Thermal energy storage (TES) systems for cooling in residential buildings

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23.1 Introduction

According to the Global Assessment Report (Urge-Vorsatz *et al.*, 2012), there are five energy services that accounted for 86% of primary energy use in buildings by end-use services in the United States in 2010, out of which 14–15% was space cooling both in residential and in commercial buildings (Figure 23.1). Moreover, Figure 23.2 shows that the total energy consumption in buildings is increasing in nearly all regions of the world, except for regions such as Europe and North America. Therefore, there is an increasing need to develop technologies to achieve thermal comfort of buildings lowering the cooling demand. Thermal energy storage (TES) is seen as one way to achieve this objective, as shown in this chapter.

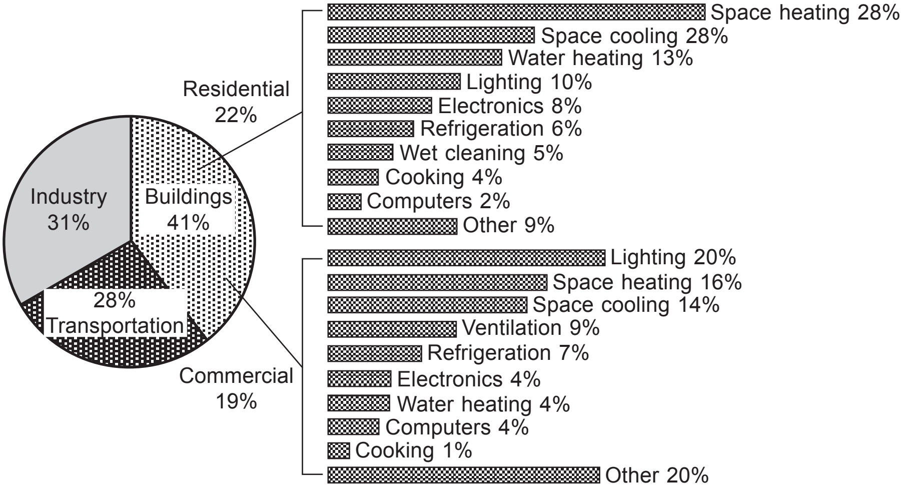

Figure 23.1 Primary energy use in US commercial and residential buildings in 2010 (Urge-Vorsatz *et al.*, 2012).

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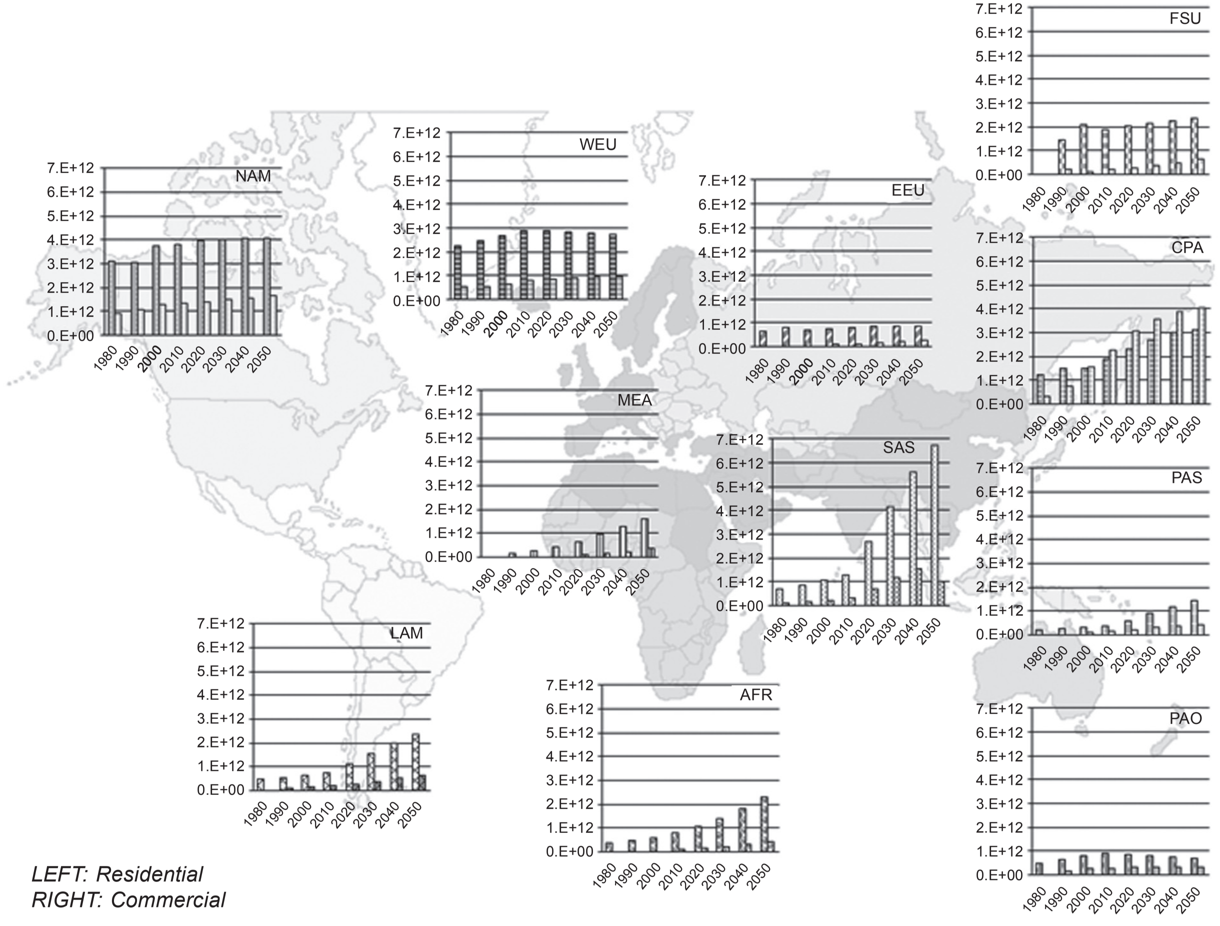


Figure 23.2 Total energy consumption in the building sector in the different regions of the world for residential and commercial buildings (Urge-Vorsatz *et al.*, 2014).
Note: historic data 1980–2000 from IEA statistics; projections 2010–2050 data based on frozen scenario Urge-Vorsatz *et al.* (2013).

23.2 Sustainable cooling through passive systems in building envelopes

The use of PCM as passive energy systems in the building sector has the objective of reducing the energy demand of space heating and cooling of the whole building, basically smoothing the indoor temperature by increasing the heat storage capacity of the envelope.

The addition of PCM in wallboards is one of the oldest options studied and published. According to Sharma *et al.* (2009), the use of phase change materials (PCM) improves the thermal comfort of lightweight buildings, since they are very suitable for incorporation (Soares *et al.*, 2013). The efficiency of these systems depends on several factors such as how the PCM is incorporated in the wallboard, the orientation of the wall, the climatic conditions, the exposure to direct solar gains, the internal gains, the colour of the surface, the ventilation rate, the PCM chosen and its phase change temperature, the temperature range over which phase change occurs, and the latent heat storage capacity per unit area of the wall.

There are three different methodologies to add PCM into building materials: impregnation, suspension and micro-encapsulation. The most common method in passive systems is impregnation. This methodology usually presents leakage problems that can be reduced with the use of specialized coatings. Schossig *et al.* (2005) showed that when the PCM is added microencapsulated, the leakage problems are overcome (Figure 23.3). Barreneche *et al.* (2013) compared in an inter-laboratory test the three different methods to incorporate PCM in building materials: micro-encapsulated, suspension, and impregnation. While suspension allows the maximum amount of PCM in the building material, only micro-encapsulation ensures avoiding leakage.

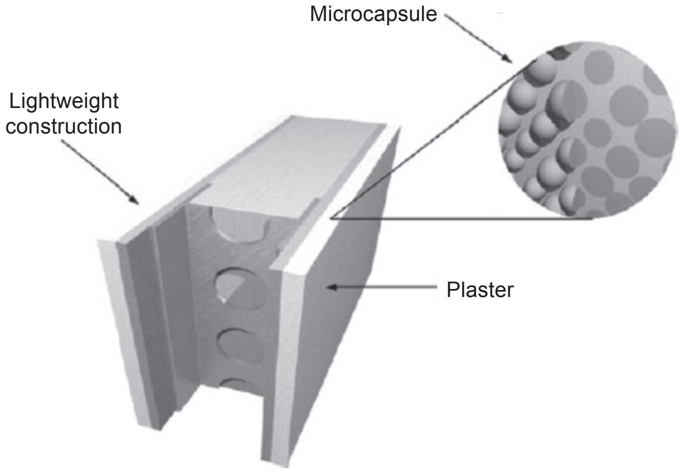


Figure 23.3 Addition of micro-encapsulated PCM in a lightweight building (Schossig *et al.*, 2005).

Dupont developed a wallboard product with PCM called Energain (Figure 23.4), which has been studied and characterized in several publications (Kuznik *et al.* 2008a, 2008b, 2011; Kuznik and Virgone 2009). Kuznik *et al.* (2008a) performed an optimization process using interior/exterior temperature evolutions within a period of 24 h to optimize the thickness of a PCM wallboard to enhance the thermal behaviour of a lightweight internal partition wall. The PCM wallboard was composed of 60 wt.% of micro-encapsulated paraffin, which has a melting temperature of about 22ºC.

The implementation of PCM in the design of a whole building can be studied accurately. The ability of PCM to stabilize the indoor environment when exposed to external temperature changes and solar radiations was evaluated by Kuznik *et al.* (2008b). An experimental test room MINIBAT was designed using a battery of 12 spotlights to simulate artificial sun exposure. Results showed that the PCM wallboard can reduce the air temperature fluctuations in the room and enhance the natural convection mixing of the air, which avoids uncomfortable thermal stratifications. Kuznik and Virgone (2009) also tested two identical test cells under two kinds of external temperature evolutions, heating and cooling steps with various slopes and sinusoidal temperature fluctuations within a 24 h period. They measured the time lag between indoor and outdoor temperature signals and demonstrated that the external temperature amplitude in the cell was reduced.

Moreover, Lv *et al.* (2006) built an ordinary room using PCM gypsum wallboard in the northeast of China. Their experimental measurements show that the increase

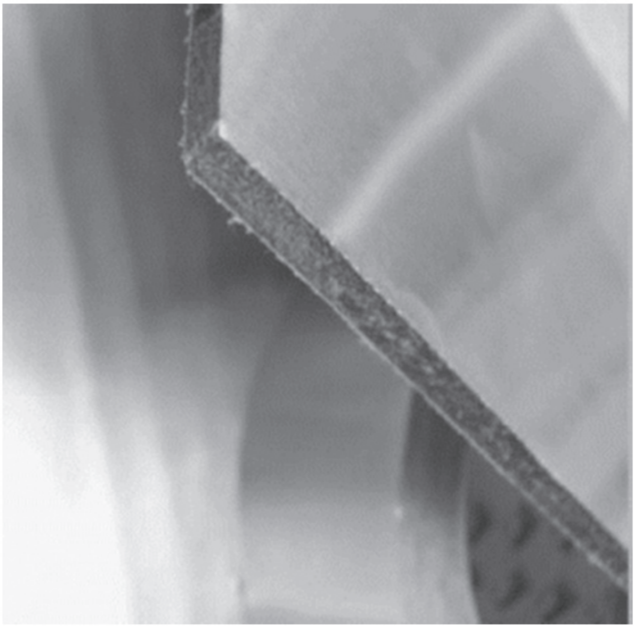


Figure 23.4 Composite wallboard from Dupont PCM (Kuznik *et al.*, 2008a).

of the heat storage capacity of the walls by adding PCM in wallboards can attenuate indoor air fluctuation and reduces the heat transfer to and from the outdoor air. Recently, Kuznik *et al*. (2011) used Dupont de Nemours PCM wallboards for the renovation of a tertiary building. After monitoring the building for one whole year they concluded that the use of these systems is very efficient if the outdoor temperature varies around the melting temperature of the PCM.

The use of vacuum isolation panels (VIP) in a wallboard together with PCM has been studied by several researchers as it can reduce the thermal loss and improve the efficiency of lightweight buildings. Two test cells were designed by Ahmad *et al*. (2006) and each cell consisted of one glazed face and five opaque faces insulated with VIPs. In one of the cells, five PCM panels were attached to the inner surface of the VIP panels, as shown in Figure 23.5. The amplitude of temperature oscillation inside the cell with PCM panels was dramatically reduced, hence reducing the energy demand for space heating and cooling of the whole building. Regarding the required maintenance of the system, the PCM panels still showed a good thermal storage capability even after more than 480 thermal cycles.

The combination of different insulation with the use of PCM has also been numerically investigated by Diaconu and Cruceru (2010). A sandwich-type insulating panel consisting of a middle layer of thermal insulation and external wallboards with different PCM was tested. The PCM used in the external layer melts at higher temperature than the inner layer. Hence it is useful during the warm season. According to the numerical simulation, the use of this combined system provides annual energy savings and reduces the peak value of cooling and heating loads by 35.4%. In the same way, Carbonari *et al*. (2006) incorporated PCM in sandwich panels used in prefabricated walls and showed the usefulness of the PCM for improving the thermal behaviour of lightweight envelopes under summer conditions.

In addition, enhanced cellulose insulation with paraffin and hydrated salts has been used in frame walls by Evers *et al*. (2010). The authors used a dynamic wall

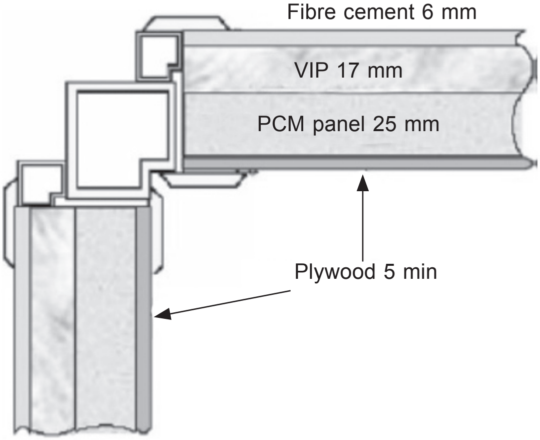


Figure 23.5 Sketch of PCM wallboard with VIP (Ahmad *et al*., 2006).

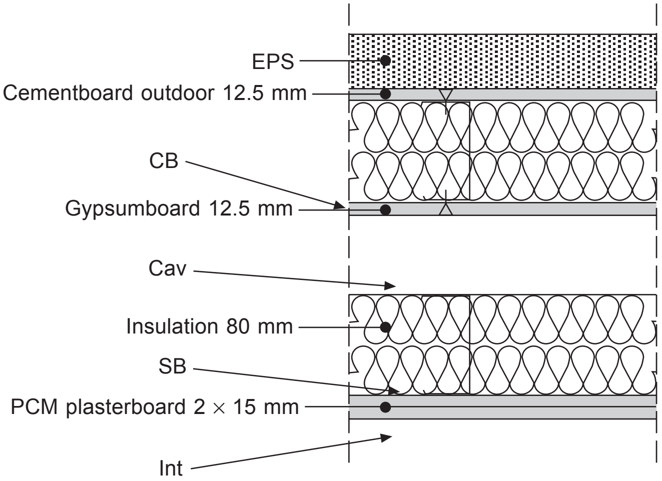
simulator to replicate a typical summer day, and demonstrated that the use of this system can reduce the average peak heat flux by up to 9.2%.

Furthermore, a full-scale lightweight demonstration house which included PCM gypsum boards was constructed in Greece. The house was designed by Mandilaras *et al*. (2013) and is presented as one of the first attempts to investigate experimentally the thermal performance of a house with PCM gypsum boards in all external walls as well as in internal partitions of the building (Figures 23.6 and 23.7). The measurements demonstrated that the indoor air temperatures in all the analysed thermal zones do not significantly vary during a 24 h day-night cycle and this can be attributed to the thermal mass increment in the building envelope.

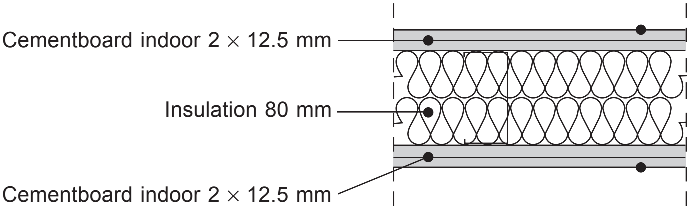
The PCM has also been introduced in the building envelope, being added directly into the bricks. Alawadhi (2008) studied numerically the performance of a common brick with cylindrical holes containing PCM for a hot climate. The addition of PCM reduces the heat flow from the outdoor space by absorbing the heat gain. At night the stored heat is released to indoor and outdoor environments. Moreover, Silva *et al*. (2012) tested experimentally the inclusion of macro-encapsulated PCM into a typical clay brick masonry wall (Figure 23.8). The authors measured the reduction in the indoor thermal oscillation, reducing from 10ºC to 5ºC the thermal amplitude, and the increase of the thermal lag (3 hours) between the indoor and outdoor thermal peak.

The use of macro-encapsulated PCM as passive systems in building envelopes has been monitored in a long-term experimental study at the University of Lleida, Spain. In this experimental set-up, different forms of PCM have been tested (Figure 23.9) in several identically shaped cubicles with internal dimensions of 2.4 m × 2.4 m × 2.4 m. The cubicles present different typical construction morphologies, for

Figure 23.6 Demonstration house including PCM wallboards (Mandilaras *et al*., 2013).



(a) External wall cross-section



(b) Internal wall cross-section

Figure 23.7 Sketch of: (a) the external wall ('CB', 'Cav', 'SB', 'Int' correspond to temperature sensors placed in the LVR east wall); (b) the partition wall with cement boards (Mandilaras *et al*., 2013).

example concrete cubicles (Cabeza *et al*., 2007), brick cubicles and alveolar brick cubicles (Castell *et al*., 2010). Each cubicle is equipped with a heat pump so two main experiments can be performed: free-floating tests and controlled temperature tests.

Castellón *et al*. (2009) compared the performance of the different morphologies using the results from the experimental set-up. As an example, the evolution of the indoor temperature of the different brick cubicles (with/without insulation and with/without PCM) is shown in Figure 23.10. Free-floating experiments were carried out in the brick cubicles, comparing the Reference, PU and RT27 + PU cubicles for a whole week during August 2008, when the outer thermal oscillation allows the PCM to work within its phase change range. As expected, the reference cubicle always presents higher thermal oscillations and it is also more sensitive to the outdoor thermal changes than the PU and RT27+PU cubicles. Furthermore, an increase of the thermal stability is observed because of the addition of PCM when the PU and the

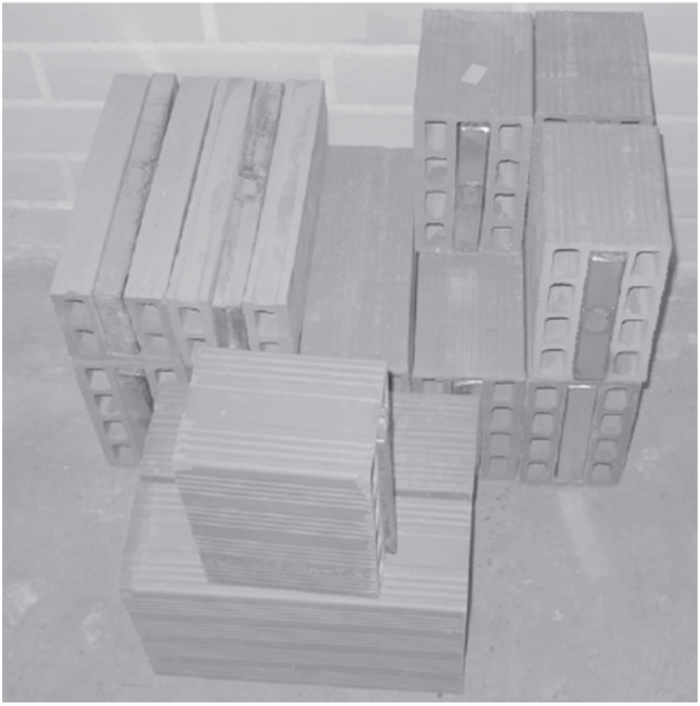


Figure 23.8 Clay bricks with macro-encapsulated PCM (Silva *et al.*, 2012).

Figure 23.9 Experimental set-up located in Puigverd de Lleida, Spain (Castell *et al.*, 2010).

RT27+PU cubicles are compared. The indoor temperature of the RT27+PU cubicle remains closer to the phase change due to the high heat storage capacity of the PCM in this thermal range. Therefore, the RT27+PU cubicle remains cooler (about 0.4°C) for most of the week, when the weather is warmer. On the other hand, at the end of the week (when the weather is cooler) the tendency is reversed, the PU cubicle is cooler than the RT27+PU cubicle. This behaviour can be explained by the higher thermal mass of the PCM cubicle, which slows down the general cooling tendency that occurs in the last days of the week. From the experimental results, it can also be observed that the PCM is only partially used, as there is no single 24 h period in which full melting and solidification are achieved.

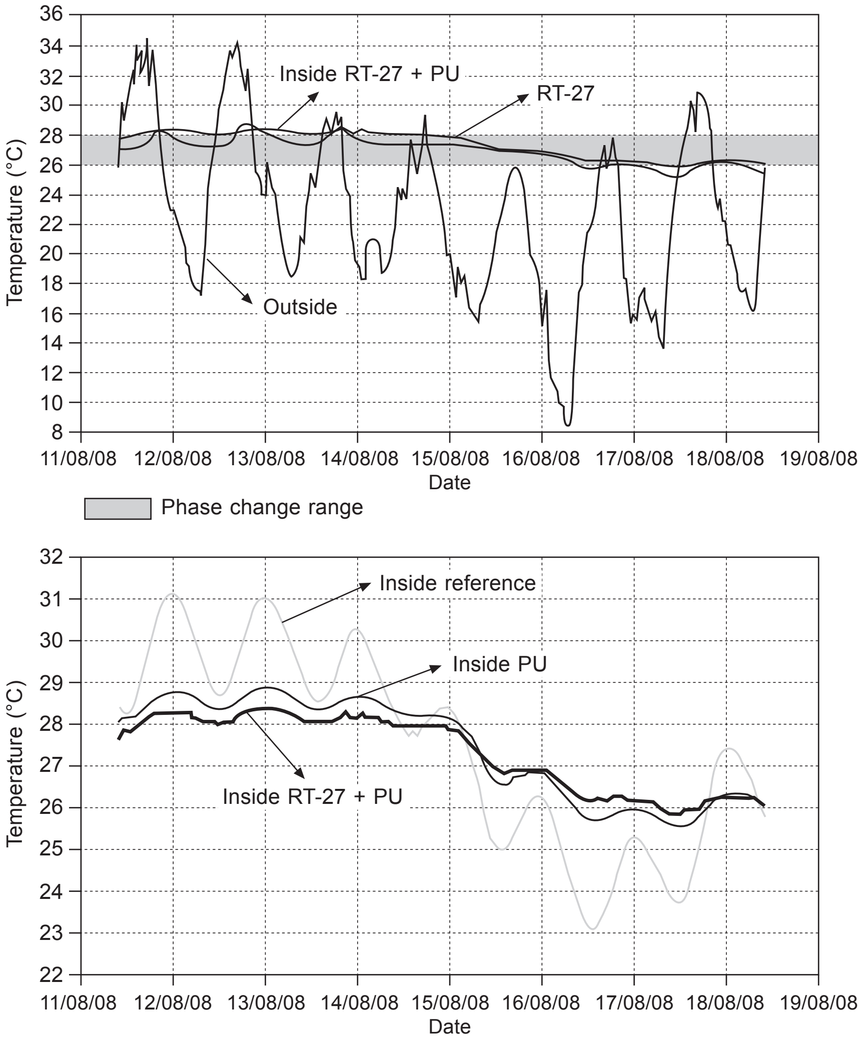


Figure 23.10 Brick cubicle free-floating experiments: (a) weather conditions and PCM operating temperature; (b) indoors ambient temperature for Reference, PU, and RT27+PU cubicles (Castellón *et al*., 2009).

In addition, electrical heat pumps were used to maintain the indoor temperature of the cubicle at a certain set point. Figure 23.11 and Table 23.1 present the results of the controlled temperature experiments at 24ºC for a week in August 2008. An electrical network analyser is used to measure the accumulated energy consumption of each construction system under these conditions. The energy consumption of the Reference cubicle is higher than all the other cubicles, being almost twice the consumption of the other cubicles. The RT27+PU cubicle is the one with the lowest

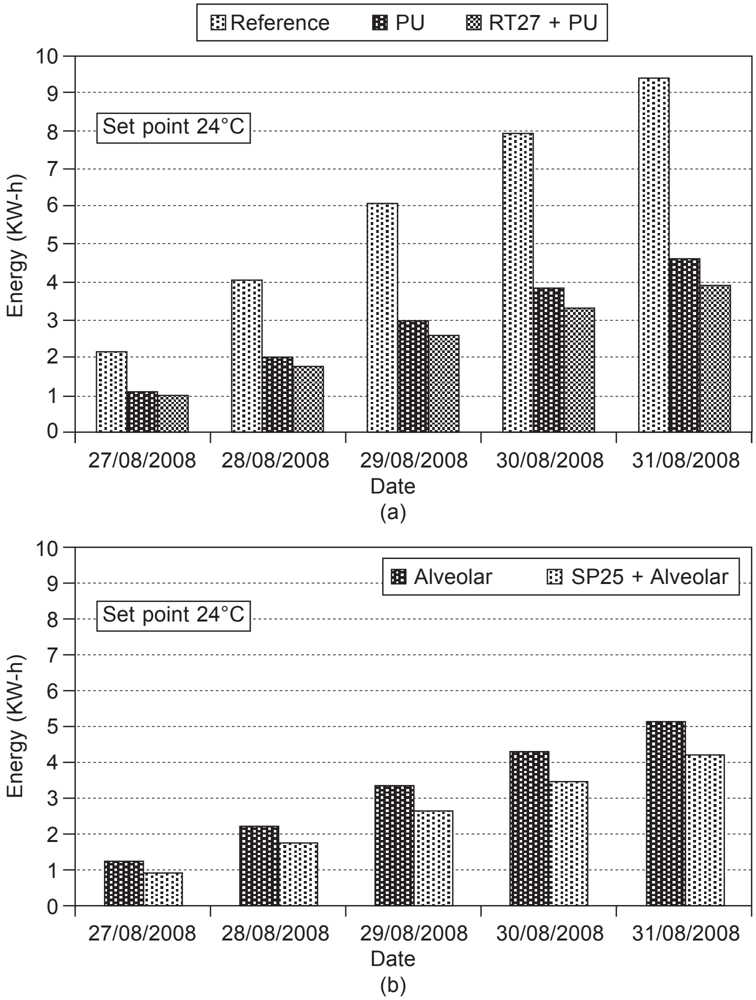


Figure 23.11 Energy consumption of the heat pumps in cooling mode for 5 days in August 2008: (a) Reference, PU, and RT27 + PU; and (b) Alveolar and SP25 + Alveolar cubicles (Castellón *et al.*, 2009).

energy consumption while the SP25+Alveolar cubicle is the second one, consuming even less energy than the PU cubicle. Both PCM cubicles reduced the energy consumption compared with the same cubicle without PCM, which demonstrates the effectiveness of using PCM as passive system under these weather conditions. The RT27+PU cubicle achieved a reduction of 14.75% compared with the PU cubicle, while the SP25+Alveolar cubicle reached 17.12% of energy savings compared with the Alveolar cubicle (Table 23.1).

Table 23.1 **Accumulated energy consumption and energy savings for the different cubicles**

	Energy consumption (Wh)[a]	Energy savings (Wh)[b]	Energy savings (%)[b]	Improvement (%)[c]
Reference	9376	0	0	–
PU	4583	4793	51.1	0
RT27 + PU	3907	5469	58.3	14.8
Alveolar	5053	4323	46.1	0
SP25 + Alveolar	4188	5188	55.3	17.1

Notes: [a] Set point of 24°C for 5 days.
[b] Refer to the reference cubicle.
[c] Refer to the cubicle with analogue constructive solution and w/o PCM.
Source: Castell *et al.* (2010)

23.3 Sustainable cooling through phase change material (PCM) in active systems

The use of night cooling ventilation in addition to PCM is a very powerful strategy for reducing the cooling demand of buildings. Nevertheless, there are inherent drawbacks in the way things have been done so far:

- the limited area of contact between PCM and the air
- the very low convective heat transfer coefficients which prevents the use of significant amounts of PCM
- the very low utilization factor of the cool stored due to the large phase shift between the time when cool is stored and time when it is required by the building.

A very powerful well-known strategy for reducing the cooling demand of buildings is the use of low outdoor air temperatures during the night to cool the structures of the building. In many cases, the night-time outdoor air climatic conditions of many Mediterranean locations allow a significant compensation of the daytime solar and internal heat gains (Allard *et al.*, 1998).

The performance of a night cooling application depends on (Alvarez *et al.*, 1997):

- the climate, which provides the availability of the heat sink in terms of its thermal level and its variability throughout the year and on a daily basis;
- the cooling needs of the building (absolute values and load profiles).

The combination of these two factors gives the extent to which the requirements can be covered by the cooling technique.

Also important is the efficiency of the technology used to transfer heat from the heat sink (night-time outdoor air) to the building.

The efficiency of a night cooling strategy lies in the ability of the building inertia to store cool during the night and to use it during the next day. The role of the inertia appears then double-linked to this strategy. It can be characterized by means of the storage efficiency and the utilization factor (Allard *et al.*, 1998; Alvarez *et al.*, 1997).

The night free cooling effect can be defined as the ability to store outdoor cold during the night and supply it to the indoor environment during the day, when required (Osterman *et al.*, 2012). This concept has been applied within several options, including building elements and external installations.

A new type of ventilated façade with macro-encapsulated PCM in its air cavity was developed by de Gracia *et al.* (2013a). The thermal performance of this special building envelope was experimentally tested to analyse its potential in reducing the cooling demand during the summer season in the Continental Mediterranean climate, and it was numerically extrapolated to different performance scenarios (de Gracia *et al.*, 2013b). Two identical house-like cubicles located in Puigverd de Lleida, Spain, were monitored during summer 2012, and in one of them, a ventilated façade with PCM was located in the south wall (Figure 23.12). Six automatic gates were installed at the different openings of the channel in order to control the operational mode of the façade. This versatility allows the system to be used as a cold storage unit, as an overheating protection system or as a night free cooling application. The experimental results demonstrated the high potential of the night free cooling effect in reducing the cooling loads of a building. This operation mode could inject air at a temperature below the set point under both severe and mild summer conditions (34.9 MJ·day^{-1} and 42.8 MJ·day^{-1}, respectively). The system can successfully prevent the overheating effect between the PCM solidification and melting periods, bringing the air inside the cavity even lower than the outer environmental temperature during the

Figure 23.12 Experimental set-up to test a ventilated façade with macro-encapsultated PCM in its air cavity located in Spain (de Gracia *et al.*, 2013a).

peak load. The thermal performance of this system is very sensitive to the weather conditions and the cooling demand of the final users.

Similarly, Yanbing *et al.* (2003) incorporated a PCM packed bed storage (Figure 23.13) which is charged using low night-time outer temperature air, and this stored cold is discharged when demanded. The authors demonstrated the efficiency of the system with experimental measurements and used a numerical model to optimize its design.

Cold storage using low temperature at night has also been explored using an independent installation connected to the building, as shown in Figure 23.14. This concept was investigated by Zalba *et al.* (2004) using a thermal energy storage device based on rectangular macro-encapsulated PCM panels, and by Takeda *et al.* (2004) using a PCM granule packed bed.

Apart from the cold storage sequences using the night free cooling, PCM has also been adapted into different building active systems in order to reduce the electrical demand by reducing the cooling load or to provide a peak load shifting and hence make use of the low tariff electricity.

Nagano *et al.* (2000) presented a floor air conditioning system with latent heat storage in buildings. The floor size of the experimental cell was 0.5 m^2. Granulated phase change material was made of foamed waste glass beads and a mixture of paraffin. The PCM packed bed of 3 cm thickness was installed under the floorboard with multiple small holes. The change in room temperature and the amount of stored heat were measured and results showed the possibilities of cooling load shifting by using packed granulated PCM. These new solutions use PCM in containers, which are located inside an air chamber, where air is moved by fans with variable flow (forced convection). This air flow is controlled by a system that can change the air flow rate, the origin and the destination of air flow. They can even stop the system totally. The PCM containers are sealed, made of a material which does not react

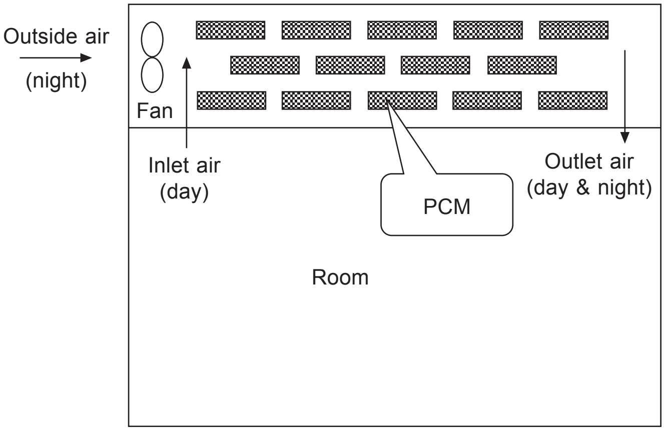


Figure 23.13 Sketch of the night ventilation with PCM packed bed storage (NVP) system (Yanbing *et al.*, 2003).

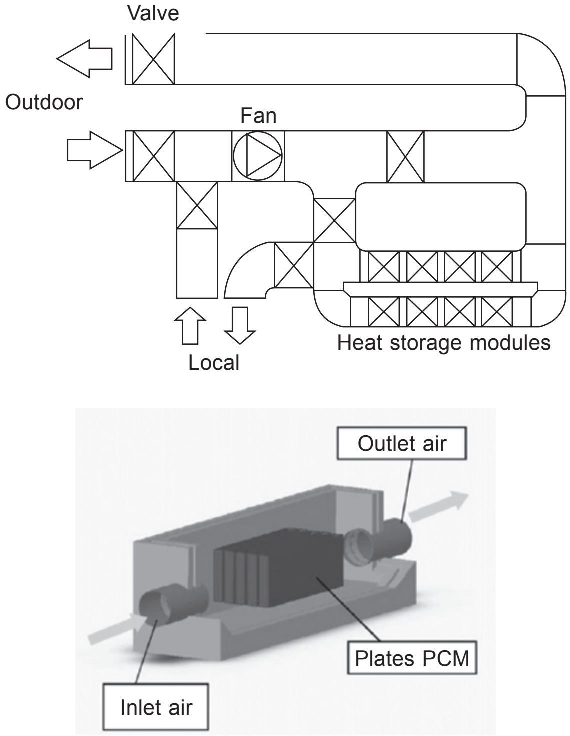
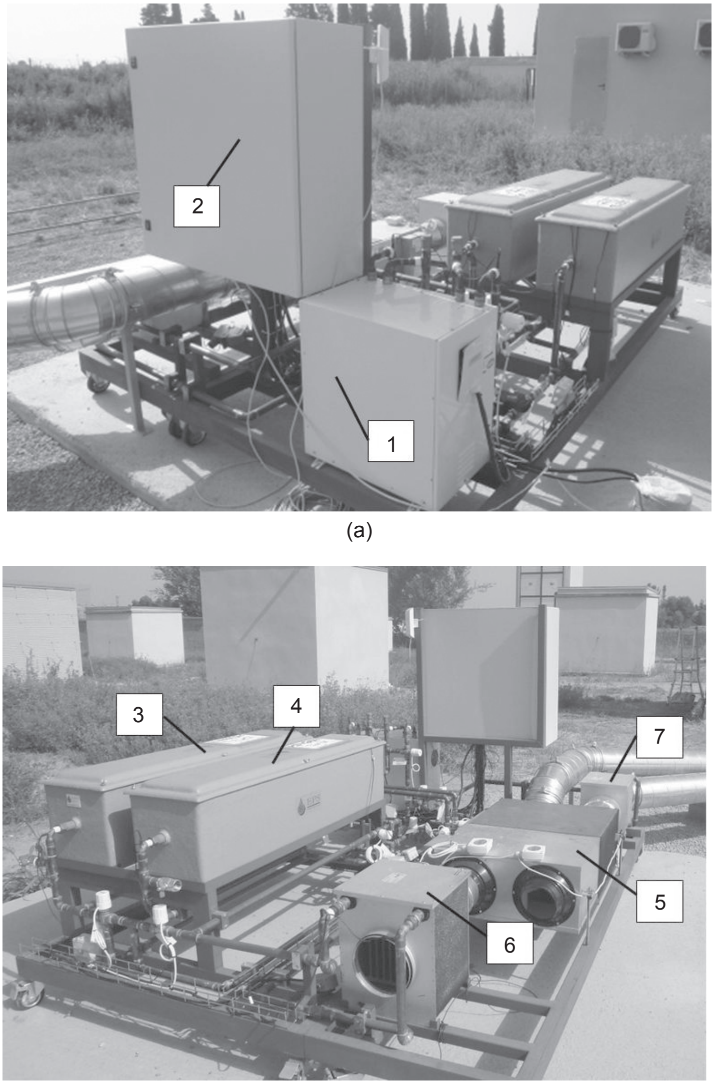


Figure 23.14 Sketch of the installation and detail of the TES device (Zalba *et al.*, 2004).

with the PCM, and its shape and its arrangement pretend to stimulate heat exchange with the air around it. In principle, three basic forms have been considered: fins, cylinders and spheres.

Furthermore, Moreno *et al.* (2013) evaluated experimentally the energetic performance of an external heat exchanger with PCM for a domestic heat pump system (Figure 23.15). In this system the cooling demand is produced in low peak periods and stored for later use when space cooling is required. A comparative study against a water storage tank with the same dimensions reveals that the use of PCM increases the supplied thermal energy from the heat pump bu 29%.

Koschenz and Lehmann (2004) put forward a new concept of thermally activated ceiling panels for refurbished buildings. The system is designed to be used in standard office buildings with high thermal loads, hence the thermal storage capacity of the ceiling panels has to accommodate the heat gains within the daily cycle. In this system, the mixture of micro-encapsulated PCM and gypsum was poured into a sheet steel tray which was used as a support for maintaining the mechanical stability of the panels. A capillary water tube system was applied to control the thermal mass. They tested the thermal performance of this system and indicated that a 5 cm layer of micro-encapsulated PCM and gypsum was enough for a standard office to keep within comfortable temperatures.

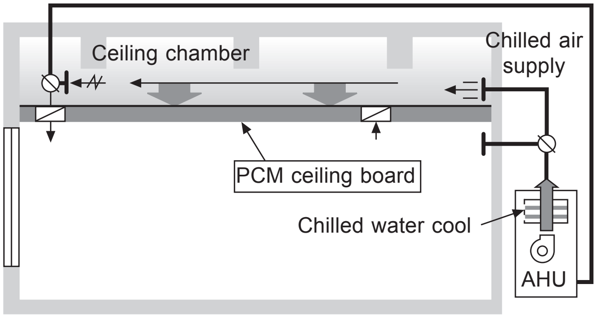


(a)

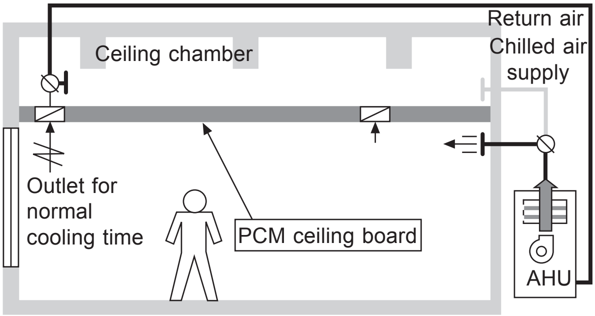
(b)

Figure 23.15 HVAC system devices: (1) heat pump, (2) control panel, (3) cold storage tank, (4) heat storage tank, (5) air handling unit, (6) outlet water-to-air heat exchanger, (7) inlet water-to-air heat exchanger.

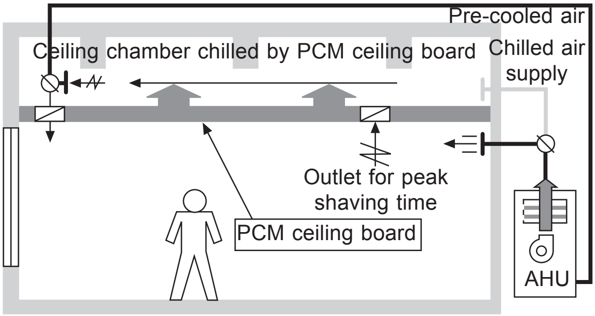
Moreover, ceiling boards can incorporate PCM for heating and cooling of buildings. An example is that developed by Kodo and Ibamoto (2002), where PCM is used for peak shaving control of air conditioning systems in an office building (Figure 23.16). The authors claim that these systems have some advantages over conventional building thermal storage systems that use concrete floor slabs:



(a) Overnight thermal storage time



(b) Normal cooling time



(c) Peak shaving control time

Figure 23.16 Ceiling board with PCM for cooling peak shaving (Kodo and Ibamoto 2002).

- more efficient thermal storage is expected, since high density cool air pools on the PCM ceiling board that forms the floor of the ceiling space;
- all of the ceiling board can be used for thermal storage, since the cool air can flow through the ceiling chamber without being interrupted by beams;
- since the surface temperature of the ceiling board is kept at the PCM melting point for an extended period, the indoor thermal environment, including the radiant field, can be improved.

Ceiling boards incorporated with PCMs for air conditioning systems play an effective role in the peak shaving control. Saman and Belusko (1997) developed a roof-integrated solar air heating storage system. The latent heat storage unit, in which an existing corrugated iron roof sheet is used as solar collector, is to store heat during the day and supply the heat at night or when sunshine is unavailable. Besides experimental analysis, many numerical works were also carried out on the thermal performance analyses of this system (Vakilaltojjar and Saman, 2001; Saman *et al.*, 2005).

23.4 Sustainable cooling through sorption systems

Most sorption systems are being developed for heating, although they may be adapted to be used for cold applications.

ClimateWell (Jonsson *et al.*, 2000; Bolin, 2005; Olsson and Bolin, 2007) developed a system combining short-term absorption thermal storage and solar cooling technologies based on a three-phase absorption cycle. The tests showed that with a 35 kWh heat input, a cooling storage capacity of 22 kWh could be obtained. The calculated energy density for LiCl was 253 kWh/m^3, giving a final energy density 1.2 times that of water.

The working pair zeolite 13X/water was used by Lu *et al.* (2003) in a closed adsorption cold storage system. This prototype has one adsorber and a cold storage tank (Figure 23.17). The average cooling power reported is 4.1 kW and the total

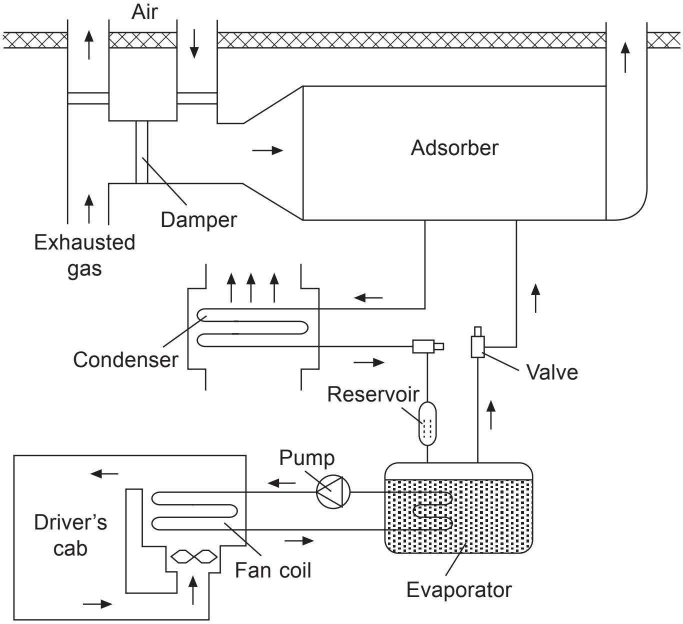


Figure 23.17 Zeolite/water adsorption cold storage system (Lu *et al.* 2003).

experimental capacity of the cold storage 5.5 kWh when the temperature of the adsorption bed reached its maximum value of 125ºC.

The SWEAT prototype was developed by Boer *et al.* (2004). It contains a modular chemical adsorption cooling system using the working pair Na_2S/H_2O (Figure 23.18) with a shell and tube design, a condenser, and an evaporator coil. The results showed that a cold storage capacity of 2.1 kWh and a cooling coefficient of performance (COP) of 0.56 were achieved with a heat input of 3.7 kWh.

Mauran *et al.* (2008) demonstrated that the most challenging feature that needs to be overcome in this types of concept are the heat transfer problems encountered. They used a storage prototype with the reversible chemical reaction between $SrBr_2$ and H_2O. The reactor integrated an evaporator/condenser for the solid-gas reaction.

Stitou *et al.* (2011) developed a solar air conditioning pilot plant with a daily cooling capacity of 20 kWh with a working pair of $BaCl_2/NH_2$ (Figure 23.19). The heat input was at 60–70 ºC from 20 m^2 of flat plate solar collectors. As well as Mauran *et al.* (2008), this prototype included expanded graphite in the design to

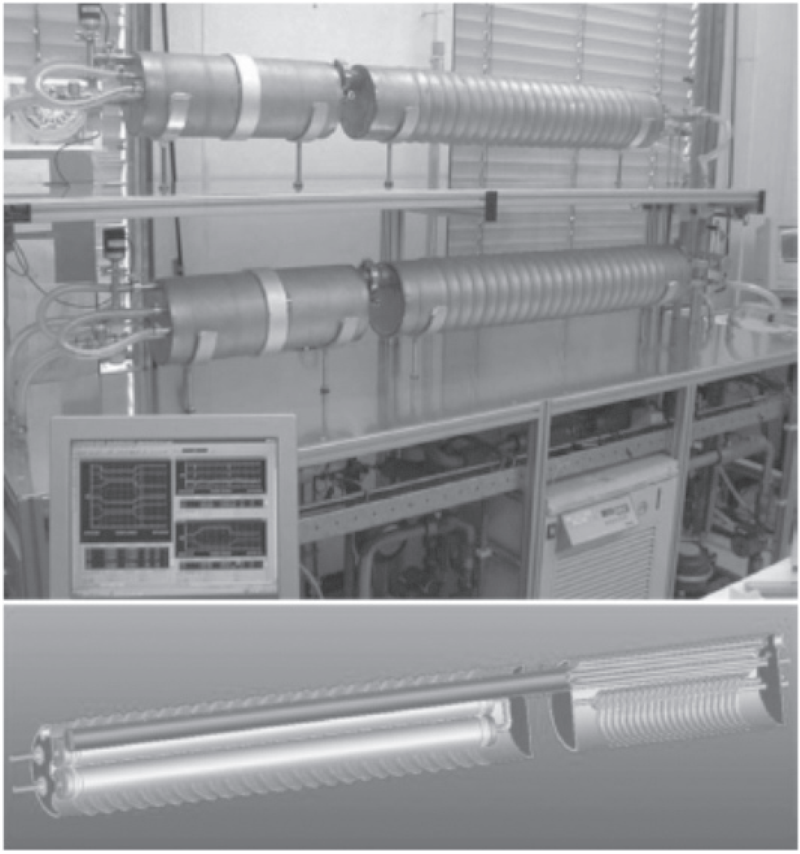


Figure 23.18 SWEAT storage concept (Boer *et al.* 2004).

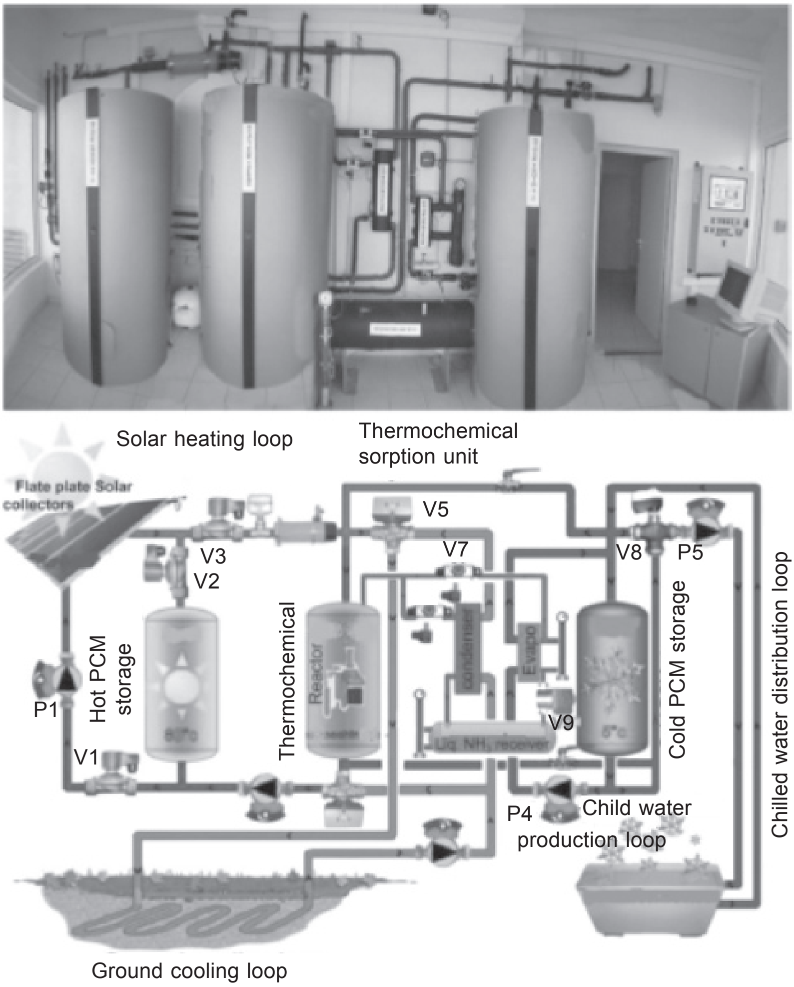


Figure 23.19 Solar sorption pilot plant for air conditioning (Stitou *et al.*, 2011).

improve the heat transfer. The prototype also included a hot PCM tank to store the excess solar heat, and a cold PCM tank to supply cooling when the sorption reaction is not available. Experiments over 2 years showed an average yearly efficiency of solar collectors of 0.4–0.5 and COP of 0.3–0.4. The daily storage capacity was about 0.8–1.2 $kWh \cdot m^{-2}$ plate solar collector at 4°C.

ZAE Bayern installed a large-scale open adsorption TES using zeolite 13X/water to heat a school building in winter and to cool a jazz club in summer in Munich (Hauer, 2002, 2007) (Figure 23.20). The prototype obtained storage densities of 124 $kWh \cdot m^{-3}$ for heating and 100 $kWh \cdot m^{-3}$ for cooling with a COP of 0.9 and 0.86, respectively.

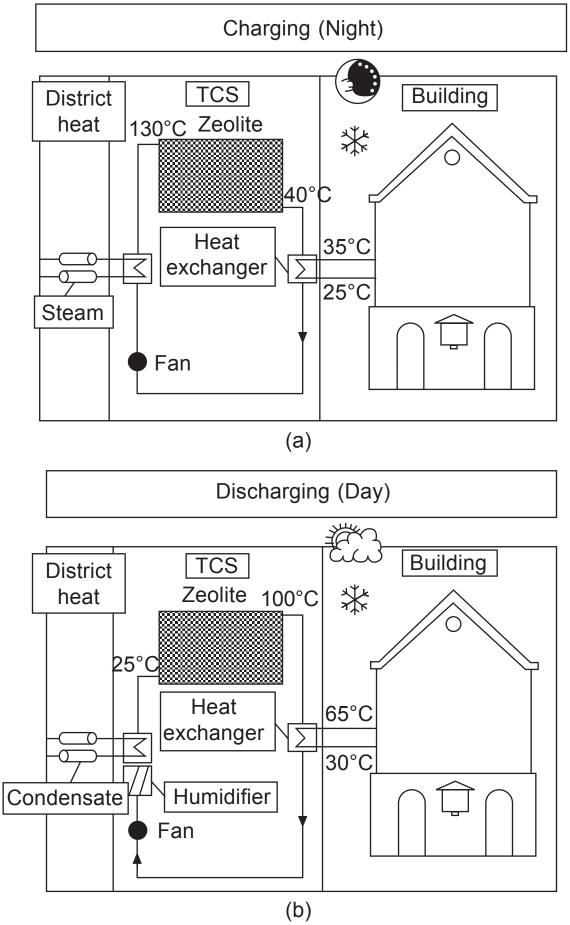


Figure 23.20 Open adsorption TES system connected to the district heating system in Munich (Hauer, 2002).

23.5 Sustainable cooling through seasonal storage

23.5.1 Underground thermal energy storage (UTES)

Underground thermal energy storage (UTES) both with boreholes (BTES) and aquifers (ATES) are the most developed storage concepts and are mostly used for seasonal storage. Descriptions of the concepts can be found in Paksoy (2007) and Cabeza (2012).

Heat/cold storage in ATES consists in extracting groundwater from a well, heating/cooling this water with an available heat/cold source, and then re-injecting it back into the aquifer in the other well. The estimated heat storage capacity of 10^5 m^3 of aquifer is 3 MJ for each 10 K temperature range (Hasnain, 1998).

23.5.2 Water pits and solar ponds

Novo *et al*. (2010) reviewed TES systems in large basins (water tanks and gravel-water pits). These authors claimed that the energy costs can be reduced with increasing storage volume in large-scale solar applications. Up to now, these systems have only been used for heating. Novo *et al*. (2010) presented a comparison of these storage systems, stating that the gravel-water pit technology can reduce construction costs and the upper part of the store can be used as part of the residential area, but needs more volume to store the same thermal energy as a water tank design. The demonstration sites showed that solar collector efficiency and heat losses from the storage tank and the piping network are most important.

23.5.3 Thermochemical storage

Most of the concepts presented in Section 23.4 as sorption systems are being further developed today for seasonal storage, mostly for heating.

23.6 Conclusions

Statistics show that there is a need to develop technologies to achieve thermal comfort in buildings, lowering the cooling demand. Thermal energy storage is one way to do so. This chapter reviews TES in buildings using latent heat and thermochemical energy storage.

Sustainable cooling with TES in buildings can be achieved through different systems:

- *Passive systems in building envelopes*. The use of PCM as a passive energy system in the building sector has the objective of reducing the energy demand of space heating and cooling of the whole building, basically smoothing the indoor temperature by increasing the heat storage capacity of the envelope. Different studies are shown here.
- *PCM in active systems*. This chapter shows that a very powerful well-known strategy for reducing the cooling demand of buildings is the use of low outdoor air temperatures during the night to cool the structures of the building. This can be done, for example, through the HVAC system, through active floorboards or ceilings, or with ventilated façades with macro-encapsulated PCM in their air cavity.
- *Sorption systems*. Most sorption systems are being developed for heating, although they may be adapted to be used for cold applications. This chapter has presented the current research in this topic.
- *Seasonal storage*. This can be carried out with UTES, water pits and solar ponds and with thermochemical storage.

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References

Ahmad M, Bontemps A, Sallée H and Quenard D. Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material. *Energy and Buildings* 2006; 38: 673–681.

Alawadhi E.M. Thermal analysis of a building brick containing phase change material. *Energy and Buildings* 2008; 40: 351–357.

Allard F, Santamouris M, Álvarez S, Guarraccino G and Maldonado E. *Natural Ventilation in Buildings: A Design Handbook*. Berlin: Earthscan/James & James, 1998.

Alvarez S, Maestre I and Velazquez R. Design methodology and cooling potential of the environmental heat sinks. *Int J Sol Energy* 1997; 19(1–3): 179–197.

Barreneche C, de Gracia A, Serrano S, Navarro ME, Borreguero AM, Fernández AI, Carmona M, Rodríguez JF and Cabeza LF. Comparison of three different devices available in Spain to test thermal properties of building materials including phase change materials. *Applied Energy* 2013; 109: 421–427.

Boer RD, Haije WG, Veldhuis JBJ and Smeding SF. Solid-sorption cooling with integrated thermal storage: the SWEAT prototype. In: *Proceedings of HPC 2004 – 3rd International Heat Powered Cycles Conference*, Larnaca, Cyprus, 2004.

Bolin G. Chemical heat pump working according to the hybrid principle. International patent publication No. WO 2005/054757 A1, 2005.

Cabeza LF. Thermal energy storage. In: Sayigh A (ed.). *Comprehensive Renewable Energy, Vol 3*, pp. 211–253. Oxford: Elsevier, 2012.

Cabeza LF, Castellón C, Nogués M, Medrano M, Leppers R and Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings* 2007; 39: 113–119.

Carbonari A, Grassi MD, Perna CD and Principi P. Numerical and experimental analysis of PCM containing sandwich panels for prefabricated walls. *Energy and Buildings* 2006; 38: 472–483.

Castell A, Martorell I, Medrano M, Pérez G and Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings* 2010; 42: 534–540.

Castellón C, Castell A, Medrano M, Martorell I and Cabeza LF. Experimental study of PCM inclusion in different building envelopes. *Journal of Solar Energy Engineering. Transactions of the ASME* 2009; 131: 0410061.

de Gracia A, Navarro L, Castell A, Ruiz-Pardo Á, Álvarez S and Cabeza LF. Thermal analysis of a ventilated facade with PCM for cooling applications. *Energy and Buildings* 2013a; 65: 508–515.

de Gracia A, Navarro L, Castell A and Cabeza LF. Numerical study on the thermal performance of a ventilated facade with PCM. *Applied Thermal Engineering* 2013b; 61(2): 372–380.

Diaconu BM and Cruceru M. Novel concept of composite phase change material wall system for year-round thermal energy savings. *Energy and Buldings* 2010; 42: 1759–1772.

Evers AC, Medina MA and Fang Y. Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salts phase change materials using a dynamic wall simulator. *Building and Environment* 2010; 45: 1762–1768.

Hasnain SM. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management* 1998; 39: 1127–1138.

Hauer A. Thermal energy storage with zeolite for heating and cooling applications. In: *Proceedings of ISHPC 2002 – International Sorption Heat Pump Conference*. Shanghai, China, 2002.

Hauer A. Sorption theory for thermal energy storage. In: Paksoy HO (ed.) *NATO Sciences Series, II. Mathematics, Physics and Chemistry, Vol. 234: Thermal Energy Storage for Sustainable Energy Consumption: Fundamentals, Case Studies and Design*, pp. 393–408. Dordrecht: Springer, 2007.

Jonsson S, Solsson R and Kaarebing-Olsson M. A chemical heat pump. International patent publication No. WO 00/37864 A1; 2000.

Kodo T and Ibamoto T. Research on using the PCM for ceiling board, IEA ECES IA, Annex 17, 3rd workshop, Tokyo, Japan, October 1–2, 2002.

Koschenz M and Lehmann B. Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. *Energy and Buildings* 2004; 36: 567–578.

Kuznik F and Virgone J. Experimental investigation of wallboard containing phase change material: data for validation of numerical modelling. *Energy and Buildings* 2009; 41: 561–570.

Kuznik F, Virgone J and Noel J. Optimization of a phase change material wallboard for building use. *Applied Thermal Engineering* 2008a; 28: 1291–1298.

Kuznik F, Virgone J and Roux JJ. Energetic efficiency of room wall containing PCM wallboard: a full-scale experimental investigation. *Energy and Buildings* 2008b; 40: 148–156.

Kuznik F, Virgone J and Johannes K. *In-situ* study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. *Renewable Energy* 2011; 36: 1458–1462.

Lu YZ, Wang RZ, Zhang M and Jiangzhou S. Adsorption cold storage system with zeolite-water working pair used for locomotive air conditioning. *Energy Conversion and Management* 2003; 44: 1733–1743.

Lv SL, Zhu N and Feng GH. Impact of phase change wall room on indoor thermal environment in winter. *Energy and Buildings* 2006; 38: 18–24.

Mandilaras I, Stamatiadou M, Katsourinis D, Zannis G and Founti M. Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls. *Building and Environment* 2013; 61: 93–103.

Mauran S, Lahmidi H and Goetz V. Solar heating and cooling by a thermochemical process: first experiments of a prototype storing 60 kWh by a solid/gas reaction. *Solar Energy* 2008; 82: 623–636.

Moreno P, Solé C, Castell A, Zsembinszki G and Cabeza LF. Experimental analysis of TES tank using PCM in space cooling system. *International Conference on Applied Energy* 2013, ICAE 2013-157.

Nagano K, Mochida T, Iwata K, Hiroyoshi H, Domanski R and Rebow M. Development of new PCM for TES of the cooling system. In: Benner M, Hahne EWP, eds. Terrastock: *8th International Conference on Thermal Energy Storage*, 2000, pp. 345–50.

Novo AV, Bayon JR, Castro-Fresno D and Rodriguez-Hernandez J. Review of seasonal heat storage in large basins: water tanks and gravel-water pits. *Applied Energy* 2010; 87: 390–397.

Olsson R and Bolin G. Chemical heat pump working according to the hybrid principle. International patent publication No. WO 2007/139476 A1, 2007.

Osterman E, Tyagy VV, Butala V, Rahim NA and Stritih U. Review of PCM based cooling technologies for buildings. *Energy and Buildings* 2012; 49: 37–49.

Paksoy HO (ed.) *NATO Sciences Series, II. Mathematics, Physics and Chemistry, Vol. 234: Thermal Energy Storage for Sustainable Energy Consumption: Fundamentals, Case Studies and Design*, pp. 393–408. Dordrecht: Springer, 2007.

Saman WY and Belusko M. Roof integrated unglazed transpired solar air heater. In: Lee T., ed., *Proceedings of the 1997 Australian and New Zealand Solar Energy Society*. Paper 66, Canberra, Australia, 1997.

Saman W, Bruno F and Halawa E. Thermal performance of PCM thermal storage unit for a roof integrated solar heating system. *Solar Energy* 2005; 78: 341–349.

Schossig P, Henning H-M, Gschwander S and Haussmann T. Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Mater Solar Cells* 2005; 89: 297–306.

Sharma A, Tyagi VV, Chen CR and Buddhi D. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews* 2009; 13: 318–345.

Silva T, Vicente R, Soares N and Ferreira V. Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: a passive construction solution. *Energy and Buildings* 2012; 49: 235–245.

Soares N, Costa JJ, Gaspar AR and Santos P. Review of passive PCM latent thermal energy storage systems towards buildings' energy efficiency. *Energy and Buildings* 2013; 59: 82–103.

Stitou D, Mazet N and Mauran S. Experimental investigation of a solid/gas thermochemical storage process for solar air-conditioning. *Energy* 2011; 41: 261–270.

Takeda S, Nagano K and Mochida T. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. *Solar Energy* 2004; 77: 329–338.

Urge-Vorsatz D, Eyre N, Graham P, Harvey D, Hertwich E, Jiang Y, Kornevall C, Majumdar M, McMahon JE, Mirasgedis S, Murakami S and Novikova A. Energy end-use: building. In *Global Energy Assessment – Toward a Sustainable Future*, Cambridge University Press, Cambridge, 2012, pp. 649–760.

Urge-Vorsatz D, Petrichenko K, Staniec M and Eom J. Energy use in buildings in a long-term perspective. *Current Opinion in Environmental Sustainability* 2013: 5(2): 141–151.

Urge-Vorsatz D, Cabeza LF, Serrano S, Barreneche, C and Petrichenko K. Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews* 2014; in Press.

Vakilaltojjar SM and Saman W. Analysis and modelling of a phase change storage system for air conditioning applications. *Applied Thermal Engineering* 2001; 21(3): 249–263.

Yanbing K, Yi J and Yinping Z. Modeling and experimental study on an innovative passive cooling system – NVP system. *Energy and Buildings* 2003; 35: 417–425.

Zalba B, Marín JM and Cabeza LF. Free-cooling of buildings with phase change materials. *International Journal of Refrigeration* 2004; 27: 839–849.