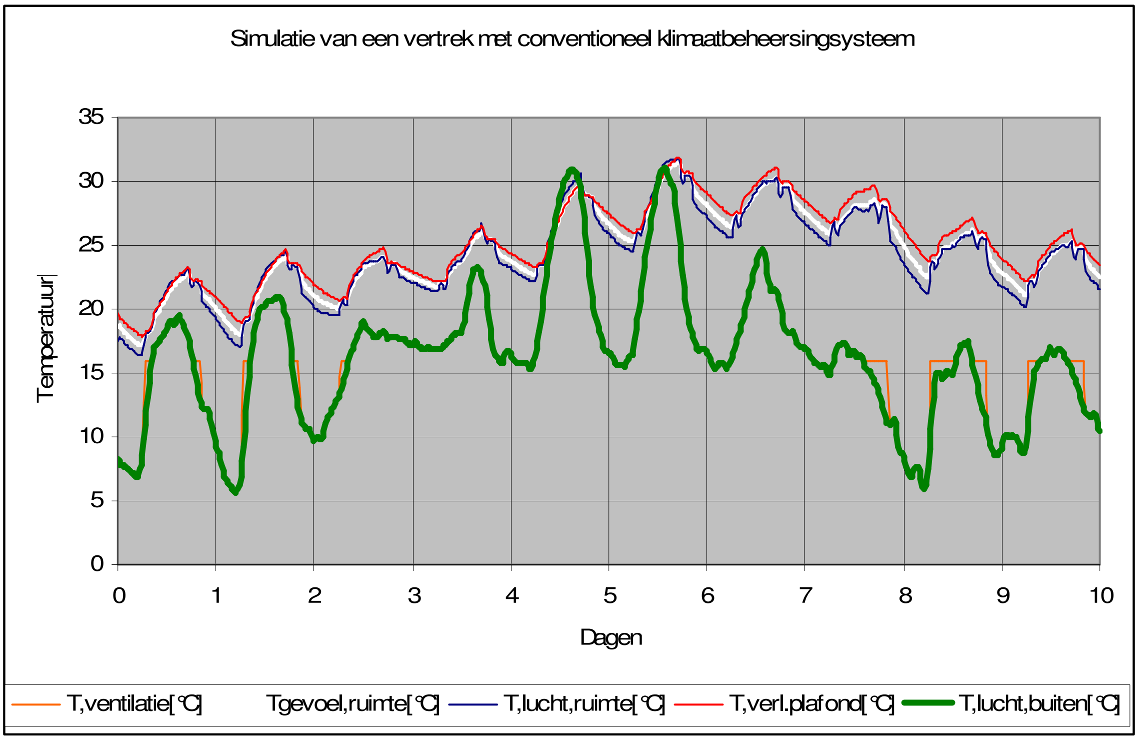
Figure 6.2: Simulation results reference case 1

The graphs indicate that the effective temperature reached a maximum of 26.7°C on the fifth day. This conventional HVAC system worked quite well.

It can also be noted that for a few days after the two warm days the room continued at quite a high temperature level. Apparently the night ventilation was not sufficient to disperse the heat from the building adequately. This is relevant, because a great deal more heat will have to be removed when PCM is used.

6.3.2 REFERENCE CASE 2 – BALANCED VENTILATION WITHOUT COOLING

The reference simulation can also be carried out without any use of mechanical cooling. In that case the supply air temperature will be the same as the temperature of the outside air, assuming ventilation with outside air without warming up by fans (e.g. outer wall grilles with supply fan). If the cooling system is not used, but everything else remains the same, the following occurs:



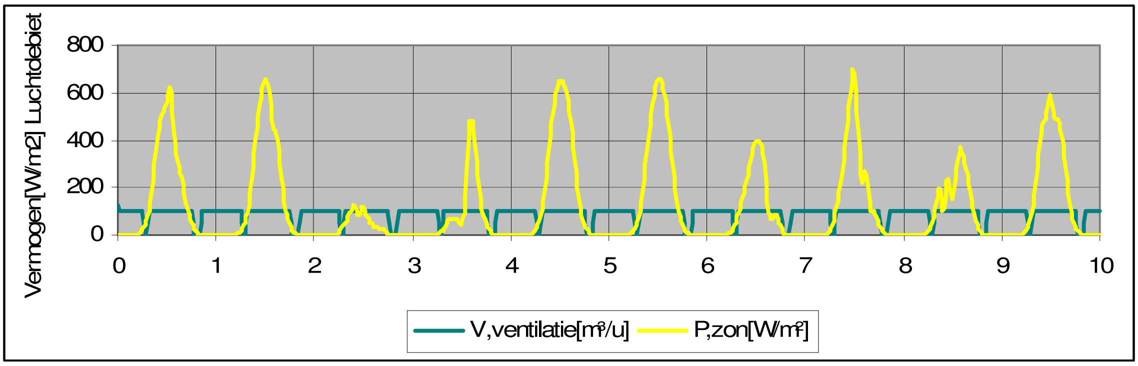


Figure 6.3: Simulation results reference case 2

In contrast to the previous reference simulation the inside temperature now reaches at least 31°C. Without cooling it will become very warm in this building. The night time ventilation of 100 m³/h is insufficient to remove the heat within a couple of days, therefore after the two hot days the building remains warmer than 25°C for a further two days. In practice in this situation the windows would be opened really wide resulting in much more ventilation. This is simulated in the following reference case.

6.3.3 REFERENCE CASE 3 – BALANCED VENTILATION WITHOUT MECHANICAL COOLING OPENING WINDOWS AND NATURAL NIGHT VENTILATION.

The difference between this simulation and the reference simulation is that the ventilation increases at night to 400 m3/hour, equivalent to an air change rate of 8x, which is achieved by opening windows wide during the night. This is what the occupants of buildings without mechanical cooling systems do automatically during a heat wave. This may well not be desirable behaviour in relation to the security of the building and potentially damaging gusts of wind in an office environment with plenty of paper. An eight times air change rate can be achieved using suitable grilles in the outer walls. The simulation assumed open windows to demonstrate the maximum effect on the regeneration of the PCM.

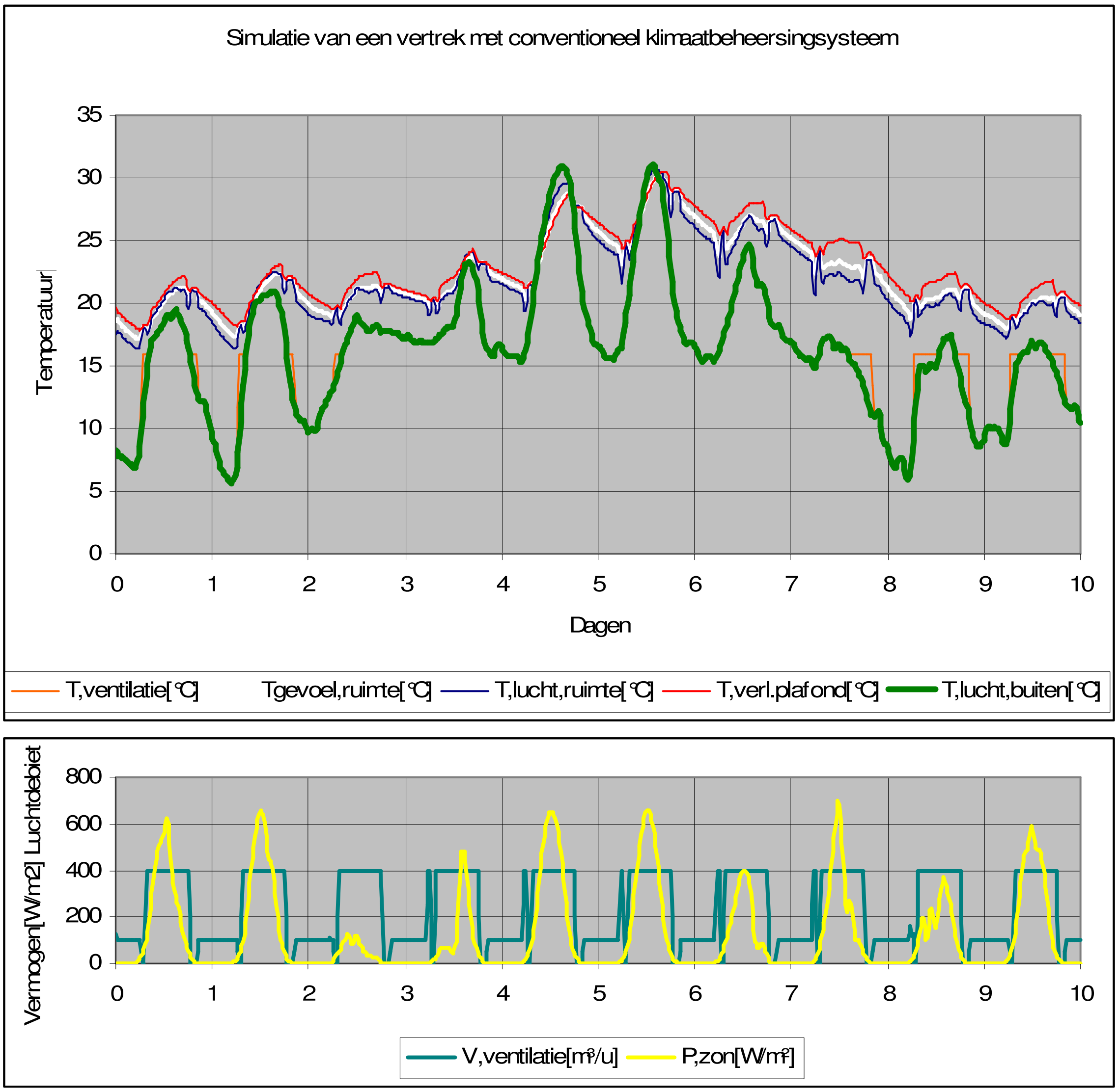


Figure 6.4: Simulation results reference case 3

The increased night time ventilation speeds up the cooling of the building considerably and ensures less temperature excesses during the day. However during the two hot days the day time temperature was still too high to be comfortable.

6.4 SIMULATION WITH PCM IN THE BUILDING

The following sections illustrate simulations of the same room, but with the use of a PCM buffer. There are two simulations of the application of PCM in the ceiling. Here use is made of balanced ventilation in the building and regeneration with and without natural night time ventilation is considered. The third simulation with PCM uses it a as a buffer in the air handling unit. First we will look at the principles of the system and the objectives of the simulations.

6.4.1 PCM CEILING SIMULATION 1 – BALANCED VENTILATION WITHOUT MECHANICAL COOLING AND WITHOUT NATURAL NIGHT TIME VENTILATION

In this simulation the suspended ceiling is constructed using PCM plates. The characteristics of the system are as follows:

Table 3: Assumptions for PCM concept simulation

HVAC system with PCM ceiling		
PCM ceiling		
Area	80% of the floor area	
	15.5	m^2
Thickness of the PCM plates	15	mm
Mass of the PCM plates	20	Kg/m^2
PCM type	Rubitherm SP22a17	
PCM melting temperature	22	°C
PCM specific heat of melting	130	kJ/kg
PCM specific heat	2.5	kJ/kgK
PCM total installed mass	317	Kg

Now that the PCM ceiling has been installed a significant damping of the temperature rise in the room can be seen in the first five days. On the first hot day (day 4) the maximum temperature reached is well under the maximum temperature on the same day in the previous simulation. On this day the temperature in the room remained comfortable. However during the following night the PCM was not cooled sufficiently. The night time ventilation was not adequate. The second hot day and the following days resulted in temperatures much the same as those encountered during the reference situation without a PCM ceiling and without night time ventilation.

It can be concluded that if the PCM cannot be properly regenerated during the night, it will not be effective the following day and the temperature in the room will be excessively high. In that case the PCM is only useful for one hot day. Effective regeneration is therefore essential!

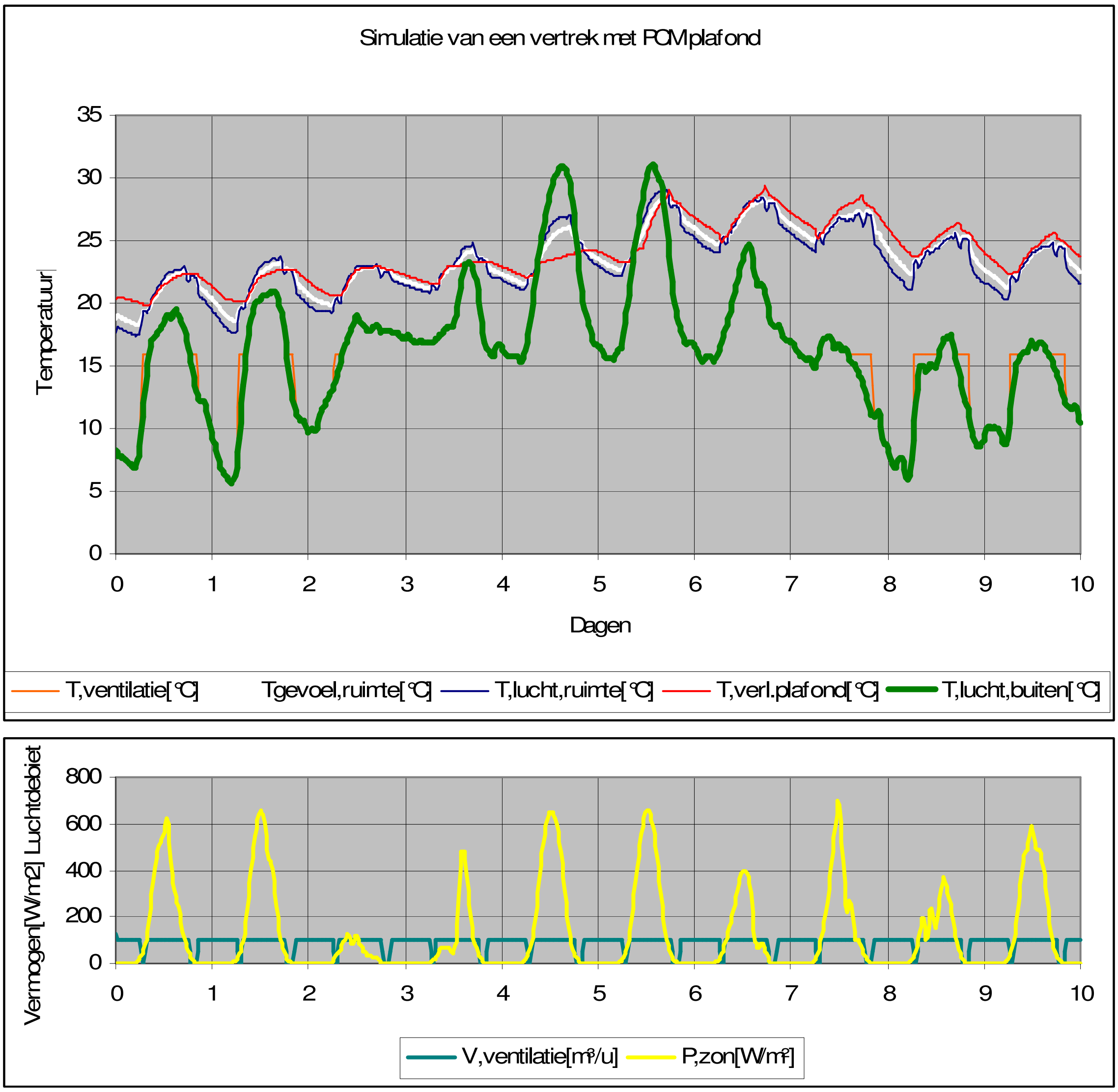


Figure 6.5: Simulation results for PCM ceiling without night time ventilation

6.4.2 PCM CEILING SIMULATION 2 – BALANCED VENTILATION WITHOUT MECHANICAL COOLING AND WITH NATURAL NIGHT TIME VENTILATION

The same system as in the simulation discussed in section 6.6 will now be supplemented by natural night time ventilation as used in reference simulation 3. The windows are opened at night or ventilation grilles in the outer walls are opened to achieve the 8-times air change rate of the room. The temperatures are now as follows:

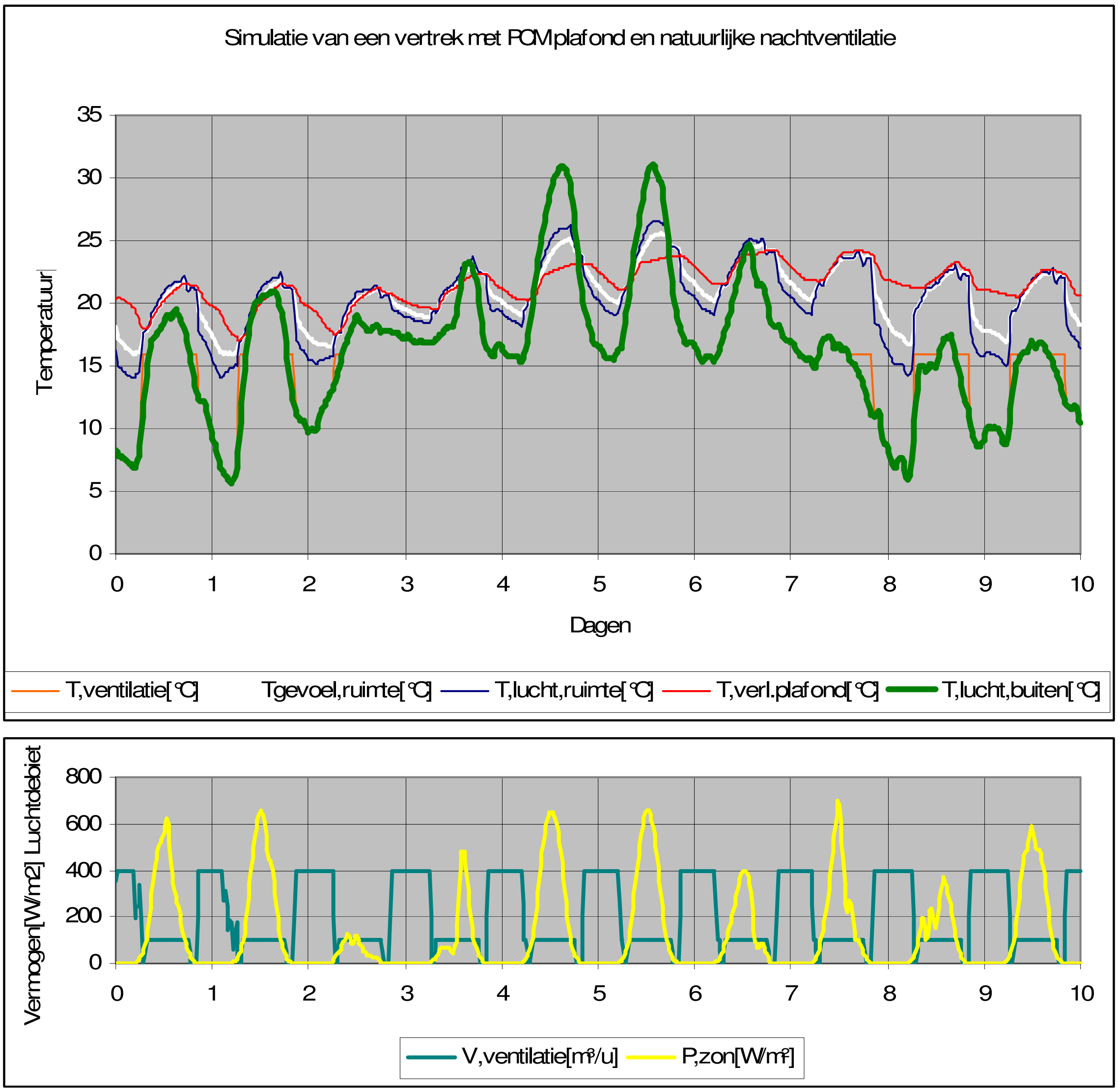


Figure 6.6: Simulation results for PCM ceiling with night time ventilation

The difference between this and the preceding simulation is that the PCM temperature (suspended ceiling temperature) drops every evening to the starting situation. This immediately leads to lower temperatures during the day and also to efficient temperature control in the room, even on the second hot day.

During the days following the two hot days it can be seen that the heat in the PCM ceiling hangs around for a while. The night time ventilation evidently had insufficient capacity to remove the heat quickly. During the night between day seven and day eight a large difference between the air temperature in the room and the temperature of the suspended ceiling developed. This meant that in this period a great deal of heat was removed from the PCM. The reason is the low temperature during this night. Based on the simulation results it can be expected that if there had been three rather than two warm days in this simulation, the PCM may well not have been able to control the situation on the third day. This illustrates a weak point of this PCM system; that no more than a few warm days can be 'bridged' before the PCM cooling capacity is exhausted. If it is not sufficiently cold outside at night then (logically) the night ventilation will not be adequate.

In the simulated period, which was the warmest period during climate reference year 1964, the PCM ceiling system being investigated did function. The performance was equivalent to that of reference system 1 with mechanically cooled supply air. The PCM ceiling made mechanical cooling redundant while at the same time keeping the room comfortable; this was also during the warmest period of the reference year.

6.5 SIMULATION OF A PCM COOLING BUFFER IN A CONVENTIONAL AIR HANDLING UNIT

During hot weather the PCM buffer in the air handling unit with enthalpy wheel has the function of further cooling the outside air (which is pre-cooled in the enthalpy wheel) to 20°C. This enables very warm and moist air to also be partly dehumidified. Subsequently the air is further cooled and dehumidified by the cooling coil.

During normal warm weather the PCM buffer is used as a means of saving energy because the cooling coil has less cooling work to carry out. Due to this, the amount of cooling needed on a hot day is less. During extremely hot and/or humid weather the PCM buffer is used as a peak-shaver, i.e. the peak of the cooling demand is handled by the PCM buffer. This enables the cooling coil and the cooling system to be of lower capacity. In this case dehumidification of the air can also take place, making a drip tray and condensed water discharge necessary for the PCM buffer.

The PCM buffer is regenerated at night by ventilation with outside air. If it is too warm outside the mechanical cooling can be used in recirculation mode.

6.5.1 OPERATING PRINCIPLE

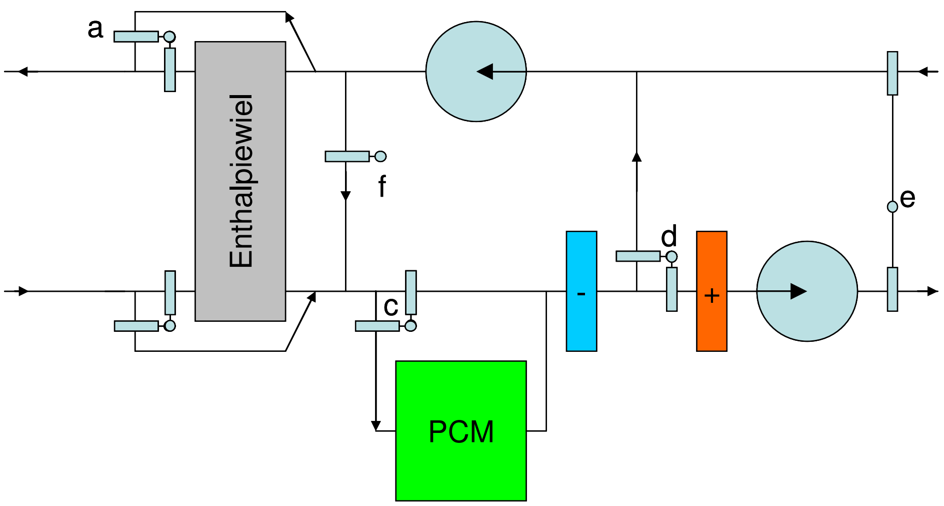


Figure 6.7: Operating principle of air handling unit with PCM-buffer

The above diagram illustrates how a PCM buffer can be fitted in an air handling unit with heat recovery. The three-way-damper ‘d’ is necessary to make circulation with outside air through the PCM buffer at night possible, using the top fan. Three-way-damper ‘c’ is used to switch the PCM buffer in and out. Damper ‘e’ is required to switch off the air handling unit from the building during circulation with outside air.

Otherwise the air handling unit is constructed and switched as a normal air handling unit. Damper 'f' is required to make possible the complete cooling of the PCM buffer by the cooling coil if it is warm outside at night.

6.5.2 SET-UP OF THE SIMULATION

Simulating an operational year of an air handling unit with a PCM buffer has enabled an estimate to be made of the annual energy savings and also of how effectively the PCM buffer can operate as a peak-shaver, expressed as a percentage reduction in the size of the cooling coil and cooling system required.

The simulation of the air handling unit with PCM buffer was a simple setup. Dynamic effects of shorter duration than one hour were neglected. Based on the climate reference year 1995, the equilibrium condition of the LBK was determined every hour under the influence of the outside air temperature and humidity, a fictitious return air temperature and humidity and a simple control system.

Carrying out a simulation where the PCM buffer worked simultaneously as peak-shaver and energy saving device was beyond the scope of this study, because a suitable forecasting control system was needed for this. Without such a system it is not possible to deploy the PCM buffer in a controlled manner during critical, extremely hot days, as a result of which the buffer is used up too quickly and the mechanical cooling system becomes overloaded towards the end of the day. For saving energy it is best to make use of the buffer as often as possible. This aspect of the control system will have to be investigated in more depth during a subsequent investigation.

To get an idea of the potential of the PCM buffer as a means of energy saving on the one hand and as a peak-shaver on the other, two simulations were carried out in each case. In the first simulation the PCM buffer was switched in as soon as the temperature of the air after the heat exchanger rose above 20°C. The annual energy saving was calculated using this. In the second simulation the buffer was only deployed when the temperature of the air after the heat exchanger rose above 20 + X°C, where X was chosen to be as small as possible under the condition that the peak load on the hottest day was just handled by the buffer, before this was 'full'. The remaining maximum cooling capacity needed from the cooling coil and cooling system was calculated using this. This would be lower than when no PCM buffer was present.

At night the PCM was regenerated using outside air when possible. If after some time this was not fully successful because it was too warm outside, the cooling machine could be deployed. In the simulations the cooling machine was deployed if the PCM buffer had not been adequately regenerated by 4 am using outside air. Then there were four hours remaining for mechanical cooling. This is another optimisation question that calls for more detailed investigation.

6.5.3 SIMULATION ASSUMPTIONS

Table 4: Assumptions made for HVAC system with PCM in air handling unit

HVAC system with PCM in air handling unit		
PCM buffer		
Operational hours	11	h
	9.00 to 20.00	
	365 days per year	
Capacity of air handling unit	10	m^3/s
Heat recovery unit efficiency	0.7	-
	For heat and moisture recovery	
Supply air temperature	18-20	°C
	Depending on outside temperature	
PCM melting and solidification temperature range	20-25	°C
PCM heat capacity	135	kJ/kg

No additional dehumidification and post heating was carried out. The heat capacity of the PCM buffer is a conservative but typical value, which is representative of commercially available products from several suppliers.

Three designs were simulated. A reference with the air handling unit without PCM buffer, one with a buffer of 2X2X2 m and a simulation with a double PCM buffer. The following table gives the characteristics.

Table 5: PCM buffer in air handling unit

Characteristics of PCM simulations		
PCM buffer in air handling unit		
Dimensions	2 x 2 x 2	m
Heat capacity	100	MJ
Thickness of the PCM plates	10	mm
Space between the PCM plates	5	mm

The double buffer has twice the capacity, or 2000 MJ
In total five simulations were carried out:

- Reference simulation: LBK setup without the PCM buffer being connected.
- Single PCM buffer: as energy saving device (T_{air} > 20°C) and as peak-shaver (T_{air} > 20 + X°C)
- Double PCM buffer: as energy saving device (T_{air} > 20°C) and as peak-shaver (T_{air} > 20 + X°C)

6.5.4 CARRYING OUT THE SIMULATION AND RESULTS

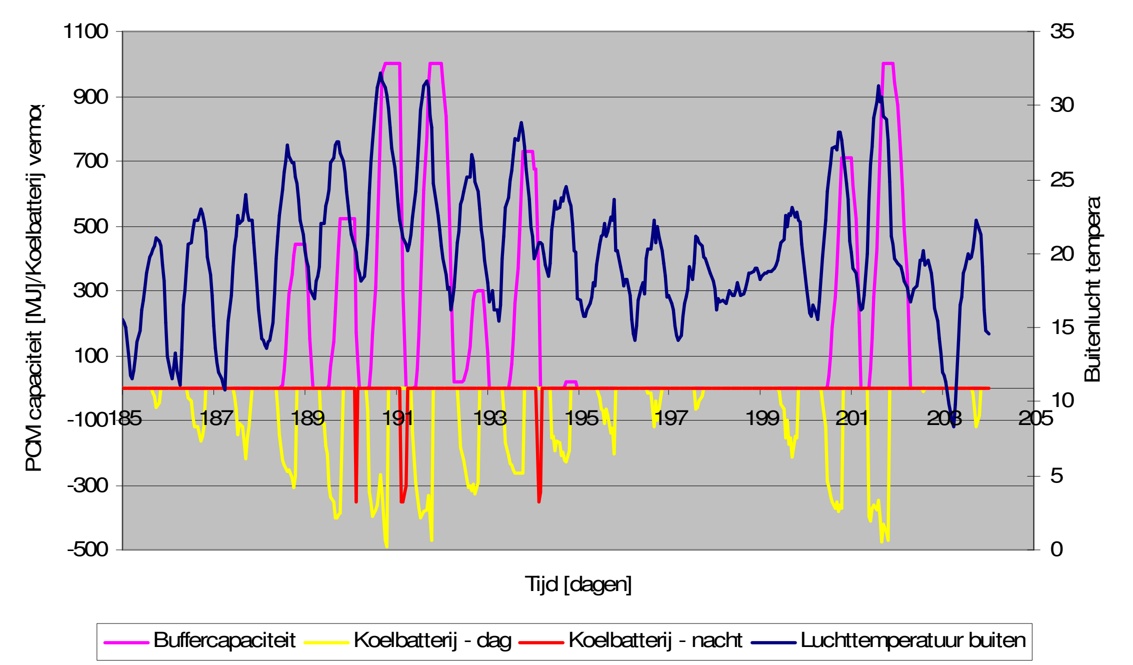


Figure 6.8: Simulation results of air handling unit with PCM buffer

The graph above illustrates part of the simulation during a period with a number of hot days. The outside air temperature, the capacity of the PCM buffer (maximum 1000 MJ) and the supplied (required) cooling coil capacity are shown. Also the night time operation of the cooling coil can be seen (in red) at moments when it was too warm outside to fully cool the PCM. The results of the various simulations are shown in the table below.

Table 6: Results of simulations of PCM buffer(s) in air handling units

Properties of PCM simulations	Reference air handling unit	Single PCM buffer (1000 MJ)		Double PCM buffer (2000 MJ)	
		Savings	Peak-shaver	Savings	Peak-shaver
$T_{setting\text{-}point}$, °C		20	24	20	22.5
$P_{max,\ cool}$, kW(th)	174	174	136	174	114
Q_{cool} day, kWh(th)	41,400	25,142	34,960	20,081	27,517
Q_{koel} night, kWh(th)	0	694	937	750	7002
Day time fan, h	4015	4015	4015	4015	4015
Night time fan, h	0	422	188	496	230
Total electricity consumption, kWh	29,860	25,516	28204	23,996	28,026
Savings compared to reference, %		15	5	20	6
dx cooling capacity reduction, %			22		34

The above table shows the results of the simulations with a 1000 MJ PCM buffer. Shown in the columns, from the top downwards:

1. The temperature setting point used to control the PCM buffer.

2. The maximum mechanical cooling capacity required to always achieve the supply air condition needed.
3. The annual cooling consumption in kWh during the day.
4. The annual cooling consumption in kWh during the night for regeneration cooling of the PCM during very warm nights.
5. The operating duration of the fan during the day (two fans in operation)
6. The operating duration of the fan during the night for regeneration of PCM (one fan in operation)
7. The total consumption of electricity, COP 3 chiller, fans (each 4 kW).
8. The energy savings compared to the reference situation.
9. The reduction in the mechanical cooling capacity needed during peak shaving

It can be seen that depending on the size of the buffer, an energy saving (electrical) of 15% or 20% is possible. Also a reduction of the mechanical cooling capacity of 22% or 34% is possible. Both benefits can be realised at the same time if an effective control system is used which is capable of optimising both the energy saving mode and the peak shaving mode.

6.6 VALIDATION OF THE SIMULATION MODEL

No validation of the simulation model used was carried out during this investigation. This was not necessary, because use was made of the model that was developed by J. van Dorp for his Ph D thesis [5] and [6]. Part of this thesis involved the validation of the model.

CHAPTER 7 Financial feasibility

This chapter covers the costs and benefits of the application of PCMs.

7.1 COMPARING CONVENTIONAL SYSTEMS WITH PCM SYSTEMS

To make a comparison between conventional and PCM-based systems possible it is necessary to compare systems that result in an equivalent level of comfort. The differences in use and performance of PCM systems versus conventional systems are considerable. It is difficult to make a useful comparison on the basis of installed maximum cooling capacity, because the cooling capacity supplied by PCM systems is generally a function of time, in contrast to the cooling capacity supplied by conventional installations.

An exception to this is the application of PCMs as cooling buffer in an air handling unit. In this type of situation, the performance of an air handling unit with a PCM buffer can be compared to a conventional air handling unit. The performances will be determined on the basis of equivalent air outlet conditions and on the basis of the electrical power used for cooling and ventilation. The energy and economic parameters can be easily determined based on this.

The economic value of the application of PCMs will be examined in two ways, each having its own advantages and disadvantages. The first method examines the price per Joule of cooling supplied by the PCMs and the second method examines the investment cost savings.

7.2 THE ECONOMIC VALUE OF PCMS ON THE BASIS OF COOLING SUPPLIED

If PCM is considered to be a storage medium for cold then a price can be determined for the useful cooling that is supplied during the service life of the PCM. In this case the preliminary assumption is made that the cold stored is free, for example in the case of cooling supplied by night time outside air (free cooling) and use made of systems that would be present in the building even if no PCM was used.

This price is then a function of the cost price of the PCM, the heat storage capacity and the number of times that the PCM is ‘discharged’ during its service life.

$$P = \frac{C}{NQ}$$

where P is the price per GJ cooling, C is the cost price of the PCM per kg, N is the number of complete cooling cycles during the service life, and Q is the amount of cooling supplied per cycle.

For C the price of 4 euros/kg given by several suppliers has been used.

N is determined by the number of days counted during the reference year 1964-65 when the maximum allowable operative temperature based on the adaptive temperature limit for 90% satisfaction for alpha-buildings is higher than 24.5°C. This is approximately 100 days per year. On these days it is assumed that the temperature in the room may be high enough for the PCM to absorb the heat. The service life of PCM is assumed to be 15 years. In total there will be 15*100=1500 cycles during the service life. Because PCM is still a fairly new product little evidence is available about its long-term performance.

For Q the reference latent heat storage capacity of 100 kJ/kg used for PCM in this report has been assumed.

Considering the above assumptions, the price P per GJ is equivalent to
P=4/(1500*100/1,000,000) = 26 euros/GJ.

The price of cooling supplied by one chiller at an electricity price of 0.10 euros/kWh, including maintenance costs and financing costs is approximately 10 euros/GJ. The price of cooling supplied by PCMs (excluding the costs associated with the storage and discharge of heat) is therefore at least twice as high as the cooling supplied by a chiller.

Determining the economic value of PCM in this way gives no reason to use PCM instead of a chiller.

7.3 THE ECONOMIC VALUE OF PCM AS AN ALTERNATIVE TO OTHER TYPES OF INVESTMENT

This manner of calculation includes the investments no longer required if PCM s are used, plus any savings on energy use. If PCMs are used for the supply and emission of cooling then the installed conventional cooling capacity and conventional cooling equipment can be on a smaller-scale. This will be handled on the basis of the cooling buffer for air handling units in covered in section 6.8. This calculation has not included how much savings can be achieved in the area of building mass, because this is highly dependent on the construction of a building.

An estimate can also be made of the economic feasibility based on the considerations in section 6.8. It is interesting to look also at a possible future scenario. In the future scenario, electricity will be more expensive, but the price of PCM will drop due to economies-of-scale and the automation of production facilities.

Table 1: Assumptions relating to the feasibility of PCMs in a future scenario

Factor	Current	Future scenario
Electricity price	0.10 €/kWh	0.12 €/kWh
Price of mechanical cooling	200 €/kW	200 €/kW
CO_2 emission of electricity production	0.76 tonnes CO_2 /MWh	n.a.
Price of CO_2	25 €/ton	50 €/tonne
Price of PCM	4 €/kg*	1 €/kg**

** The current price of PCM plates varies between 2 and 8 €/kg, depending on the supplier, PCM type, packaging method and size of order.*

*** The future price of PCM is based on an estimate of the current basic manufacturing cost of PCM.*

The cost price of adding a PCM section having 1000 MJ heat storage capacity is the sum of the casing, the construction, and the PCM. The mass of the PCM required is approximately 7000 kg. The PCM buffer then costs approximately €31,000. To connect the buffer, ducting, dampers and control facilities will be required. The estimated cost of this is approximately €4000, resulting in a total of €35,000.

Adding the buffer saves 22% on the mechanical cooling capacity. Based on the reference this would give a saving of 38 kW x 200 €/kW, or €7600. The additional price of the buffer does still come to €27,400.

The annual electricity consumption drops by 15%. In this case that is approximately 4300 kWh/year. The electricity savings are thus approximately €430.

The reduction in CO_2 emission is 3.3 tonnes CO_2/year.

The time needed just to recover costs is therefore 63 years; much longer than the service life of the system. The price per tonne of CO_2 saved is at least €700, assuming a depreciation period of 10 years. In comparison, wind energy costs around €100 per ton of CO_2 saved. Therefore, currently the PCM buffer is not economically viable and it is also not a cheap way of reducing CO_2 emission.

Almost every innovative idea has a long payback time in the early stages – e.g. solar panels. This is a result of low initial demand due to the familiarity with trusted conventional systems. This can change in a few years under the influence of rises in energy costs, technical developments and feedback from practical experience.

The conclusions of this straightforward feasibility calculation are given in the following table. In the third column are the results of an identical calculation, but then making assumptions for a future scenario (see table)

Table 4: Assumptions for payback time calculation

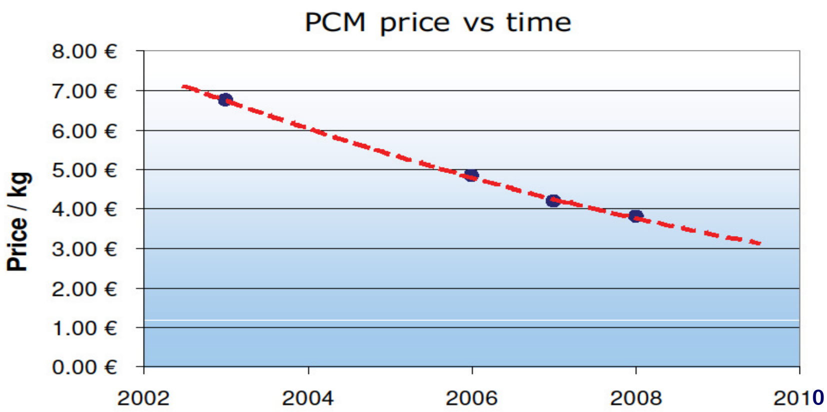
	Current	Future
Cost price of PCM buffer	€35,000	€14,000
Savings on installation of mechanical cooling unit	€7,600	€7,600
Savings on annual electricity costs	€430	€516
Payback time	63 years	12 years
Cost of CO_2 emission savings per year	€706	€38

If electricity prices rise faster in the future, or it becomes possible to sell CO_2 emission savings in the form of CO_2 emission rights, or the use of PCM is subsidised (e.g. by the Energy Investment Deduction (EIA) regulation) then payback time may become shorter.

7.4 PCM PRICE DEVELOPMENT

The price of the PCM itself remains a significant factor in the feasibility of PCM projects. In general, the basic material is not very expensive, but the costs of investigation into the correct addition of salts or other chemicals to obtain the ideal melting/solidification points do need to be repaid by the market. The graph below [11] shows the expected price development for PCM.

Fig 7.1 PCM price / time curve



If this is an accurate forecast such projects may well become feasible quite quickly, making it important to follow pricing developments closely.

CHAPTER

8 Simulation software

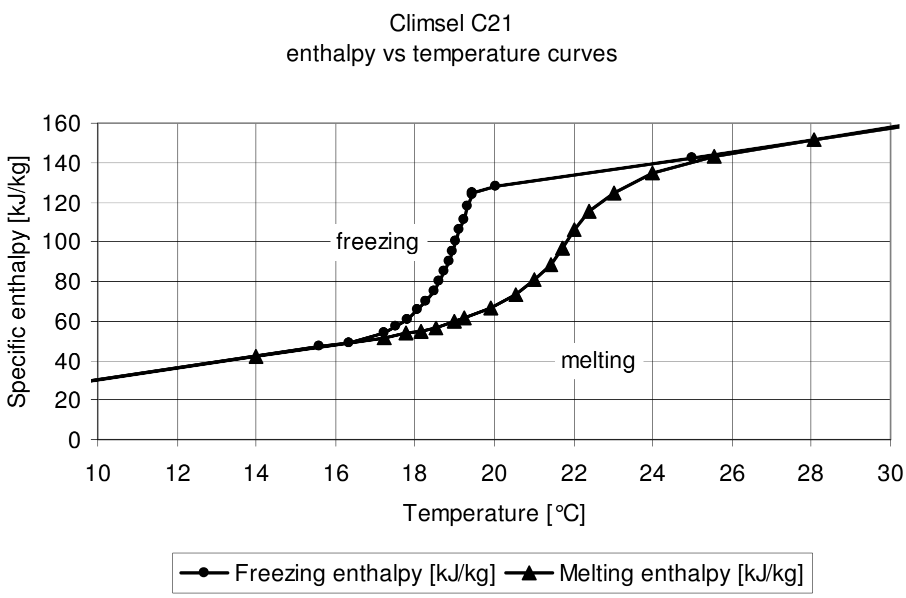
Simulation software for calculating the performance of PCM applications must be programmed using a PCM model based on empirical material properties. Section 6.2.1 includes a description of how such a model can be set up. This chapter covers the details of the mathematical algorithms.

8.1 STATE-OF-THE-ART MODELLING FOR PCM PROPERTIES

Feustel (1995) describes a simplification of the Egolf and Manz (1993) formulation for the specific enthalpy of PCM by making use of hyperbolic functions. The enthalpy can be calculated as a function of temperature using his formulas for the specific enthalpy of PCMs. The assumption is that there is a one-to-one relationship between the temperature of the PCM and the specific enthalpy, i.e. there is no hysteresis and there is no supercooling or heating.

Empirical investigations into PCM have indicated that the popular PCMs with a melting temperature between 15 and 30°C show significant hysteresis and sometimes also sub-cooling. The following graph of the temperature/enthalpy curves for Climsel C21 shows the typical behaviour of a PCM based on salt-hydrates. The enthalpy is set to 0 for a PCM temperature of 0°C.

Figure 8.1 Enthalpy change vs temperature



The curves in the above graph can be determined by testing a macroscopic quantity of PCM (e.g. 1 kg) using differential thermal analysis (DTA). The quantity of PCM must be large enough to ensure that issues such as crystal growth and the formation of voids during the solidification process do not have a significant influence on the results. This can cause problems during testing of PCMs in a differential scanning calorimeter (DSC). Care must also be taken that the thickness of the PCM sample is not so great that the internal thermal conductivity influences the temperature measurements, or that the sample can no longer be considered to be a lumped mass, or mass at a homogenous temperature. A sample thickness of 0.5 to 1 cm maximum meets this requirement, depending on the thermal conductivity of the material.

The empirical data for Climsel 21, a PCM based on sodium sulphate (Glauber's salt), shows that the direction of the process (i.e. heating or cooling) affects the curve. Examining the graph shows that at 20°C an enthalpy difference of at least 60 kJ/kg occurs, while the temperature difference at 120 kJ/kg is 3ºK. Experimental work has shown that these differences between the curves are not caused by testing errors, large internal temperature gradients, or the magnitude of the heat flows that occur. It appears that the temperature/enthalpy curves of all PCMs in exhibit this behaviour to some degree, making it necessary to take account of this during the modelling.

The temperature difference between the two curves is indicated as the hysteresis of the PCM. The hysteresis of PCMs differ. Pure PCMs consisting of one single raw material, such as paraffins and salts without additives have a small hysteresis. PCMs made from a combination of materials can have a larger hysteresis.

When simulating the thermal behaviour of PCMs it is sometimes possible to look at the heating and cooling as separate processes. This is the case if the PCM fully changes phase during each process, i.e. fully solidifies or melts. In that case each process can be simulated individually using the appropriate curve from the above graph. If however the process to be examined does not consist of a complete phase change, e.g. when the PCM in a PCM ceiling or a PCM induction unit only partly solidifies or melts during a simulated day, then it will no longer be possible to define the condition of the PCM in accordance with one of the two curves. This is because in the area where the hysteresis occurs the enthalpy of the PCM cannot be clearly defined. The model that is described in this chapter overcomes this problem.

8.2 A UNIVERSALLY APPLICABLE PCM MODEL

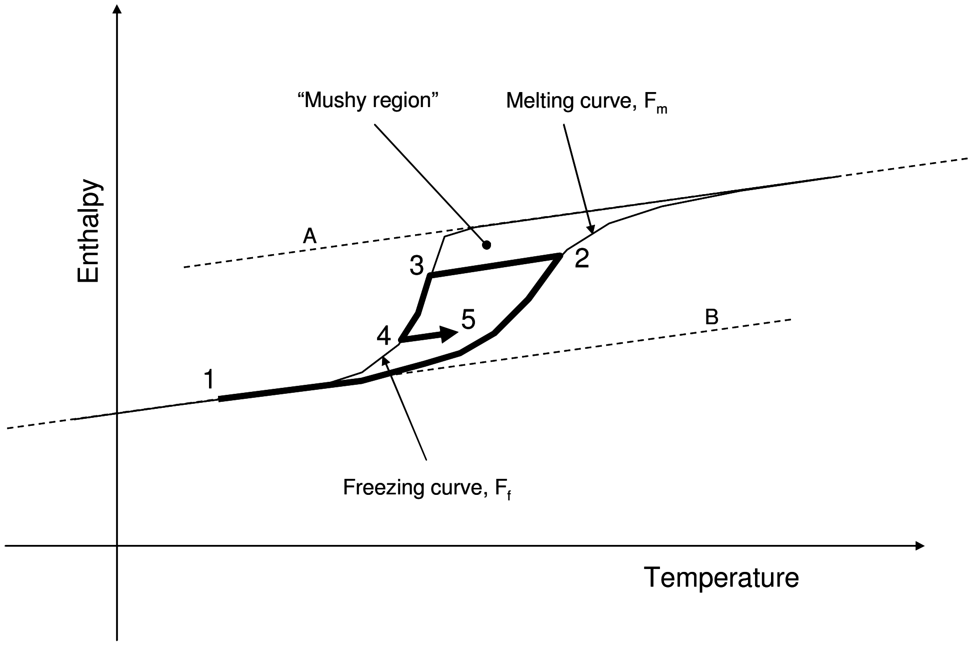
The model has a few characteristics that make it suitable for fast numerical simulation in accordance with the lumped mass model. In this type of model the PCM is considered to be a thermally homogeneous mass. This assumption applies under normal circumstances in an application for heat or cold storage for climate control in buildings, and if the thickness of the PCM is not excessively high (sufficiently low Biot number).

Characteristics of the model:

- Based on empirical data concerning the thermal behaviour of the PCM.
- A relatively small number of calculations needed, enabling simulations to be calculated quickly.
- Takes account of hysteresis automatically.
- Works independently of the direction of the thermal process (heating or cooling).

Empirical data about the behaviour of the PCM to be modelled is required to set up the model. The following graph shows the heating and cooling curves of the PCM Climsel 21. The graph shows various lines that characterise the behaviour of the PCM. There is also a series of condition changes drawn as an example, with the aim of describing the model in more detail.

Figure 8.2 Example of calculation of behaviour in simulation model



The straight lines A and B represent the specific heat of the PCM when it is fully solidified, or melted. These lines do not need to be parallel. Most PCMs have a slightly higher specific heat in the solid phase than in the liquid phase.

The curves F_m and F_f represent the change of enthalpy as a function of temperature at melting and solidification respectively. The area between the curves is known as the mushy region. In this area the PCM is partly liquid and partly solid. In this state it is comparable to butter that has been out of the fridge for a while.

To make the model described here possible, the assumption now made is that in the mushy area the PCM only absorbs or emits perceptible heat when the condition does not deviate outside the curves F_m and F_f. The specific heat of the PCM in the mushy area is assumed to be a function of the condition of the PCM, defined as the relationship between the enthalpy difference with the asymptote A(T) and the enthalpy difference between A(T) and B(T). This can be described as follows.

$$s = \frac{h - A(T)}{B(T) - A(T)} \qquad [1]$$

Where s is the condition of the PCM with a value between 0 and 1 for a PCM temperature T and enthalpy h, using the asymptote A(T) and B(T) as shown in the figure.

$$c_{eff} = s(c_l - c_s) + c_s \qquad [2]$$

Where c_{eff} the effective specific heat is as a function of the condition s of the PCM and the specific heats c_l and c_s of the PCM in the completely liquid and solid condition respectively, where this is assumed to be a constant.

The resulting temperature T_{n+1} of the PCM and the enthalpy h_{n+1} can now be calculated for each T_n and h_n as a as a consequence of a random addition or removal of heat Δh_n. This is described in the following formulas.

$$T_{n+1} = \begin{cases} F_m\left(h_n + \Delta h_n\right), T_n + \dfrac{\Delta h_n}{c_{eff}} > F_m\left(h_n + \Delta h_n\right) \\ T_n + \dfrac{\Delta h_n}{c_{eff}} \\ F_f\left(h_n + \Delta h_n\right), T_n + \dfrac{\Delta h_n}{c_{eff}} < F_f\left(h_n + \Delta h_n\right) \end{cases} \qquad [3,4]$$

$$h_{n+1} = h_n + \Delta h_n$$

The term Δh_n (unit kJ/kgPCM) must be calculated on the basis of normal calculation methods, e.g. as a function of the temperature difference between the PCM and the environment (or air flowing along it), depending on the application to be simulated, multiplied by the size of the time step.

The above formulas can be easily used as the basis of a mathematical algorithm in MATLAB, Visual Basic or TRNSYS for example.

Care must be taken that c_{eff} is not calculated at temperatures where the asymptotes A(T) and B(T) cross each other. The temperature where that happens does lie a long way outside the normal operating field of the PCM, so it is sufficient to limit the application of the algorithm in the simulation between 0 and 60°C for example.

Also the initial condition of the PCM in terms of T and h is so chosen that this lies in the mushy area, or on one of the curves, because otherwise a large change in the PCM temperature is calculated in the first step of the calculation, which could lead to instability of the calculation.

The use of the mathematical algorithm described here at heat flows less than 10 W/kgPCM makes it possible to simulate PCM with time steps of one hour with very accurate correlation with experimental work.

APPENDIX 1 References

The following literature was used in this study:

No.	Description
1	Introduction to Phase Change Materials Literature review, theoretical backgrounds, applications and sustainability aspects of PCMs as applied in built environment S.F. Koekenbier 1st assignment, July 2009 PE 2235
2	American Institute of Architects http://www.aia.org/static/state_local_resources/adv_sustainability/… …/HTML/2030_challenge.htm
3	Bouwman, I.M. Passive cooling: feasible or not? Feasibility of passive cooled lightweight buildings based on heat accumulation in PCM Delft University of Technology / HunterDouglas, Delft, Netherlands, 2006
4	Bouwman, I.M. PCM in the built environment - combining comfort and sustainability presented at Delta Energy Convention, RijksUniversiteit Groningen, Netherlands, 2008 available online: http://www.rug.nl/energyconvention/edc/archive/edc2008/… …/presentations2008/sideevents/Bouwman.pdf
5	Dorp, J.E. van A computational scheme for approximating phase change material behaviour to be published
6	Dorp, J.E. van An approach to empirical investigation of performance of passive PCM applications in office buildings based on the t-history method Arcadis, Den Haag, Netherlands, 2004
7	Farid, M.; Kong, W.J. Underfloor heating with latent heat storage Proceedings Institution of Mechanical Engineers 215, part A (2001) 601-609
8	Farid, M.M.; Chen, X.D. Domestic electrical space heating with heat storage Proceedings Institution of Mechanical Engineers 213, part A (1999) 83-92
9	Feustel, H.E. Simplified numerical description of latent storage characteristics for phase change wallboard University of California, Berkeley, United States of America, 1995
10	Feustel, H.E.; Stetiu, C. Thermal performance of phase change wallboard for residential cooling application University of California, Berkeley, United States of America, 1997
11	Bouwman, I.M.. MSc PCM in the built Environment Combining comfort and sustainability Deerns Consulting Engineers

APPENDIX 2 Producers and suppliers

This appendix contains a list of suppliers of PCM systems and products in alphabetical order. The market is changing continually, so the useful life of this list may be limited.

Autarkis B.V.
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info@autarkis.nl

Capzo International B.V.
The Mors 112
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Fax: +31 (0) 541 294446
pcm@capzo.nl

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Tel: + 49 (0) 2330 63355
bvf@doerken.de

Emco Bau- und Klimatechnik GmbH & Co. KG
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Postfach: 1860
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Tel: +49 (0) 591 91400
Fax: +49 (0) 591 9140 851
klima@emco.de

ENVIRONMENTAL PROCESS SYSTEMS LIMITED
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INDIA
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Fax: 91-22-23728264, 23746242.
info@pcmenergy.com

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APPENDIX 3 Project references

The following are descriptions of projects in which PCM has been used. This list is not exhaustive and there is often a lack of data. Some of the projects have been completed and others are still under construction. The results and the final design/construction details are also often not known.

Project 1: The Wilo office building in Zaandijk, The Netherlands
PCMs mixed in concrete in the steel roof and cooled for regeneration by water piping. Consulting Engineers - Deerns.

Project 2: Norfolkline at Vlaardingen, The Netherlands
Building with baffle ceiling constructed in 2003.
Consulting Engineers – ARCADIS, The Netherlands;

Principal:	Norfolkline Shipping
Construction costs:	€35,000,000
Project start:	2005
Project completion:	2007

The new construction of a goods terminal for Norfolkline at Vlaardingen. This project involved the metamorphosis of a dilapidated shipyard at Vulcaanhaven in Vlaardingen to a hyper-modern ferry terminal.

The buildings were designed by the architects/engineers ARCADIS. The terminal installations and buildings were designed by ARCADIS Internal Environment & Energy. There are two buildings on the terminal site:

- - A new technical services building for the repair and maintenance of trailers.
- - A renovated control room for offices and lounges - formerly a changing room and restaurant.

These were to be purpose-built company buildings designed to use minimal energy without extra investment and to meet current energy performance standards.

Sustainable installation concept

The terminal buildings are unique from the perspective of sustainability and energy efficiency. Lower energy consumption without extra costs for installing equipment was achieved by making optimum use of natural sources of energy, such as rainwater and night time cooling using cool outdoor air. The particularly low use of energy was achieved by the application of:

- - HR ventilation and air handling.
- - Reuse of rainwater.
- - Sustainable and energy-efficient cooling.

HR ventilation and air handling

For refreshing the air in buildings, use was made of ventilation and air handling systems fitted with high efficient heat recovery units with an efficiency of at least 90%.

Reuse of rainwater

Rainwater from the roof of the new technical services building was collected and used to supply the automatic trailer washing unit, as coolant for the washing and changing rooms, flushing water for the toilets and for cleaning the workshops.

Sustainable and energy-efficient cooling systems

The cooling of the control building was done in a unique way, without the need for the installation of mechanical cooling equipment. Instead, a combination of the following was used:

- The use of phase change materials (PCMs) in the lounges to increase the thermal mass of the building, in combination with open thermal suspended ceilings.
- During the day the PCM melts as the internal temperature rises and during the melting stage it absorbs excess heat. During the night this excess heat is released outside.
- Night time cooling of the PCMs using outside air and motor operated ventilating windows. During this night time cooling the PCMs re-solidify, giving off even more heat.
- Supply of cooled air to the lounges using thermally driven displacement ventilation for the supply air.
- Indirect adiabatic cooling with heat recovery and rainwater as coolant. The air is cooled by intensive moistening and a heat recovery unit is used to cool the outside supply air. The supply air to the lounges is completely free of moisture, bacteria etc.

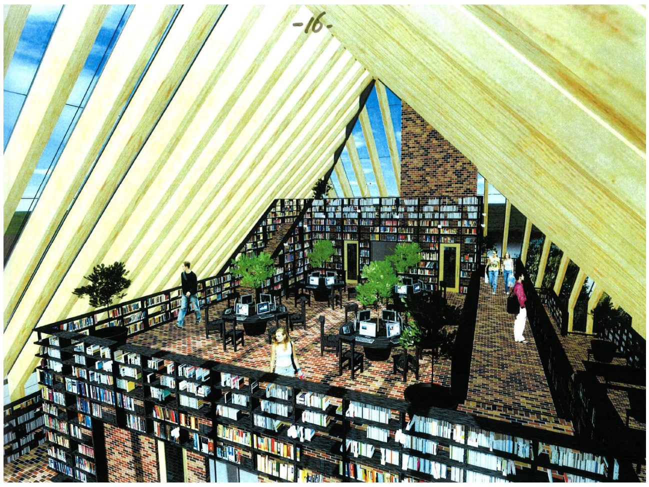
Following a very short design and construction period of two years the terminal was commissioned early in 2007.

Project 3: New library in Spijkenisse in the Netherlands
MVRDV architects

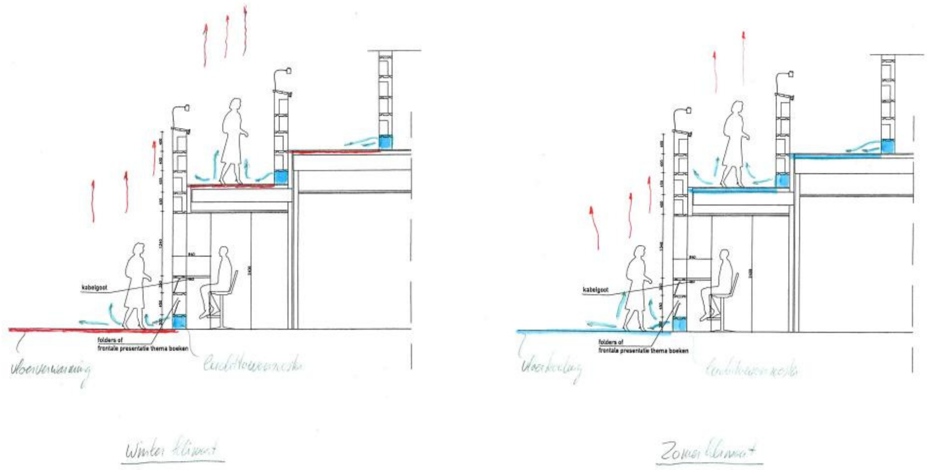
The total installation concept for this building was submitted for the 2008 'Vernufteling' (an annual award for innovative design by engineering companies) and it was the only building nominated that year. Below follows a detailed description of the project that is being constructed in 2010 and 2011.

The new library at Vredehofplein in Spijkenisse – a design by the architects MVRDV – will be a prominent eye catcher in the area, as well as a model of ingenious integrated sustainable techniques. With an energy performance certificate (EPC) of 0.7, the building meets the highest energy efficiency requirements and in addition does that for a relatively small additional investment. The compact construction and the use of sustainable sources of heating, cooling and water for the HVAC system make this possible. The intelligent use of various materials and energy flows in and around the building will enable the maximum benefit to be achieved and losses to be kept to a minimum.

From the outside, the library will be characterised by an imposing transparent outer shell supported by a wooden frame. Internally the library will consist of several pyramid-shaped levels. The presence of large plants and an abundance of natural daylight will ensure a unique atmosphere.

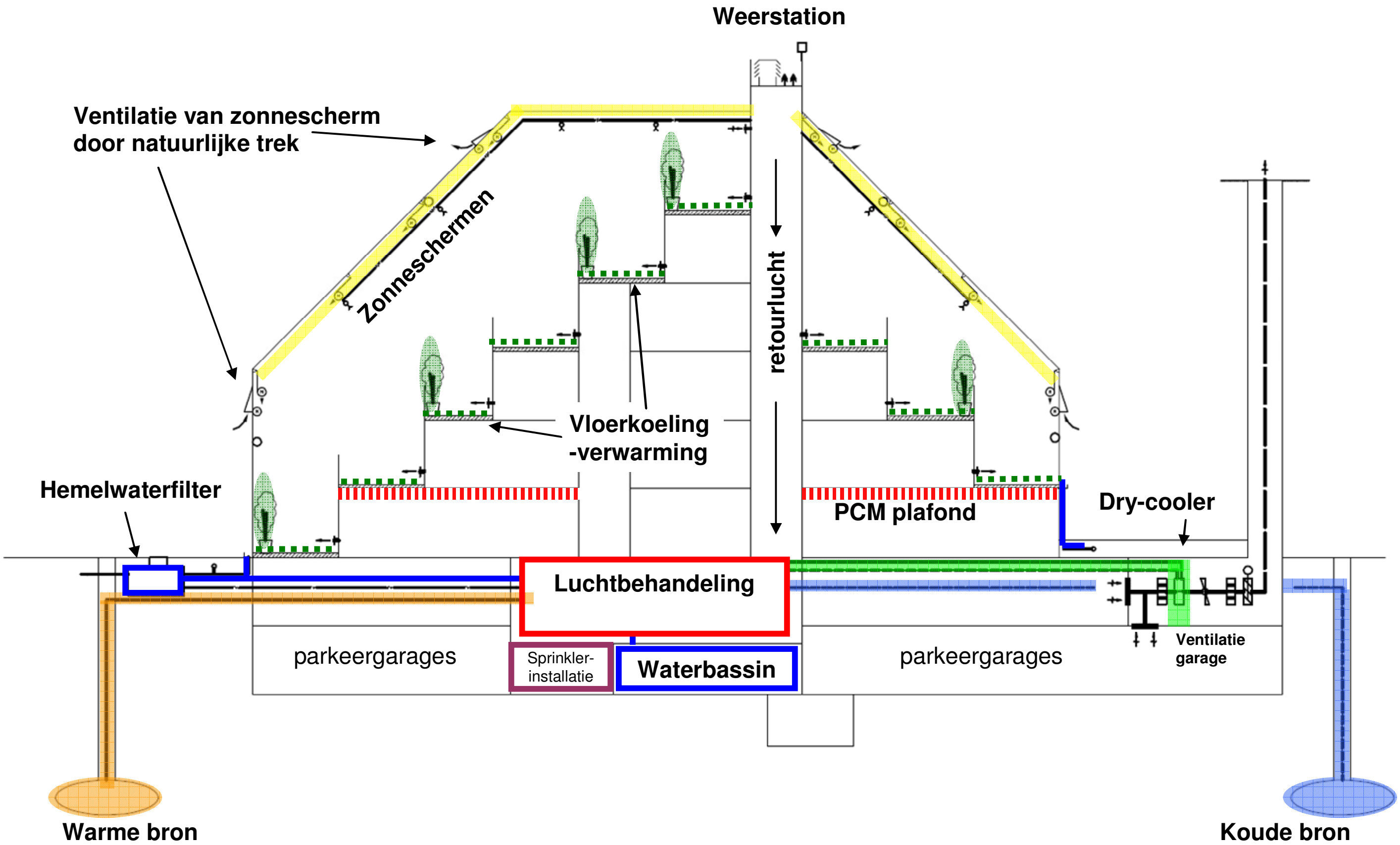


The internal climate control technology used in this building will be kept out of sight as far as possible. The grilles for the supply of fresh air will be carefully concealed underneath the bookcases. Ventilation ducts will be built into the floors. The air supply will operate by the displacement principle so that fresh air takes the place of warmer (contaminated) air and this will be disposed of by extracting upwards. This rising air, discharged at the peak of the building, will be used during the winter as a source of heat for warming the fresh supply air by means of a high-efficiency heat exchanger.



The warming of the supply air and the underfloor heating system will be done using reversible heat pumps connected to an aquifer thermal energy storage system (in duplicate). There will be neither a gas-fired central heating boiler nor a gas supply point in the building! Because the demand for cooling in the summer will exceed the demand for heat in the winter, during the winter extra cooling capacity stored using a dry-cooler. This dry-cooler will be installed in the continuously operating ventilation system of the parking garage – an intelligent combination of functions.

In the summer various parts of the building and installations will operate in close cooperation to maintain the quality of the internal climate using minimal energy.

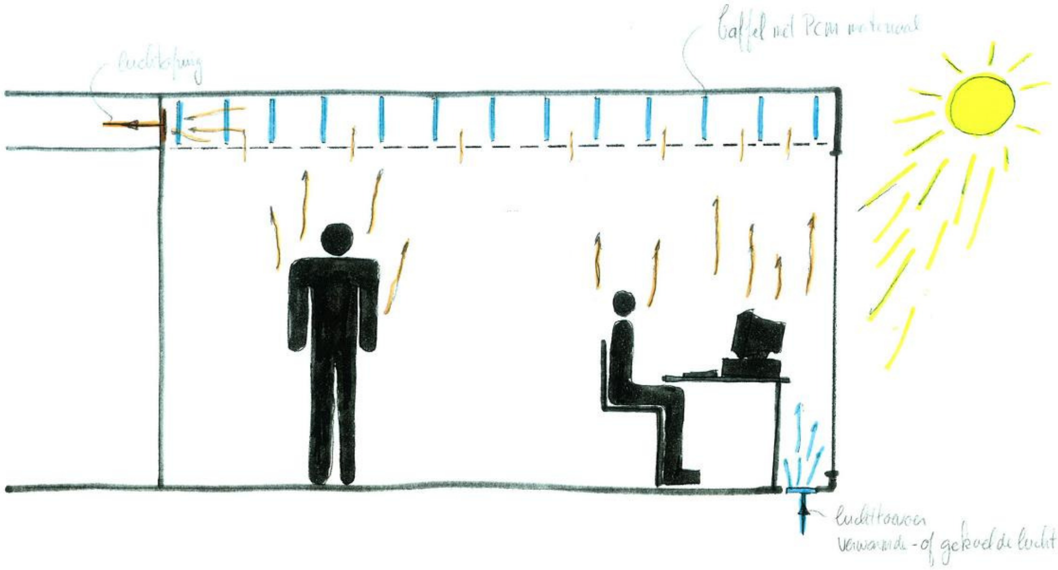


Protection from the sun will be provided by an automatically operating system of sun blinds. The retractable blinds will form an effective second skin, enabling excess solar heat to be removed upwards via natural ventilation between the building shell and the blinds. Automatically opening windows in the ridge and at the base of the building shell will control the flow of air. This will provide protection from at least 90% of the heat from the sun and prevent excessively high temperatures in the building. The system of sun blinds will be controlled so that during the day sufficient sunlight will be able to enter the building to keep the plants flourishing.

Sun energy entering the building in the form of radiation will mainly hit the library floors. These floors will be constructed with a water piping system to efficiently remove excess heat coming from both the sun and people. This heat will not be lost! A reversible heat pump will be used to store it in the aquifer thermal energy storage system for reuse during the winter.

In addition to their aesthetic value, the large plants in the library will make an important contribution to the internal climate. They will provide visitors and monitor users with shadow and have a favourable influence on the humidity and temperature of the air.

Phase change materials will be incorporated in the ceilings of the inside rooms in the library, such as the offices on the ground floor.

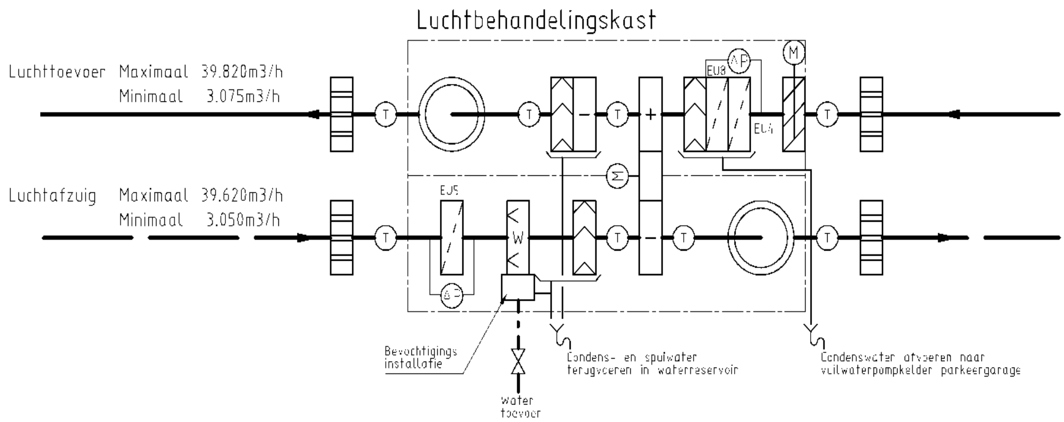


Kantoorruimte (begin van de dag)

These materials are specially formulated salt solutions that melt and solidify at temperature ranges around those that will be comfortable for the building users. These materials are not hazardous to people or the environment. If the temperature in the rooms exceeds 24°C then the salt/water mixture melts, but if the temperature drops to below 20°C then the mixture solidifies again. During melting the mixture absorbs a great deal of heat, which brings excessive temperature rises in these spaces under control.

During the night room temperature will be lowered by ventilation until the phase change material re-solidifies, ready for the following day. These materials lead to the effective thermal mass of the building being increased significantly, damping temperature fluctuations in the building and transferring part of the demand for cooling in the building to night time.

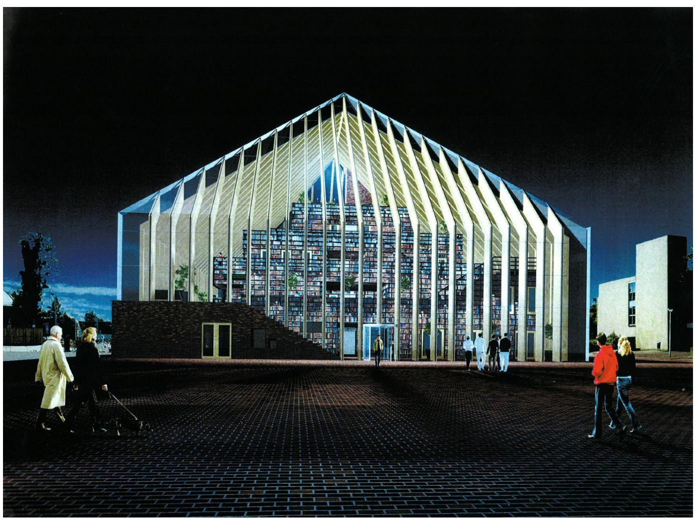
In the summer the fresh supply air will be cooled using indirect adiabatic cooling. This technique includes the spraying of water into the return airflow, cooling the air. In the heat exchanger this cooled return air absorbs excess heat from the fresh supply air. Additional cooling of the supply air is then done by a cooling coil fed by cold from the underground storage system.



The water used for the adiabatic cooling will not be drinking water, it will be rainwater that will be collected during the year, filtered and stored in a large underground basin. This rainwater will also be used for flushing toilets, watering plants and for the sprinkler system in case of fire.

The machinery room containing the air handling installation will be located in the car park underneath the building. The room will have a transparent wall so that the equipment can be clearly seen by interested passers by. They can have a look behind the scenes and see what such a sustainable climate control system involves.

To summarise, the new library in Spijkenisse will be a 'melting pot' of various sustainable techniques, creating a whole that is much greater than the sum of its parts. A bold architectural design, a fully transparent and activated building envelope, collection and use of rainwater, heat recovery and adiabatic cooling, aquifer thermal energy storage using reversible heat pumps, the use of phase change materials and the conscious deployment of plants for climate control and improving the indoor environment. A powerful interpretation of the concepts of integral and sustainable construction. And all this for a remarkably modest extra investment compared to a conventional solution.



Project 4: Cascadepark, Almere, The Netherlands

Offices and Multifunctional complexes

Principal	Dura Vermeer RE
Construction man.	Dura Vermeer RE
Architect	Claus and Kaan Arch.
Struct. Engineering	IMD
Size of project	8000 m2
Design start	2008
Construction start	2009
Completion	2010

Description

The new construction for the Cascadepark in Almere in the Netherlands consists of three office buildings situated on a semi-sunken car park. The office buildings are characterised by the attention that has been paid to sustainability, both in the form of the construction and in the type of systems used.

Interesting details

The load-bearing structure of the building consists of a timber frame and with wooden floors. Thanks to the use of FSC timber, the degree of sustainability of this concept is high and the CO2 emission for the production of the building has been substantially reduced.

A consequence of the selection of timber is that the building is sensitive to overheating; there is a limited buffer capacity. Accordingly, a great deal of attention has been paid to sun blinds. The building has large overhangs on the east, north and west sides.

Two variants were designed for the climate control concept. The first and most innovative variant is the Climate Adaptive Skin (CAS) façade. This façade ventilates depending on needs, and the ventilation air is warmed and cooled by Phase Change Materials (PCMs). These materials absorb or release energy when melting and solidifying. During 80% of the year this makes the use of additional energy unnecessary.

Many dynamic simulations were carried out in cooperation with Delft University of Technology to determine the optimum façade - amount of PCM in the façade, ventilation flow rate required etc. This finally resulted in a concept that that fully met the schedule of requirements.

If the completion of the building turns out to be earlier than the market introduction of the climate adaptive skin façade, a more conventional emission-control system will be installed. In spite of this an energy-performance will still be achieved that is approximately 30% lower than the Building Decree requirements.

Consulting engineer - Deerns.

Other projects

- RDM site, floating pavilion, application of PCMs. Under construction;
- Acantus head office, Veendam Housing Association. Constructed, but not known whether the PCM system was actually used.

It is noticeable that there are many projects on the market where investigation has been carried out into the use of PCM systems, but very few projects using PCMs have actually been completed.
Most projects do not proceed due to cost considerations.
There have been a number of applications in equipment, e.g. to decrease buffer volumes. These tests have also invariably been pilot projects and have not directly involved construction.